BIOPOLYMERIZED SLOPE AND SUBGRADE STABILIZATION AND ADVANCED FIELD MONITORING

F I N A L R E P O R T

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16. Abstract

The slightly overconsolidated glacial tills and weathered shales in Midwestern states of the USA often show substantial strength degradation after construction. This strength reduction often causes time dependent slope failures along the roadside. This study investigated the possibility of applying biopolymer based soil modification techniques to mitigate the strength reduction phenomenon of these soils. For this research, several different biopolymers were evaluated through laboratory tests, two biopolymers were selected for extensive weathering tests, then a higher-performing biopolymer, Xanthan, was applied to a test slope in Verdigre, Nebraska with heavy instrumentation. The followings are the summary of the results.

The unweathered laboratory shear strength of the weathered shales from Verdigre was improved by 20%, 30%, and 40% by mixing 0.5%, 1.5%, and 2.5% of Xanthan gum, respectively. On the other hand, the weathered shear strength of the weathered shales at Verdigre treated with 1.5% of Xanthan gum after 8 wet-freeze-thaw-dry cycles still retained 83% of the untreated unweathered ones. A similar result was obtained for glacial tills, manifesting that the Xanthan based polymerization method may be used as a new eco-friendly method to enhance the strength of weathered shales and glacial tills in Midwestern states. The field applied Xanthan treated soils showed similar behavior to laboratory test results based on pressuremeter and vane shear test results so far. However, further monitoring is required to fully verify the findings.

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Chapter 1

Introduction

Nebraska experiences a high number of landslides concentrated along roadside slopes (Eversoll, 2013). The previous NDOT research, project M-061 (Nebraska Specific Slope Design Manual), discovered that the strength degradation of slightly overconsolidated glacial tills from Lincoln and weathered shales from Verdigre is a major cause of the landslides. Proper remediation techniques, therefore, need to be devised.

A typical remediation technique would be the one that relies on external structures to support the slope when the strength of field soils is severely degraded. Another common option may be to fortify the soil and maintain the initial strength of field soils. The techniques based on the first principle are earth anchors, soil nailing, and berms. These techniques are usually expensive or require extra space on the downstream side of the slope. The techniques based on the second principle are grouting or field mixing, and these options are usually more economical. Due to the mineralogy of soils and weather conditions in Nebraska, most grouting liquids are not optimal; many may exhibit either injectability issues, environmental issues, or develop premature deterioration in cold weather, based on Karol (2003).

The M-061 study found that the strength reduction of field soils and associated slope failure may be effectively prevented by applying biopolymers to field soils due to their high tolerance to sub-freezing temperature. Besides, biopolymers are environmentally friendly because they are produced for food additives. The application of biopolymers is rapidly increasing (De Jong et al. 2010, Chang et al. 2015, 2016) in the geotechnical area.

They have not, however, been widely used for the stabilization of slopes up to date. In the M-061 study, six different biopolymers were preliminarily tested at UNL's Geotechnical Lab. They demonstrated significant strength gain, with up to a 300% strength increase. Two promising biopolymers, Xanthan and Gellan were further tested under well-controlled, severe weathering conditions. They presented minimal strength degradation over time for glacial tills. The result also shows that the strength reduction was stabilized after 8 weathering cycles.

In addition to their strength enhancing properties, biopolymers are economical, where 1 lb. of biopolymer costs approximately $20-$50 and can treat approximately 100 lbs. of soils. Based on the promising laboratory test results, this research conducted additional lab tests for local soils (glacial tills for road bed materials in Lincoln, NE, and weathered shales from a failed slope in Verdigre, NE) and a follow-up field application to failed slopes in Verdigre, Nebraska. Subsequently, this research performance evaluation of the biopolymers as a sustainable and economic slope stabilization/retrofitting technique. Selected biopolymers from this study can be easily applied to fields by field mixing technique.

Evaluation of the field performance of biopolymer-treated soils shall be accompanied by proper testing and monitoring plan with sophisticated equipment and novel evaluation techniques. This research team plans to utilize laboratory testing(Direct shear tests) and in situ testing techniques such as CPT and Selfboring pressuremeter to monitor the strength and the modulus degradation of soils throughout the field weathering process. Fiber optic cable based deformation measurements and rapid aerial imaging based deformation measurements were adopted to monitor the overall deformation configuration of the test sites.

Chapter 2

Literature Review

In this chapter, a thorough literature review on the existing works, particularly on the effect of different biopolymers on the shear strength, permeability, and compaction parameters of different soils, was conducted. The durability of the biopolymer/soil mixtures under severe weathering cycles was also investigated.

2.1 Cement

Soil/cement mixture has been used widely in many geotechnical applications. Studies show that cement has a significant effect on increasing the shear strength of the soils. However, despite the considerable cement benefits, several environmental issues have been raised.

Figure 2.1(a) shows the ratio of CO_2 emissions during cement creation to the total CO_2 emission is about 9%. And it has consistently increased through the years (Oss, H.G.V. 2014). Furthermore, Figure 2.1(b) shows the parabolic annual growth rate of CO_2 emission from cement production increases; it went over 10% in 2010 (Rapier, R. 2012).

Moreover, using cement as a stabilizer raises another environmental issue in terms of soil and water pollution. The existence of cement in the soil increases the PH value of the soil, possibly up to 12 based on Taylor, H.F.W. (1997). Croft 1967 found that cement grouting worked better for Illite and Kaolinite clays, but it was unsuitable for expansive clays which contain a high amount of Montmorillonite. Lees & Chuaqui (2003) reported that regular cement grout should be used for soils with a permeability higher than $10^{-3} m/s$ which is usually gravel and sandy soils.

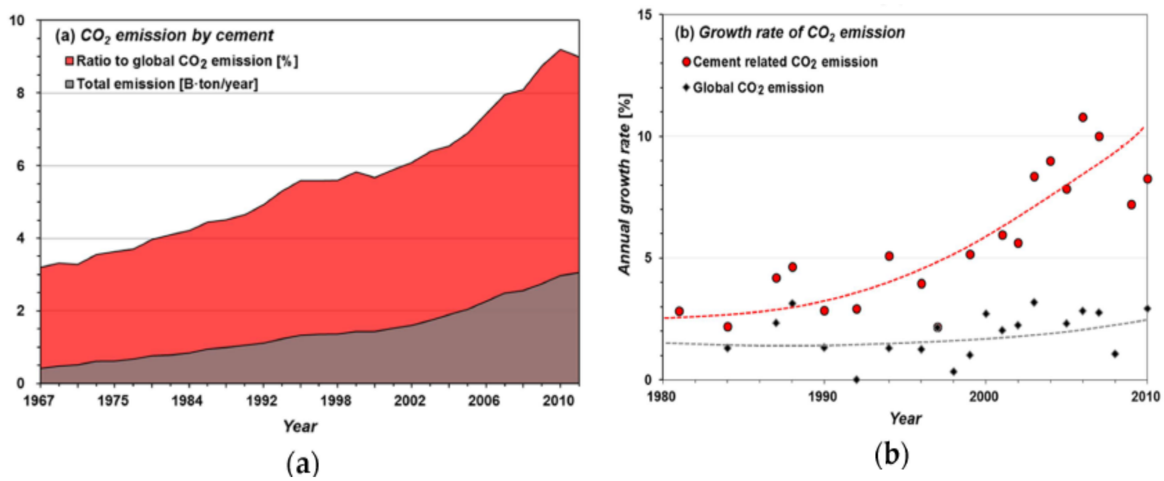


Figure 2.1 CO_2 emission of cement producing during the years (Chang et al., 2016)

On the other hand, results from Landary et al. (2000) showed that the microfine cement grout is suitable for soil with a permeability greater than $5 \times 10^{-5} m/s$ which is usually sandy-silty soils. Figure 2.2 shows grain size ranges for chemically groutable soils. From this figure, cement grouting might not be appropriate for clayey soil, since its permeability ranges between 10^{-5} to 10^{-9} *m/s* or even lower. Therefore, applying cement grouting in Verdigre slopes in Nebraska which mostly contain clayey particles, might not be an effective solution in improving the soil properties.

Besides, research conducted by Au et al. (2003) showed a decrease in long term cement/bentonite grout efficiency of lightly overconsolidated and normally consolidated clays.

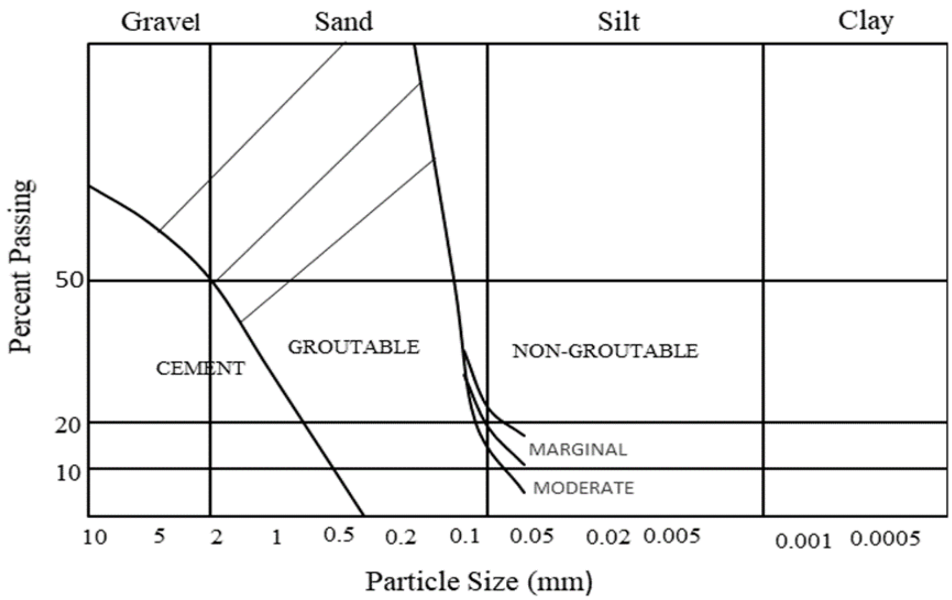


Figure 2.2 Grain size ranges for chemically groutable soil (Replotted from Lees & Chuaqui, 2003)

2.2 Sodium silicate

Sodium silicate SiO_2Na_2O, is a colloidal solution whose strength and penetrability depend on the thickness of the solution. Silica gels are usually considered permanent material. However, water may separate from the gel during the hardening process, resulting in grout shrinkage. Suganya et al. (2016) studied the effect of sodium silicate on soft clayey soils stabilized with cement. The soil that was used had a high liquid limit and a high plasticity index. The results showed that the strength of the stabilized soil increased by increasing the percentage of sodium silicate, as shown in Figure 2.3. However, Figure 2.3 also indicates that grouted soils become more brittle, which is not very desirable.

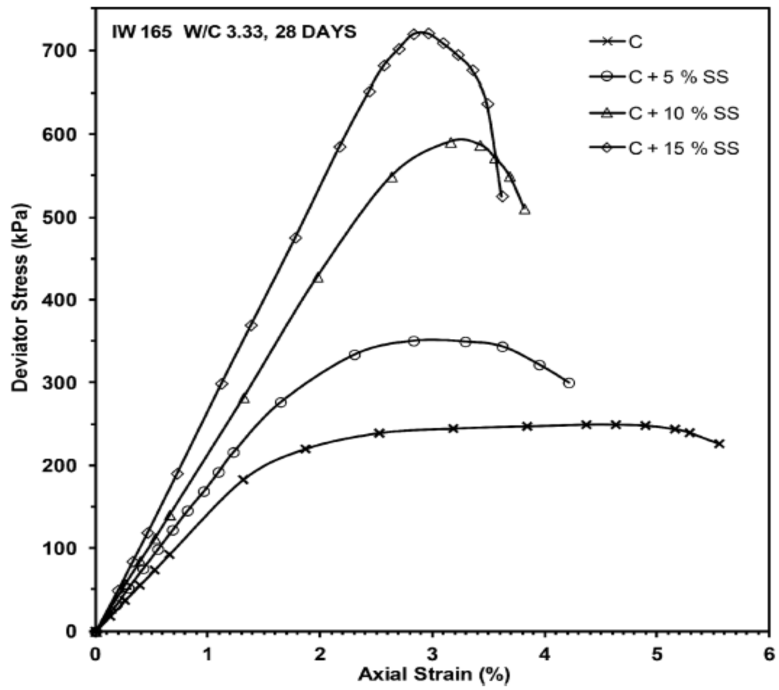


Figure 2.3 Stress-strain behavior of cement (C)–treated soil with sodium silicate (SS) additive (Suganya et al., 2016)

2.3 Acrylamide

This chemical grouting was introduced as a stabilizer around 1950. The unique advantage of this material is its water-like viscosity and density. According to Kazemian and Barghchi (2012), this material can easily penetrate due to its low viscosity and has sufficient strength in many applications. However, another research effort made by Kutzner (1996) showed that acrylamide gel may experience mechanical failure when it is exposed to freeze-thaw cycles. Therefore, acrylamide may not be suitable for the soils in Nebraska.

2.4 Acrylate

This chemical was introduced in the early 1980s. It is more viscous but less toxic in comparison with acrylamide (Karol, 2003). It shares the same weakness with acrylamide by showing weak resistance to freeze-thaw cycles (Song et al. 2018).

Thus, it is very important to find alternative types of soil stabilizers to minimize the environmental impact of cement production and have more effective materials in enhancing the engineering characteristics of the clayey soils with high swelling potential when considering the weather conditions in Nebraska.

2.5 Biopolymers

Biopolymers are substances that are produced by living organisms such as bacteria and fungi. It consists mainly of many monomeric units bonded together. Since biopolymers are found in nature and used as food additives, they can be considered environment-friendly materials. Based on Chang et al. (2016) there are three types of biopolymers; polypeptides (composed of amino acids), polynucleotides (RNA, DNA), and polysaccharides. Polysaccharides are the most common type of biopolymers applied in different applications because they are widely found in nature. The widespread use of polysaccharides is due to their advantages as stabilizers, thickening agents, and sweeteners in the food industry. Different kinds of biopolymers in the Polysaccharides group have been tested to apply in the geotechnical engineering field due to their significant chemical bonding with the particles of the soils (Chang et al 2017).

Among the available Polysaccharides biomaterials, Gellan gum, Guar gum, Xanthan gum, Beta-glucan, and Lignin have shown better performance in fine grained soils according to Chang & Cho (2012), Chen et al. (2013), Chang et al. (2015), Chang et al. (2017), Ceylan et al. (2010), Zhang et al. (2014), and Canakci et al. (2015).

2.5.1 Xanthan

Xanthan is a kind of polysaccharide with many industrial uses, especially as a common food additive. It works as an effective thickening agent to prevent ingredients from separating because of its hydrocolloid rheology (Ochoa et al., 2000). Xanthan is produced by a metabolic process of glucose and its chemical formula is $C_{35}H_{49}O_{29}$. Figure 2.4 shows the Xanthan structure.

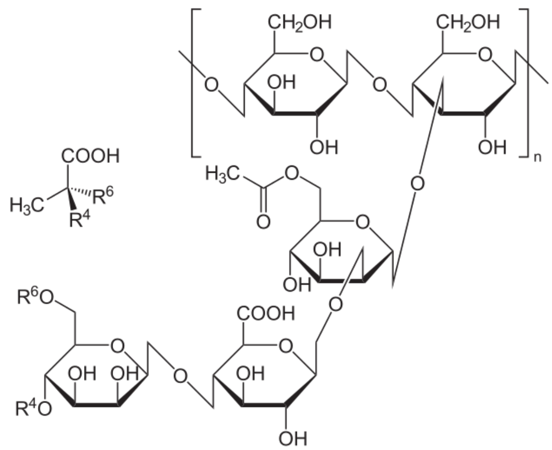


Figure 2.4 The structural formula of Xanthan (www.Wikipedia.org, 2019)

Xanthan shows a stable behavior in environments with extreme acidic and alkaline conditions, and it has good solubility in hot and cold water (Ayeldeen et al. 2016). According to Davidson (1980), 1% of Xanthan can produce a significant increase in the viscosity of a liquid. This behavior is due to the increase in the weight and the effective dimensions of the molecules. Figure 2.5 shows the result of adding a small amount of Xanthan (2 gr) to water (30 gr). The results show an extremely high viscous material. It is very similar to thick gelatin.

Figure 2.5 Solution of mixed 30 ml water and 2 gr Xanthan (Song et al., 2018)

Recent researches conducted on Xanthan/soil mixtures concluded that Xanthan decreased the hydraulic conductivity in the silty and sandy soils (Ayeldeen et al. 2016) and increased the compressive strength of the clayey and sandy soil (Chang et al. 2015).

2.5.2 Guar gum

Guar gum is similar to Xanthan because it is also a polysaccharide composed of sugar galactose and mannose. The difference between Guar gum and Xanthan is that Guar originates from seeds native to tropical Asia, while Xanthan is made from microorganisms. As shown in Figure 2.6, Guar gum has a complex structure. Guar gum is used as a thickening agent in foods and medicines, it has a very high-water thickening ability compared to the other agents, a small amount of Guar gum is enough to produce sufficient viscosity as addressed below.

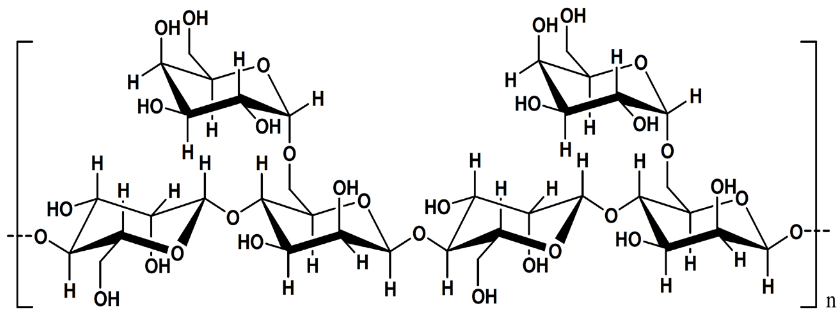


Figure 2.6 Structural formula of Guar gum (www.Wikipedia.org, 2019)

Figure 2.7 shows the results of adding 2 gr of Guar gum to 30 gr of water. The solution is dense gelatin that has an extremely high viscosity, seeming to be higher than the Xanthan with the same concentration.

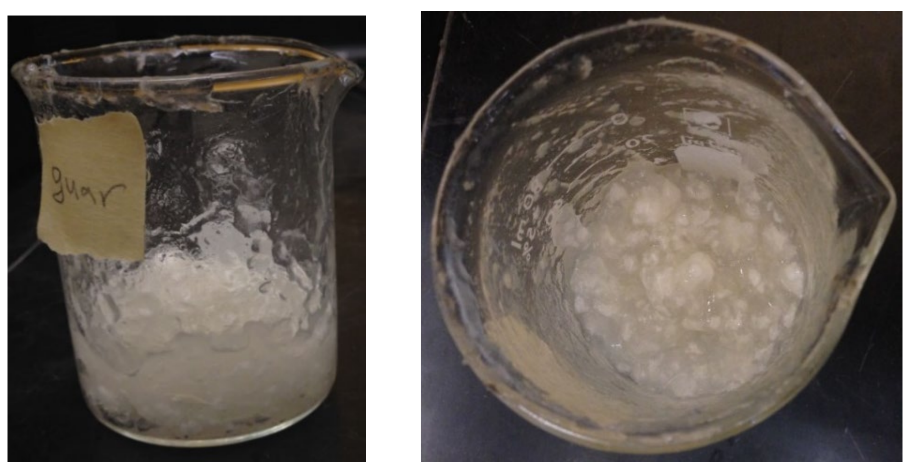


Figure 2.7 Solution of mixed 30 ml water and 2 gr Guar gum (Song et al., 2018)

According to Ayeldeen et al. (2016), Guar gum is more effective in increasing the shear strength of sandy and silty soils compared to Xanthan at the same concentrations.

2.5.3 Gellan gum

Gellan is produced from relatively long chains of carbohydrate molecules. Gellan is composed of four molecules mostly from glucose families. Figure 2.8 shows the fundamental structure of the Gellan agent, which is produced by a kind of bacteria, called Pseudomonas elodea. It can be used as a direct food additive. It is used as a gelling agent especially in the food, cosmetics, and pharmaceutical industries. The most common application of Gellan in the food industry is bakery and confection as it can tolerate high temperatures without changing in properties. Gellan is water-soluble and adding a small amount of binder to water results in an extremely viscous solution. For example, Figure 2.9 shows the result of adding 2 gr Gellan to 30 gr water. The Gellan-water solution showed a relatively durable behavior after 14 days of curing at room temperature. The solution became extremely thick.

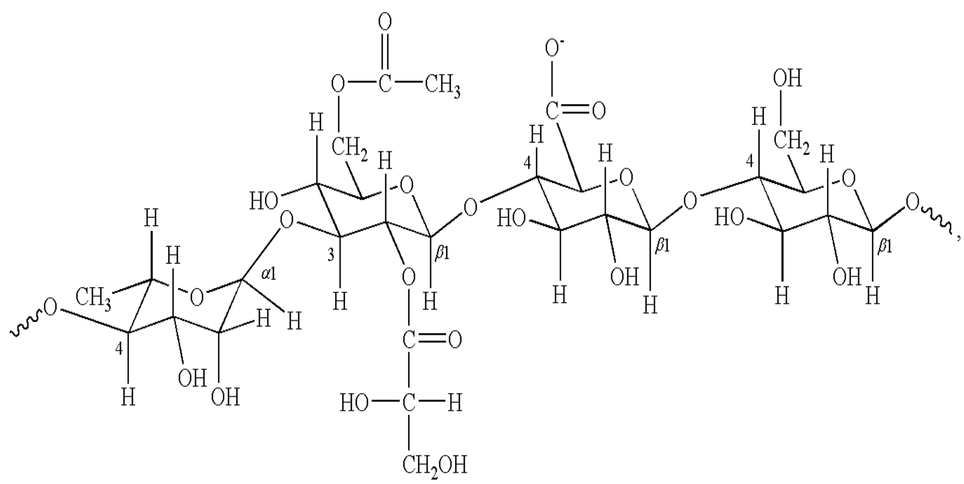


Figure 2.8 Structural formula of Gellan (www.Wikipedia.org, 2019)

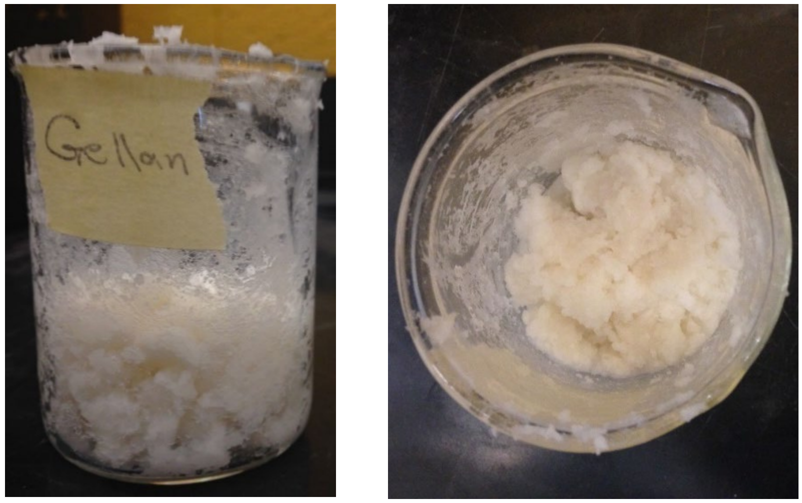


Figure 2.9 Solution of mixed 30 ml water and 2 gr Gellan gum (Song et al., 2018)

2.6 Effect of biopolymer on the shear strength

Chang et al. (2015) evaluated the effects of adding different percentages of Xanthan (1%,1.5% by weight) on the shear strength of two types of soils: sandy soils and clayey soils.

Unconfined compressive strength test results in Figure 2.10 showed notable increases in the compressive strength of the soils treated with Xanthan compared to the untreated ones. Besides, the compressive strength of the untreated sandy soils was immeasurable under the unconfined compressive test, but sandy soil treated with Xanthan exhibited a significant strength. These results indicate that Xanthan added a cohesive property to the sand. Furthermore, treated clayey soils exhibited higher compressive strength than treated sandy soils. This result may be attributed to the direct interaction between Xanthan and the negatively charged clay surface as reported by Chang et al. (2015). This interaction is due to the cation bridging and hydrogen bonding between the electrically charged clay surface and the hydroxy and carboxylic acid in the biopolymer (Nugent et al. 2009). This behavior is not expected in the case of sandy soils since sand particles do not have meaningful electrically charged surfaces. But Xanthan acts as a glue in the voids between the sand particles. It forms a coat around the particles and increases the contact surface. Besides, it creates a bridge between the soil particles. Figure 2.11 shows the interaction models between Xanthan-sand and Xanthan-clay.

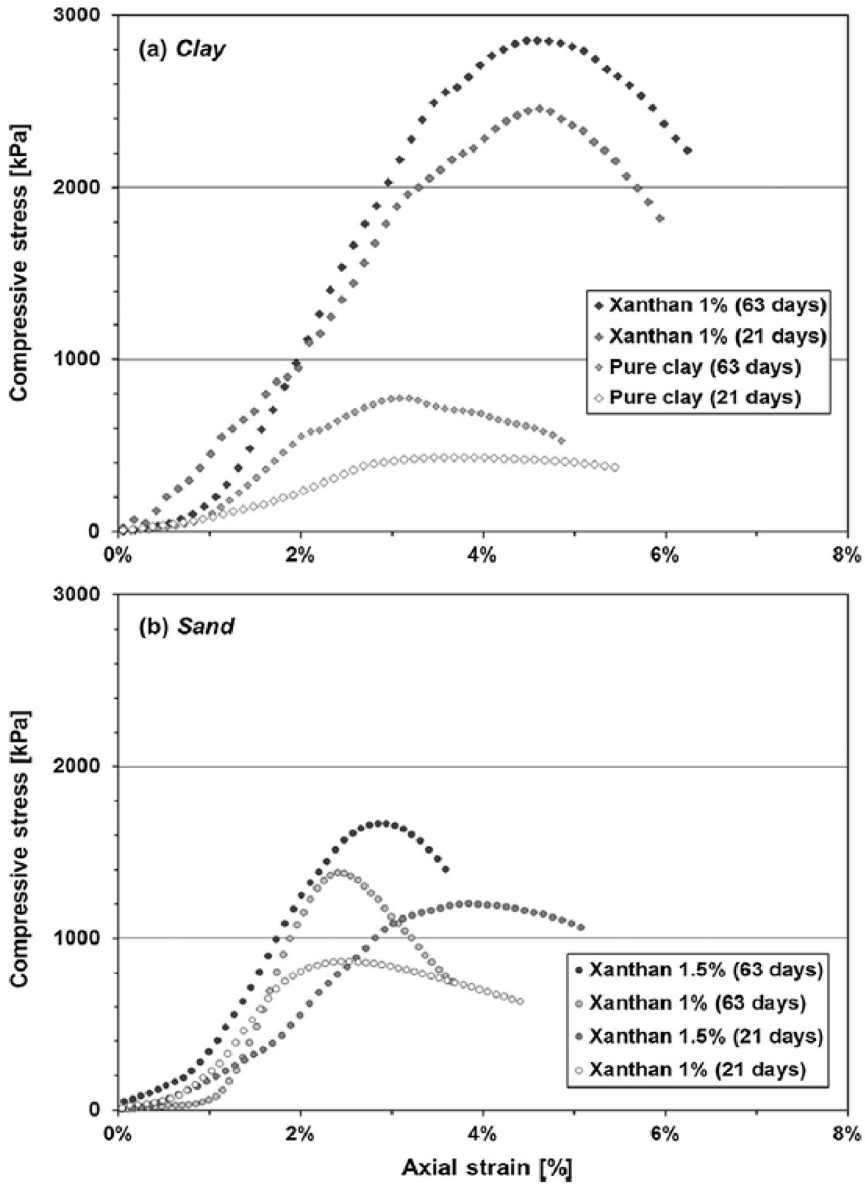


Figure 2.10 Stress–strain behavior of Xanthan treated clay (a) and sand (b) at 21 and 63 days of curing (Chang et al., 2015)

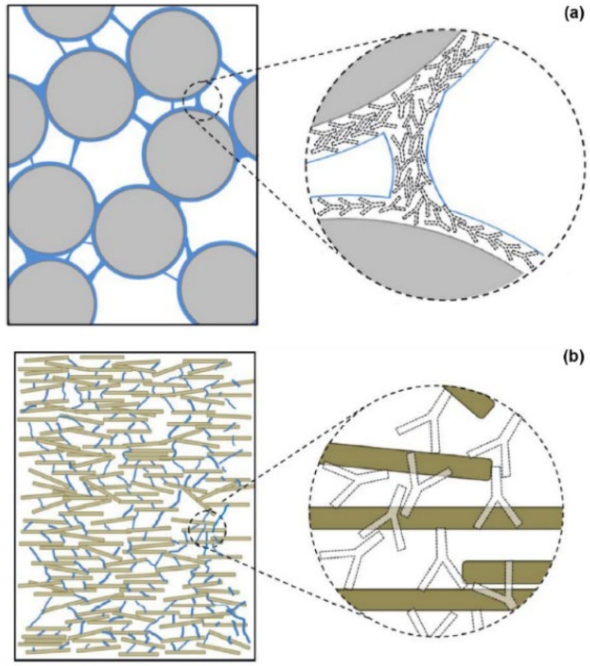


Figure 2.11 The interaction models between a) Xanthan-sand and b) Xanthan-clay (Chang et al., 2015).

Moreover, Chang et al. (2015) concluded that using Xanthan in well-graded soils is more effective than in poorly graded soils. Xanthan/fine soil matrix works as a cementation agent in the voids between the coarse particles and improves the inter-particle properties. Figure 2.12 shows the cohesion and the friction angle variation for sand-clay mixtures mixed with 1% of Gellan. This figure shows that the strengthening mechanism in the treated sand-clay mixture is a combined effect of the biopolymerized fine soils matrices (cohesion improvement) and the enhancement in the friction of the coarse particles due to increasing the contact surface between those particles.

Xanthan treated soils with higher fine content give higher strength. This is due to the strong chemical bonding with fines and enhances the significance of the presence of fine particles in Xanthan treated soils.

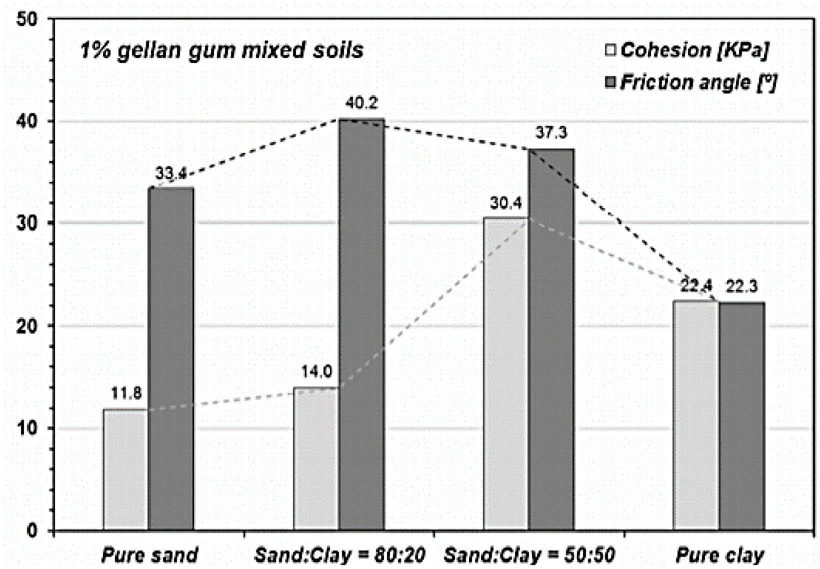


Figure 2.12 Cohesion and friction angle variation in sand-clay mixtures treated with 1 % Gellan (Chang et al., 2016)

Xanthan shows a decay behavior by aerobic bacteria. Hence, the durability of the soil treated with this biopolymer should be assessed to verify the workability of Xanthan in the geotechnical engineering area. As shown in Figure 2.10, there is a slight increase in the strength of both sandy and clayey soil at 21 and 63 days of curing. This behavior is attributed to the continuous dehydration of the Xanthan gel through time which makes it stiffer. As a result, treating the Weathered shales from Verdigre in Verdigre slopes using Xanthan will enhance the strength of the soils due to the continuous dehydration of the biopolymer during the dry season, and sustained long-term stability might be achieved.

Other experiments conducted by Chang et al. (2015) on Red Yellow soil (CL) in Korea to examine the durability of Xanthan showed that the strength at 28 days was 950 psi and it was increased by 11% at 750 days, indicating that Xanthan illustrates an encouraging durable behavior.

Another study was conducted by Ayeldeen et al. (2016) to evaluate the performance of two kinds of soils: silty soil and sandy soil, treated with three kinds of biopolymers (Xanthan, modified starch, and Guar gum). Figure 2.13 shows the direct shear test results of sandy soil mixed with 2% by weight biopolymer at 5 weeks curing time. The samples mixed with biopolymers demonstrated higher shear strength compared with the pure sand samples. Furthermore, the Guar gum/sand mixtures presented the highest cohesion strength (447 KN/m^2) compared to the samples treated with Modified starch (309 KN/m^2) and Xanthan (218 KN/m^2).

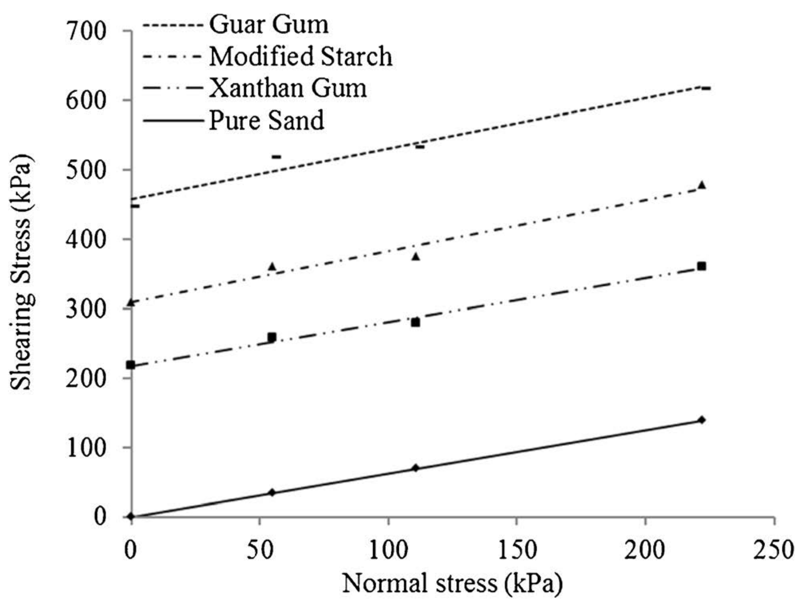


Figure 2.13 The shear test results of sand/biopolymer mixtures with a concentration of 2 % and curing time of 5 weeks (Ayeldeen et al., 2016).

Figure 2.14 shows the unconfined compressive test results of silty soil mixed with 2% of biopolymer at 5 weeks curing period. Adding a biopolymer to the silt increased the unconfined compressive strength of the soil. It reached 570 KN/m^2 for samples treated with Modified Starch and 338 KN/m^2 for samples treated with Xanthan. The highest value of the unconfined compressive stress (840 KN/m^2) was attained for the sample treated with

Guar gum. Moreover, the Guar gum mixture sample showed more ductile behavior than the other samples mixed with Modified starch and Xanthan.

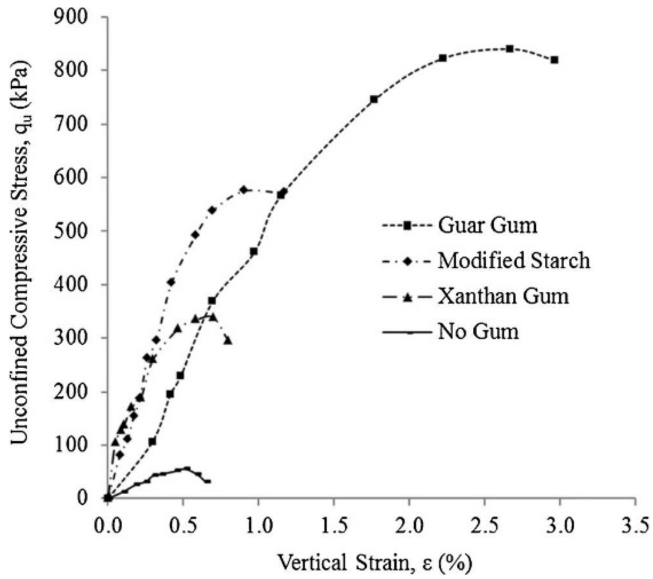


Figure 2.14 unconfined compressive strength results of silt/biopolymer mixtures with different biopolymers with a concentration of 2% and a curing time of 5 weeks (Ayeldeen et al., 2016).

The previous results obtained by Ayeldeen et al. (2016) indicated that the Guar gum/soil mixtures presented the highest shear strength. This behavior is because Guar gum has the highest viscosity solution among the three biopolymers used in the research. A high viscosity solution increases the probability of continuous hardening of the Guar gum molecules between the soil particles, which causes an increase in the shear resistance of the mixture. This result was achieved before by Chen et al. (2013).

Scanning electron micrographs for the sand biopolymer mixtures exhibited that the linkages between the soil particles were much thicker in the soil treated with Guar gum. Higher biopolymer content increases the density of these linkages and leads to a higher compressive strength.

2.7 Effect of biopolymer content on the strength of the soils

The biopolymer content is one of the main factors that affect the strength of biopolymer treated soils. For that reason, Chang et al. (2015) studied the effect of Xanthan content on the compressive strength of three types of soils. The selected soils were sand, natural soil (SP-SM), and Red Yellow soil (CL) treated with different concentrations of Xanthan (0.5%, 1%, and 1.5% by weight). Figure 2.15 shows the unconfined compressive test results after curing 28 days. Increasing the biopolymer content increases the compressive strength of the soils. Higher Xanthan content causes wider and thicker linkages between the particles in the coarse soils and more chemical interactions between the biopolymer and the surface of the fine soils. But at the same time, the authors mentioned that the most effective range of Xanthan concentrations is 1%-1.5%. Higher contents of Xanthan interact directly with the fine soils and water, forming a highly viscous solution that separates the particles easily and reduces the dry density. Besides, the highly viscous solution affects the workability of the biopolymer mixed with the soil. The author found that the dry density will slightly increase in the coarse soils due to the Xanthan gel matrices around the particle and in the voids.

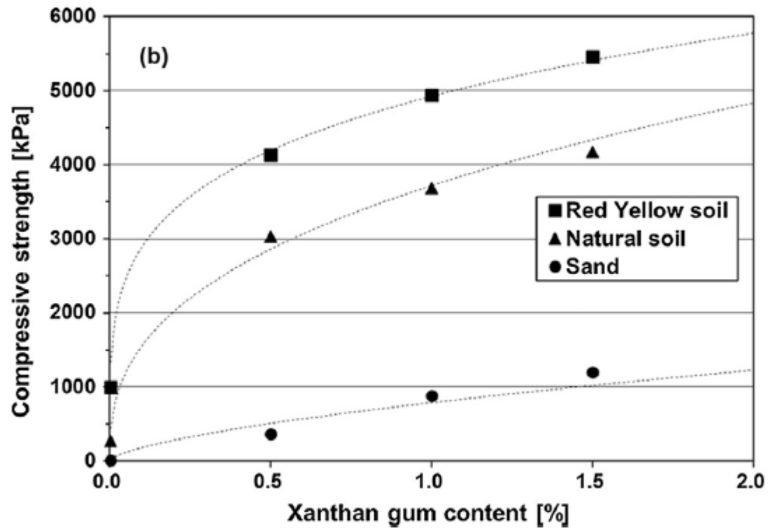


Figure 2.15 The effect of different contents of Xanthan on the compressive strength of three different types of soils (Chang et al., 2015)

2.8 Effect of biopolymer on compaction properties

Ayeldeen et al. (2016) conducted a modified compaction test according to ASTM D1557-12 on sandy and silty soil mixed with three different types of biopolymers (Xanthan, Modified Starch, and Guar gum). Modified starch is a biopolymer in the polysaccharide group. It is used as a thickening agent and stabilizer.

The biopolymer concentrations used in the study varied over a range (0.25% to 2% by weight). This test aimed to determine the maximum dry unit weight and the optimum moisture content of the soil/biopolymer mixtures.

Figure 2.16 shows that the dry unit weight of sand increases with increasing the biopolymer concentrations except for the Guar gum and Modified starch mixtures. In the Guar gum mixture, the density reached the highest at 1% concentration, and then it began to decrease. For Modified starch, the density reached the highest at 0.5 % before it declined. According to Ayeldeen et al. (2016), Guar gum and Modified starch have higher solution viscosity compared to Xanthan. Increasing the biopolymer concentrations in the case of

Guar gum and Modified Starch leads to form a highly viscous solution that separates the sand particles and reduces the dry density. Unlike the behavior of the other mixtures, the dry density of the Xanthan/sand mix increased with increasing the concentration. On the other hand, the optimum moisture content increased with increased biopolymer concentrations for all cases. This behavior is due to the increased amount of water absorbed by the biopolymer, effectively reducing the amount of free water in soils.

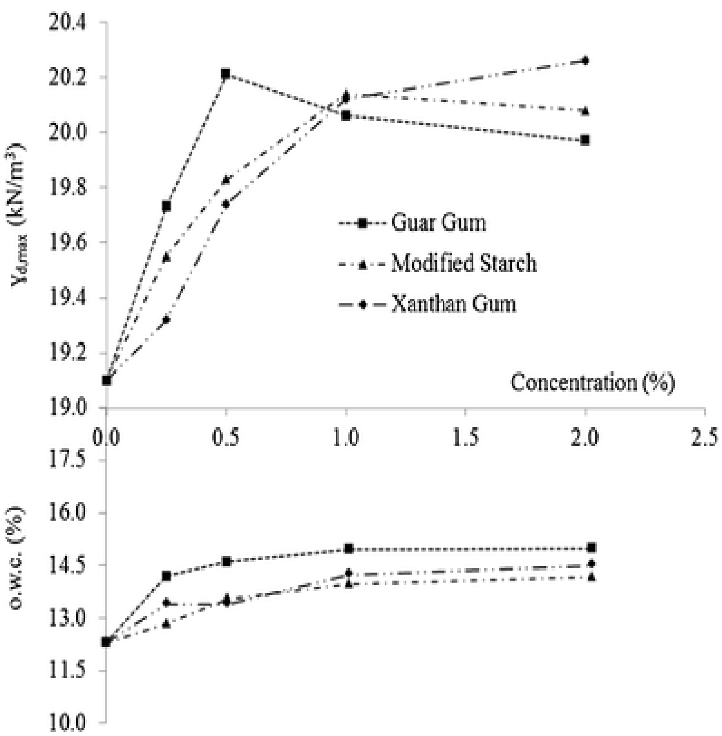


Figure 2.16 Compaction characteristics for sand/biopolymer mixtures (Ayeldeen et al., 2016)

Figure 2.17 shows the compaction results conducted on silt/biopolymer mixtures. Increasing the biopolymer concentrations caused a decrease in the density. According to Ayeldeen et al. (2016), the silt particles were separated by the effect of the viscosity of the solution regardless of the biopolymer contents. The optimum moisture content increased with increasing the biopolymer concentrations, like the sand mixtures case.

Even though the dry density of the soil/biopolymer mixture (sand and silt/Guar gum) was lower at higher Guar gum content than that at lower Guar gum content, the figure gave a higher strength at 5 weeks curing period (Figures 2.13 and 2.14). The linkages between the soil particles were much thicker in the soils treated with Guar gum (Alyedeen et al., 2016). Higher Guar gum content increases the density and thickness of these linkages. As a result, these linkages fill the voids between the soil particles leading to a higher compressive strength.

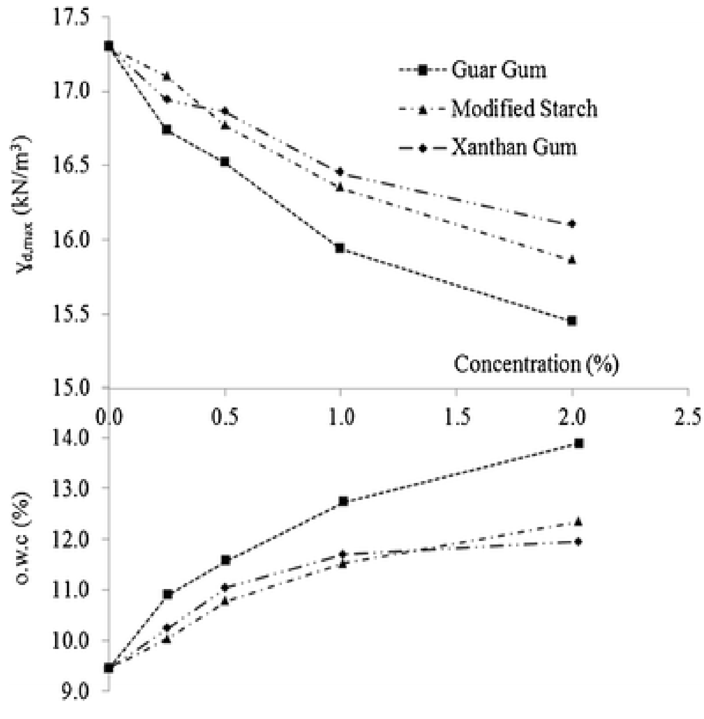


Figure 2.17 Compaction characterizations for silt/biopolymer mixtures (Ayeldeen et al., 2016)

2.9 Effect of biopolymer on soil permeability

According to Ayeldeen et al. (2016), the biopolymer has a significant effect in reducing the permeability of sandy and silty soils. Figure 2.18 shows the coefficient of permeability for soil/biopolymer mixtures with different biopolymer concentrations. The coefficient of permeability of untreated sand and silt samples was 3.4×10^{-4} m/s and 5.51×10^{-6} m/s, respectively. As shown in the figure, the permeability of both sand and silt mixtures decreased with increasing the biopolymer concentration. At the same concentration, Guar gum appeared to be more effective in reducing the permeability of sandy and silty soils compared to Xanthan and Modified starch. Besides, the reduction in the permeability was less in the silt mixtures compared to the sand mixtures. For example, the coefficient of the permeability of the Guar gum/silt mixture at 2% concentration was only 10% of the initial value, while for the Guar gum/sand mixture at 2% concentration was less than 1% of the initial coefficient of permeability. Also, a study by Czarnes and Hallett (2000), the permeability reduction in the biopolymer/soil mixtures was due to the linkages created by the biopolymers that bridge the soil particles and obstruct the flow through the voids.

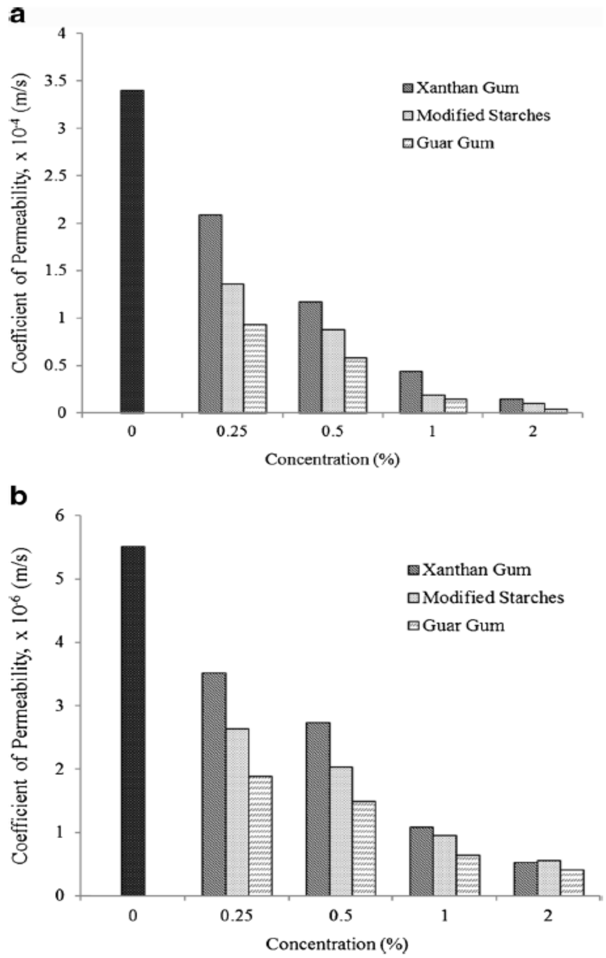
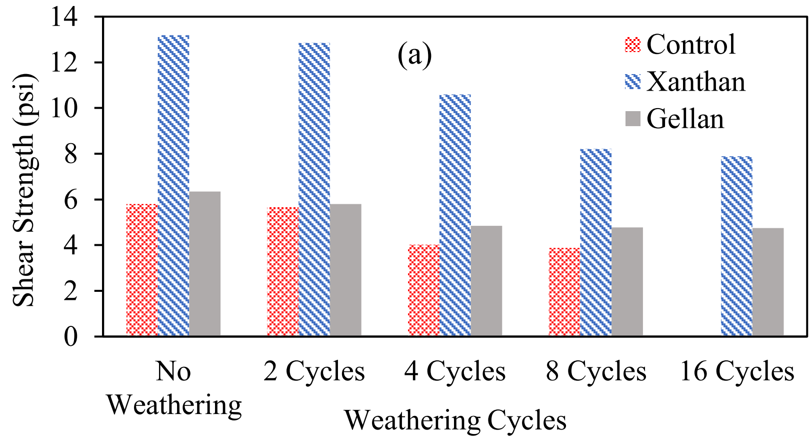


Figure 2.18 Coefficient of permeability for different soil/biopolymer mixtures with different concentrations after 5 weeks curing time: a) sand, b) silt (Ayeldeen et al., 2016)

2.10 Durability of soil/biopolymer mixtures under weathering cycles

The direct shear test was conducted in the Geotechnical Engineering Lab at the University of Nebraska to investigate the effects of weathering cycles on the shear strength of both untreated soils and biopolymer mixed soils (Song et al., 2018). This research applied two types of weathering cycles were selected: wet-dry (W-D) and wet-freeze (-6 °F)-thaw (167 °F)-dry (W-F-T-D). The soils were glacial tills and weathered shales compacted at their natural water contents and stabilized by using 1.5% by weight of Xanthan and Gellan. The comparison between Xanthan and Gellan's effect in improving the shear strength of glacial tills and weathered shales under wet-dry conditions and wet-freeze-thaw-dry conditions was presented in Figures 2.19 and 2.20, respectively.



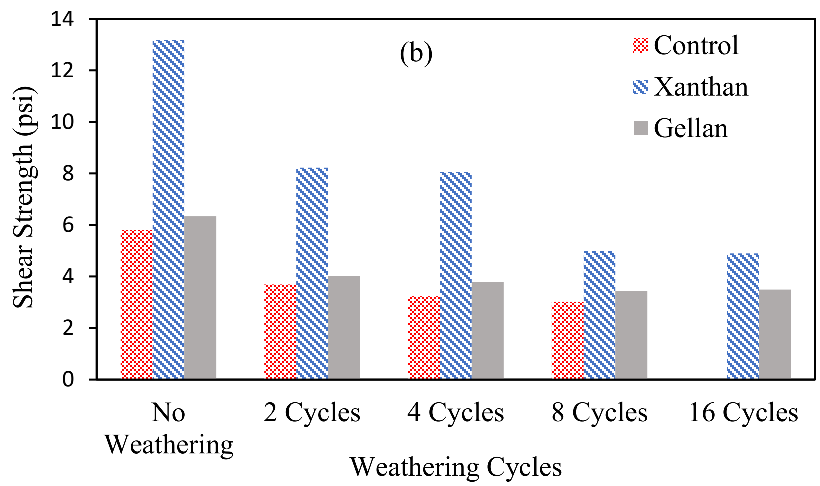


Figure 2.19 Direct shear test results for glacial tills (a) wet-dry condition (b) wet-freeze-thaw-dry condition (Song et al., 2018)

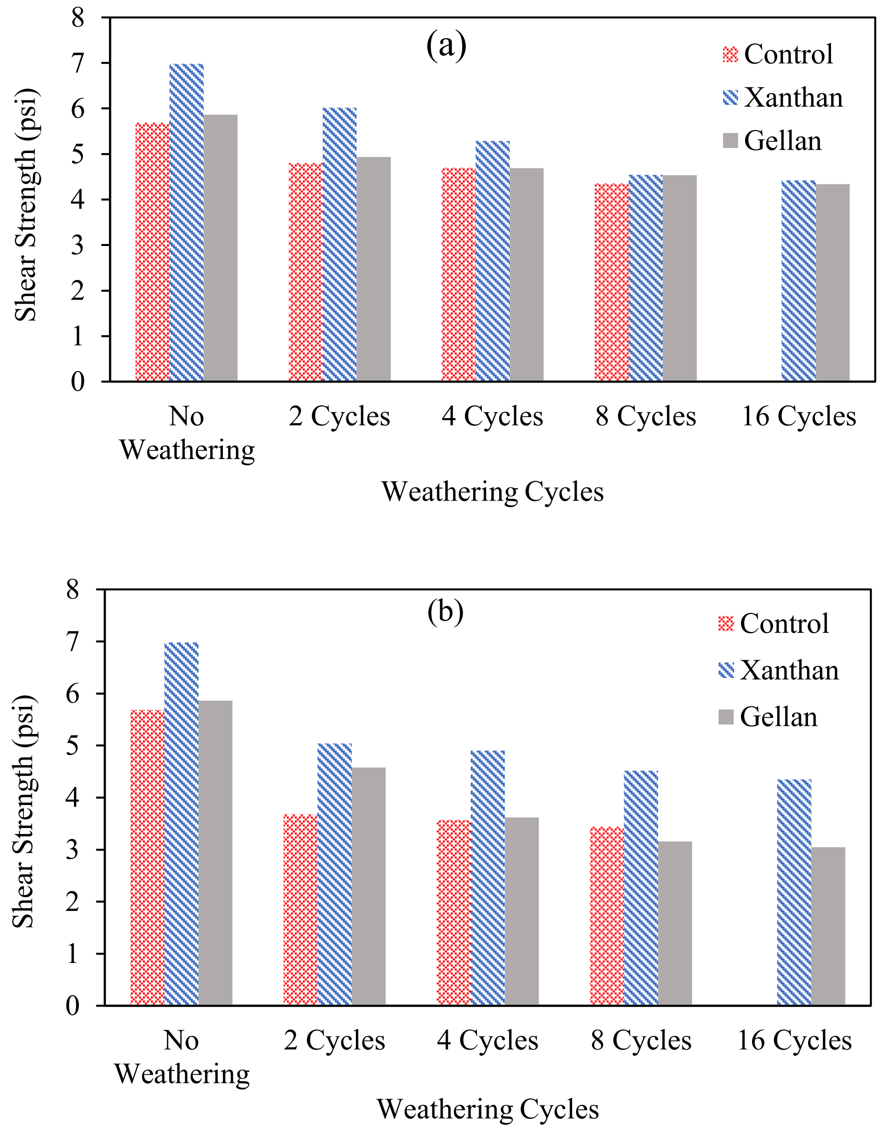


Figure 2.20 Direct shear test results for weathered shales (a) wet-dry condition (b) wet-freeze-thaw-dry condition (Song et al., 2018)

Both biopolymers increased the shear strength of the soil, but Xanthan showed higher strength than Gellan. The shear strength of the weathered shales decreased as the number of weathering cycles increased. The reduction in the shear strength stabilized after 8 weathering cycles. At the same number of weathering cycles, samples weathered under wet-freeze-thaw-dry conditions presented lower shear strength than the samples weathered under wet-dry conditions. This behavior highlighted the significance of freezing in reducing the integrity of soil samples. Xanthan exhibited superior performance in glacial tills compared to weathered shales.

Another study by Chang et al. (2017) evaluated the behavior of sandy soils treated with 1% Gellan after several wet/dry cycles, up to 10 cycles. As shown in Figure 2.21, the strength of the treated soil decreased in both wet and dry conditions at the increased number of cycles. Furthermore, there was a relatively negligible strength reduction in samples from the fifth to the tenth cycles. On the other hand, the results showed that the strength of the soil in the dry condition was much higher than in the wet condition.

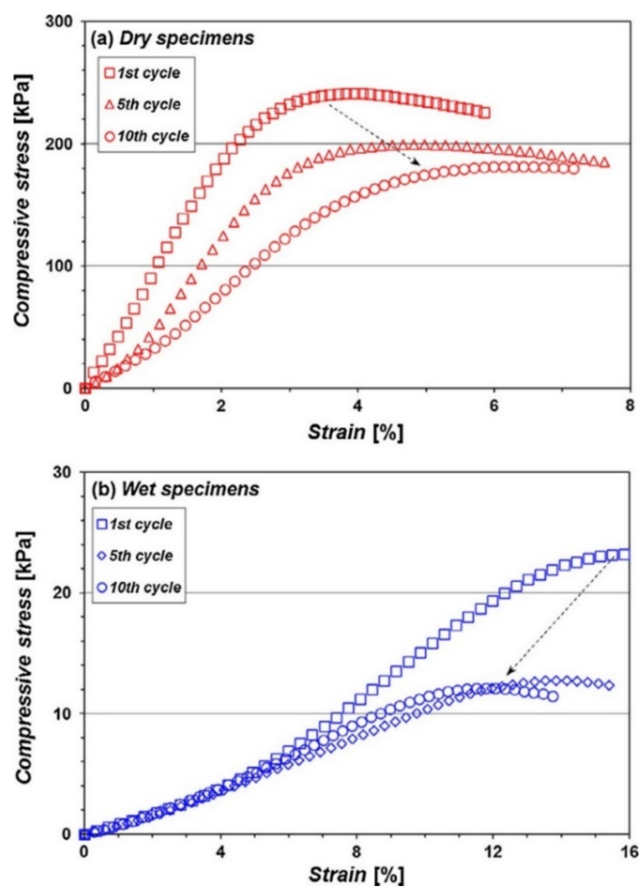


Figure 2.21 Stress-strain curves of dry (a) and wet (b) 1% Gellan-treated sands obtained from unconfined compression tests at different cycles (Chang et al., 2017).

The strength reduction with the increased number of dry-wet cycles appears to be due to the hydrophilic property of Gellan. When the sand/Gellan samples are in wet condition, the dried gel absorbed the water and separated from the surface of the sand particles based on Chang et al. (2017). By redrying the test samples, the new soil particles may attach to the remaining Gellan gel in the main structure, but the original structure of soils may not fully recover.

2.11 Mixing Method

Chang et al. (2015) evaluated the mixing methods on the strength of Red Yellow soil/Xanthan mixtures. The researchers applied both dry mixing and wet mixing techniques. In dry mixing, Chang et al. (2015) added 1% by weight of Xanthan to the soil before adding the water. While in wet mixing, they added 1% of Xanthan to the water forming a solution with 1.7% concentration, then mixed the solution with the soil. Figure 2.22 showed that the unconfined compressive strength of the soil/Xanthan mixture in dry mixing was higher than that in wet mixing. Tests conducted by Chang et al. (2015) had shown that the solubility point of Xanthan to water at room temperature was 1.4%. The researchers reported that it was difficult to attain the concentration of Xanthan higher than 1.5% due to the increased viscosity of the mixture. Furthermore, the researchers noted that a more homogeneous soil/biopolymer mixture in dry mixing. They also found that the wet mixing technique was less effective than the dry mixing when the Xanthan/water concentration is higher than the solubility point.

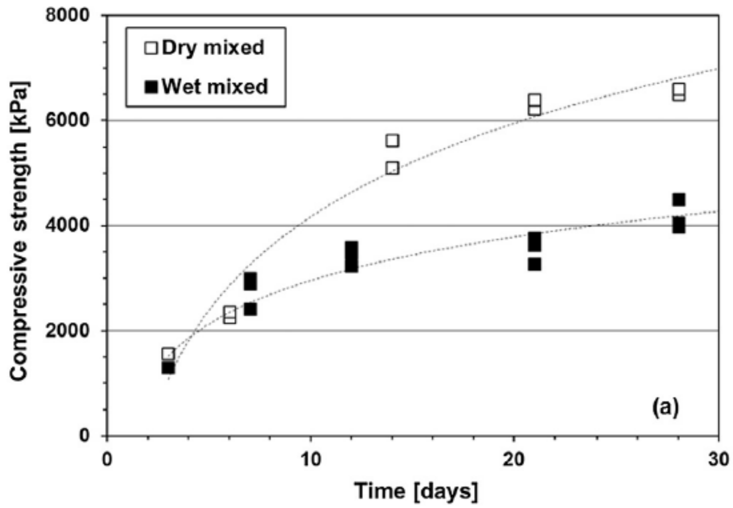


Figure 2.22 The unconfined compressive stress of Red Yellow soil treated with 1 % Xanthan in two different mixing methods; dry and wet mixing (Chang et al., 2015)

Chapter 3

Location, Materials, and Testing Methods

3.1 Verdigre slope

Verdigre is a small town in Knox County, North Central Nebraska. The failed slope is shown in Figure 3.1 and is located about 2 mi east of Verdigre along Highway 84. The slope is designed and constructed based on Nebraska's road construction standard (3:1=H:V). The width and height of the slope are 250 ft and 30 ft (Lindemann, 2011). A boring log showed that the slope soils primarily consist of weathered shale layers. Weathered shales from Verdigre are derivatives of old marine deposits formed during the Cretaceous era. Several cracks parallel to the highway shoulder appeared at the top of the slope during Summer, 2018 as shown in Figure 3.2.

Figure 3.1 Verdigre slope at Highway 84 (Song et al., 2018)

Figure 3.2 Longitude crack on top of the Verdigre slope at Highway 84
(Song et al., 2018)

3.2 Materials

3.2.1 Weathered shales from Verdigre

Weathered shales from Verdigre are associated with the several landslides in East and North-East Nebraska (Eversoll, 2013). The classification soils obtained from the Verdigre slope is in the border line of highly compressible clay (CH) or low compressible clay (CL) because their LL is close to 50%. Besides, it is noted that the soil of LL higher than 50% was not used within the top 2 ft. This soil may contain expansive clay minerals that cause volume change in the soils when subjected to the water content change. These expansive clay minerals also shrink when they are dry. These expansion and shrinkage cycles may generate fissures that ease the infiltration of the surface water and cause a loss in the strength of the soils. According to Eversoll (2013), the annual precipitation in Knox County is usually 26 to 28 inches, concentrated during Winter and early Spring. The severe weather conditions, including concentrated precipitation, freeze, and thaw, may be a significant factors to generate slides in the Verdigre slope. Weathered shales containing expansive clay minerals are extensively distributed in east and northeast Nebraska, as shown in Figure 3.3.

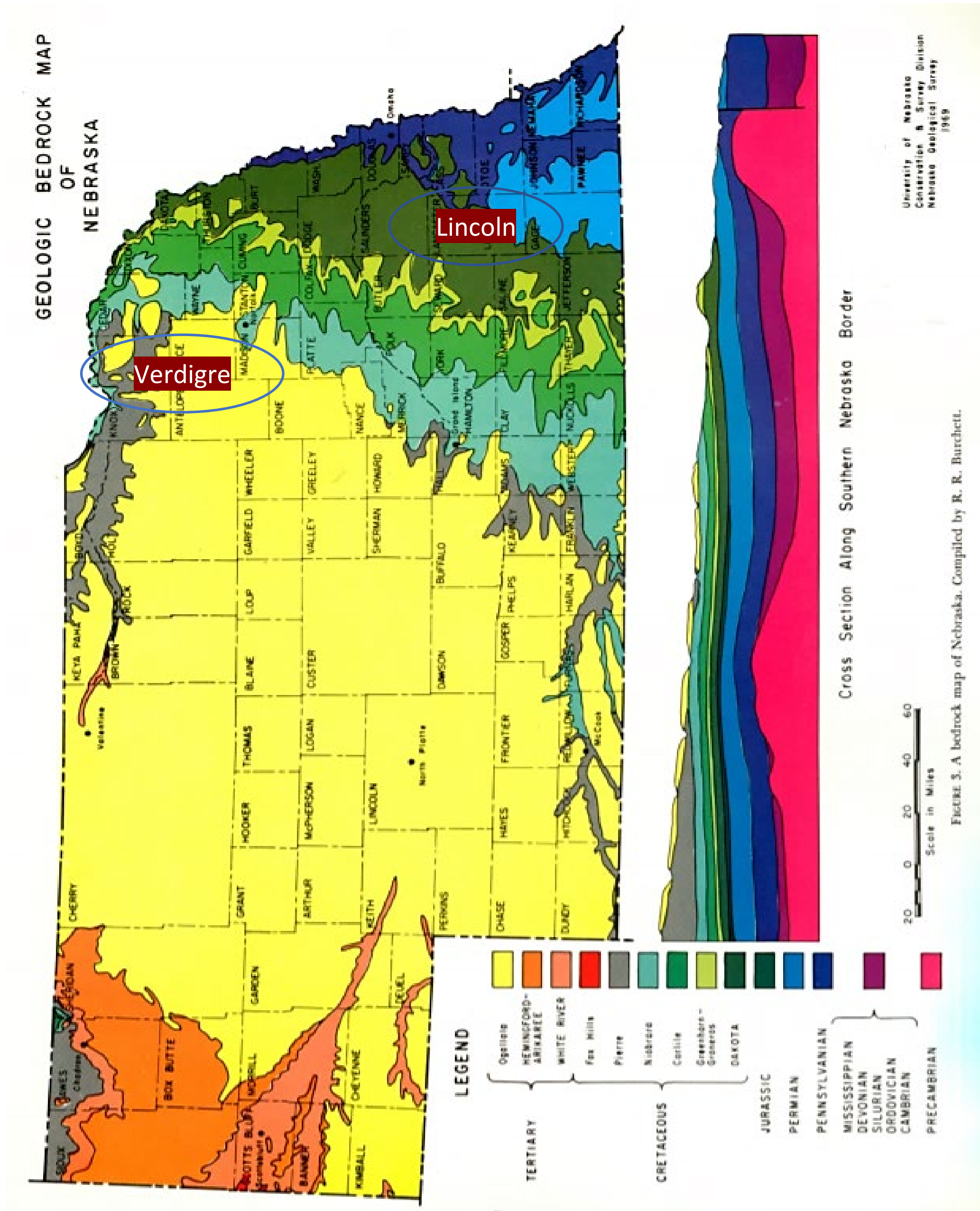


Figure 3.3 Geologic bedrock map of Nebraska (Pabian, R.K., 1970)

3.2.2 Glacial tills from Lincoln

Glacial tills are abundant in the eastern part of Nebraska. They are a mixture of clay, silt, sand, gravel, and boulders deposited when the Laurentide ice sheets and the Last

Glacial Maxima covering the United States' northern states melted away (Eversoll, 2013). Glacial tills usually are overlain by other layers such as shales. The ice melting caused an overburden pressure release. This stress release may cause expansion and cracks in the underlain shales leading to a mixture of glacial tills and shales. Figure 3.4 shows the distribution of glacial tills in Nebraska.

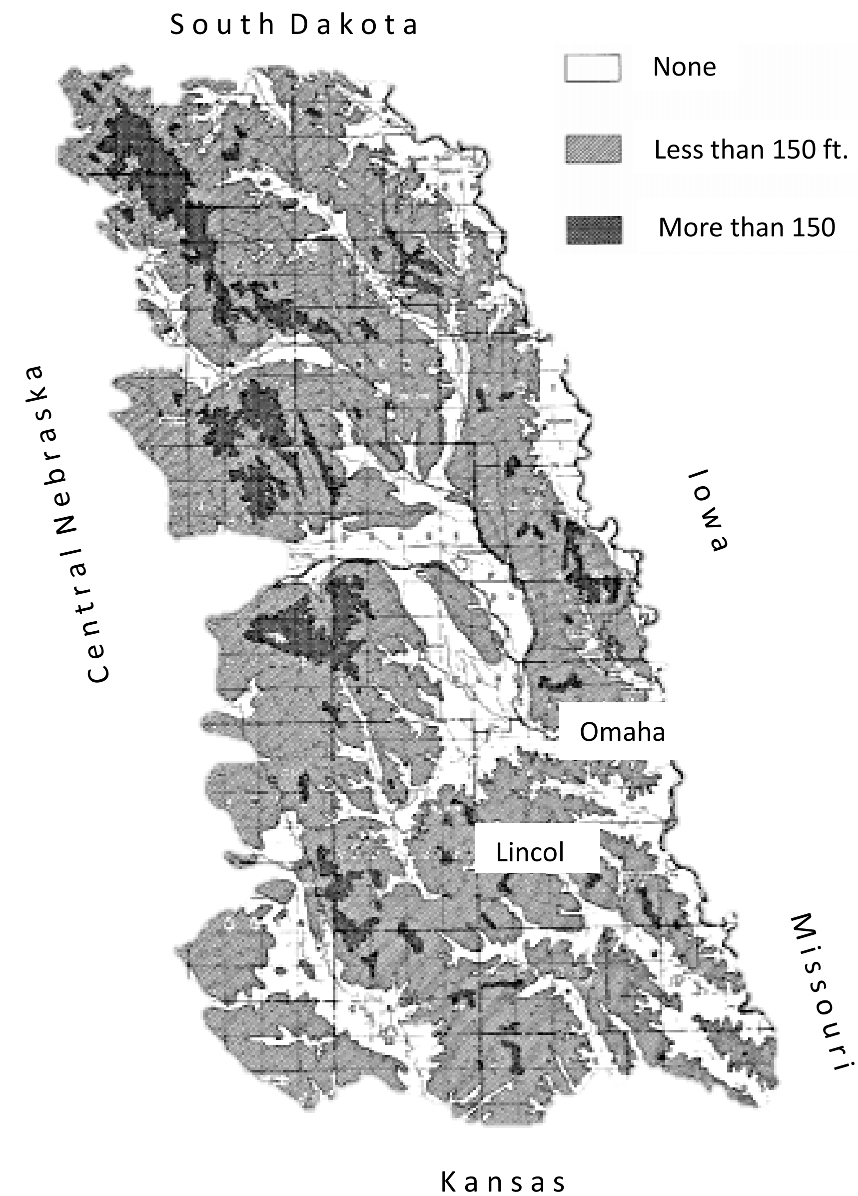


Figure 3.4 Distribution of glacial tills in East Nebraska (Replotted from Snr.unl.edu (https://digitalcommons.unl.edu/conservationsurvey/297/), 2020)

3.3 Properties of field soils and testing methods

3.3.1 Gradation

This study conducted sieve analyses and hydrometer tests on untreated and treated soils mixed with 1.5% of Xanthan and Gellan. The treated soils were mixed with the biopolymer, then the water was added gradually to the biopolymer/soil mixtures. The water content was selected to be the same as the optimum moisture content obtained from the standard compaction test, which is 18% for glacial tills from Lincoln and 29% for weathered shales from Lincoln. The gradation tests were conducted according to ASTM D-422. Figures 3.5 and 3.6 show the gradation test results for glacial tills from Lincoln and weathered shales from Verdigre, respectively. Both glacial tills and weathered shales were classified based on the unified soil classification system as clayey sand (SC).

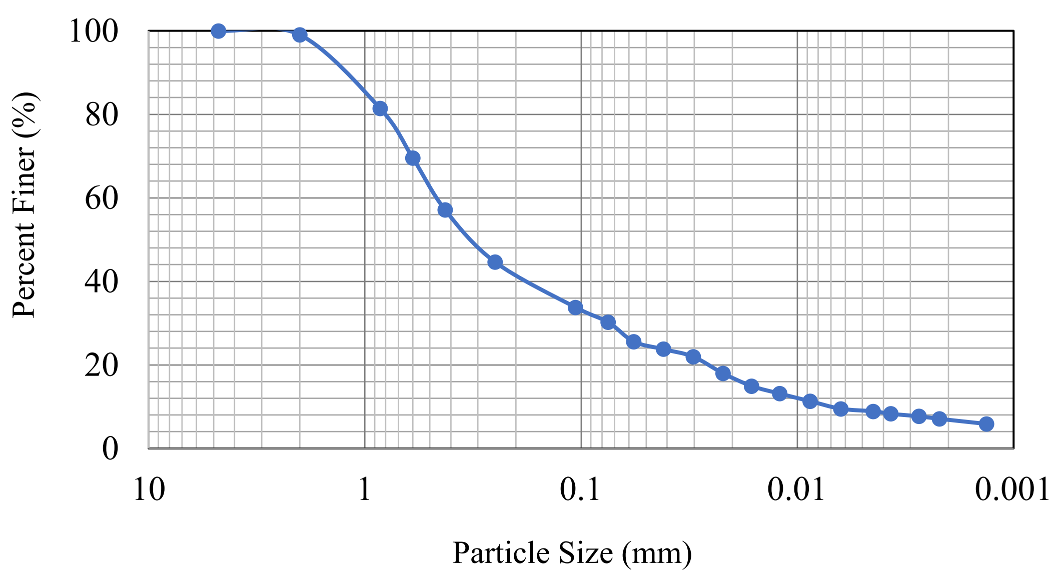


Figure 3.5 Gradation of untreated glacial tills from Lincoln

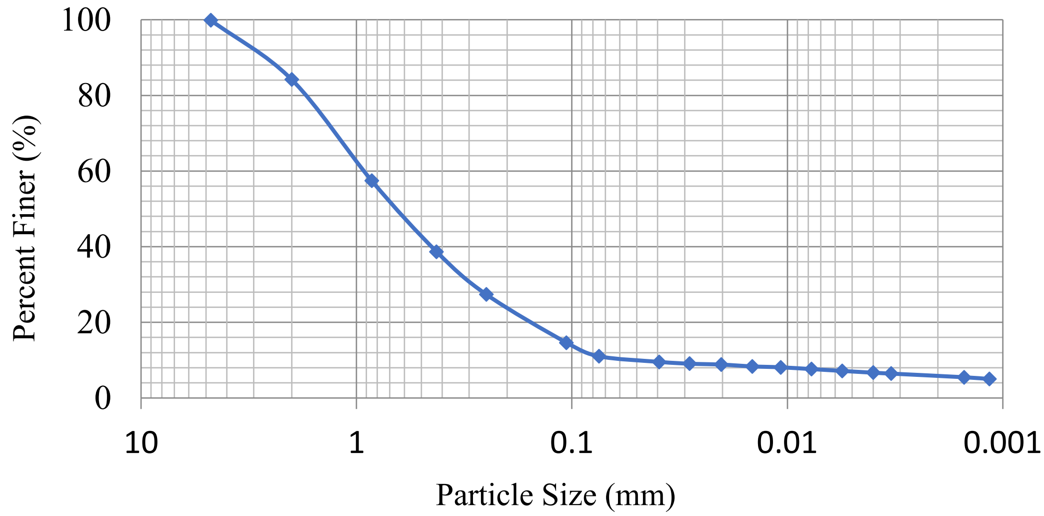


Figure 3.6 Gradation of untreated Weathered shales from Verdigre

3.3.2 Atterberg limits

Liquid limit, plastic limit, and plasticity index were determined according to ASTM D-4318 for untreated and treated soils mixed with 1.5% of Xanthan and Gellan. Table 3.1 shows the Atterberg limits tests for glacial tills from Lincoln and weathered shales from Verdigre. From this table, the treated soils have higher liquid and plastic limits compared to the untreated ones. This tendency might be due to the hydrophilic property of the biopolymers contained in soils.

Table 3.1 Atterberg limits for untreated and treated soils

Soil	Mixture	LL (%)	PL (%)	PI (%)
Glacial tills from Lincoln	Untreated glacial tills	44.7	22.82	21.88
	Glacial tills +1.5% XG	65.89	31.2	34.69
	Glacial tills +1.5% GG	93.84	44.16	49.68
Weathered shales from Verdigre	Untreated weathered shales	52.8	28.6	24.2
	Weathered shales +1.5% XG	87.93	36.21	51.72
	Weathered shales+1.5% GG	84.27	37.25	47.02

3.3.3 Standard procter test

The standard proctor test was conducted according to ASTM D-698 to determine the maximum dry unit weight and the optimum moisture content of the soils. The soils were mixed with predetermined moisture content. In a 4-inch diameter mold, the soils were compacted in three layers using a hammer weighing 5.5 pounds and a drop height of 12 inches (Figure 3.7). The optimum moisture content and the maximum dry density were obtained, as illustrated in Figure 3.8.

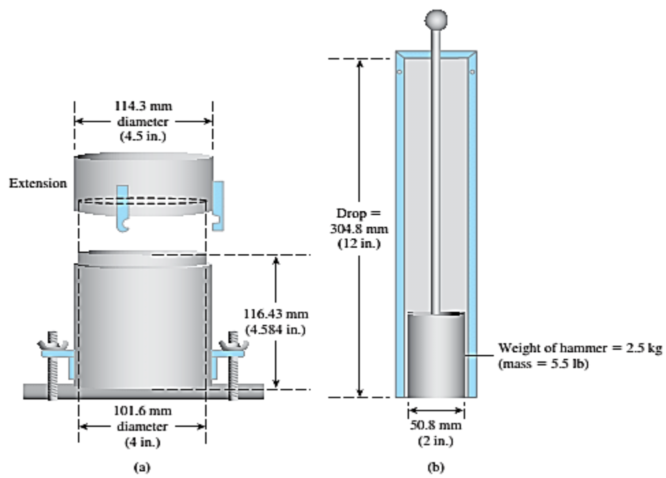


Figure 3.7 Standard proctor test equipment (Bunyamin et al., 2018)

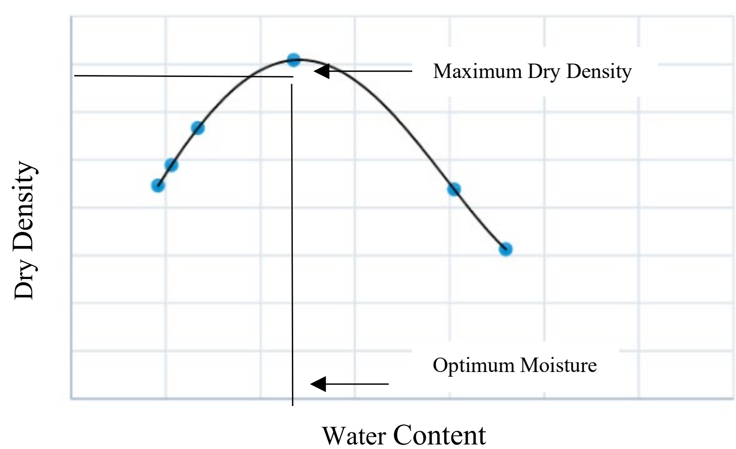


Figure 3.8 Variation of dry unit weight with moisture content (Proctor Curve) (Shalabi et al., 2019)

3.3.4 Direct shear test

The direct shear test was conducted according to ASTM D-3080 to evaluate the shear strength of the stabilized soils and the untreated ones under no weathering cycles and several wet-freeze-thaw-dry cycles.

DigiShear Automated Shear System was used to find the shear strength of the soil (Figure 3.9).

Figure 3.9 DigiShear automated direct shear system (www.geotac.com, 2020)

3.4 Sample preparation

Test soils were sieved on a # 4 sieve and kept in the oven at the temperature of 105 °C for 24 hours to ensure they were in completely dry conditions for mixing and compaction. The moisture content of soils for mixing and compaction was then controlled to be the same as the optimum moisture content obtained from the standard proctor compaction test conducted according to ASTM D-698. Figures 3.10 and 3.11 show the results obtained from the compaction test for weathered shales from Verdigre and glacial tills from Lincoln, respectively.

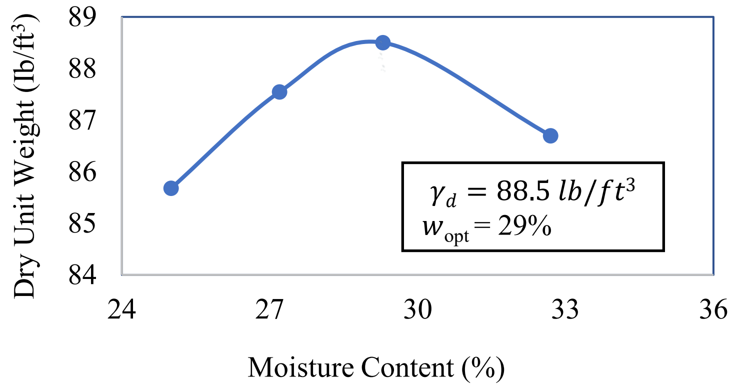


Figure 3.10 The compaction test curve for weathered shales from Verdigre

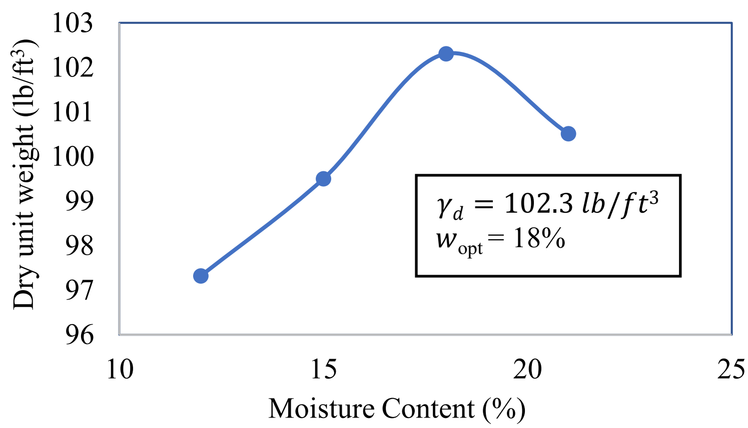


Figure 3.11 The compaction test curve for glacial tills from Lincoln

An electric bucket mixer was employed for an efficient and even mixing process. 1000 gr of dry soils was used each time in the mixer. Different percentages of the dry biopolymers (0.5%, 1.5%, 2.5%) were directly added to the dry soils and mixed with the soils for 4 minutes. Then water was added gradually up to 29% and 18% of the dry weight of the soils for weathered shales from Verdigre and glacial tills from Lincoln, respectively. The water was then added by using a squeeze bottle, and the mixing process was continued for 20 minutes until all the particles were mixed thoroughly with water. Figure 3.12 shows a scene for mixing soil, biopolymers, and water.

Figure 3.12 Mixing soil with biopolymers and water (Song et al., 2018)

For preparing compacted test specimens, a method of compaction developed by Sullivan et al. was adopted (Sullivan et al. 2015). This method is called "*Preparation of test specimens using the plastic mold compaction device*" and is intended to produce test specimens with approximate density obtained from AASHTO T 99. The method involves the use of a plastic mold compaction device (PM device) to prepare cylindrical specimens with an approximate 2:1 height to diameter (Howard et al., 2013; Sullivan et al., 2015). The PM is shown in Figure 3.13. The fixture includes a metal split-mold, collar, and base plate. The cylindrical plastic mold is 3.0 in diameter by 6.00 in tall.

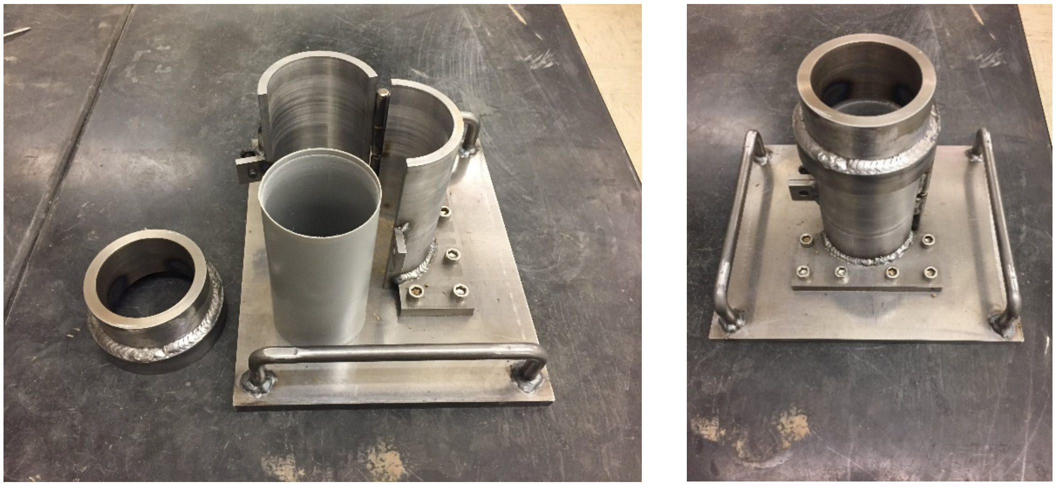


Figure 3.13 Plastic mold (PM) compaction fixture (Song et al., 2018)

For even compaction of soil samples, the soil was compacted into the plastic mold in three approximately equal thicknesses of layers. Each layer was compacted by five uniformly distributed blows, obtained by the rammer dropping from a height of 18 in. The compacted sample was then removed from the plastic mold using a hydraulic sample extruder. Figure 3.14(a) and 3.14(b) show the specimens after compaction and extrusion for glacial tills from Lincoln and weathered shales from Verdigre, respectively.

(a) **(b)**

Figure 3.14 (a): Glacial tills from Lincoln (b): Weathered shales from Verdigre

The compacted samples were cut and trimmed into three pieces to prepare samples for subsequent weathering and strength tests. Each sample was then trimmed to obtain the final sample size of a 2.5 in diameter and 1.0 in height, using a consolidation ring. Figure 3.15 showed the final samples after cutting and trimming for both glacial tills from Lincoln and weathered shales from Verdigre.

Figure 3.15 Compacted samples after cutting and trimming (Left: Glacial tills from Lincoln, Right: Weathered shales from Verdigre)

For the biopolymer additive to effectively strengthen the soils, proper curing time needs to be provided before the initiation of weathering and testing. Therefore, after the trimming process, soil samples were placed in PVC molds to prevent sample disturbance and then were wrapped and cured in vinyl wrap to prevent samples from losing their moisture as shown in Figure 3.16. The soil samples were wrapped and kept in the PVC molds in a plastic bag for a week for homogenization of moisture and texture.

Figure 3.16 Samples in Curing Stage

One of the main purposes of this experimental study was to evaluate the degradation effects of wetting and freezing cycles on the strength of biopolymer treated soils as well as untreated samples. A sophisticated weathering method was planned in this study to examine the behavior of soil samples in different weathering conditions. Since Nebraska experiences significant seasonal precipitation and temperature variations, the weathering tests were intended to simulate the condition in which soil samples are subject to repeated wetting and freezing conditions. A similar procedure to Khan (Khan 2016) was adopted, and a special fixture was designed for this purpose because it was not feasible to directly expose soil specimens to water without losing the grains of samples. The fixture included a PVC mold having an inner diameter with the same size as the soil specimens (i.e., 2.5 in), an outer diameter of 2.7 in, and a height of 1.6 in. Soil specimens were placed inside the PVC mold and between two porous stones, as shown in Figure 3.17. Porous stones were provided to allow water infiltration and drainage but preventing the migration of fine particles. While the bottom stone completely covers both mold and specimen, the top stone was inserted inside the PVC mold to sit at the surface of the specimen. The gap between the top of the mold and the top of the porous stone was about 0.3 in. This gap was considered to allow possible volume expansion of samples. Additionally, filter papers were placed between the specimen and porous stones to prevent stones from clogging. The schematic view of the weathering fixture is shown in Figure 3.17. And Figure 3.18 shows the step-by-step pictures of the placement of the specimen, filter papers, and porous stones. The whole fixture was then put between two hollowed polycarbonate plates and secured using four screws. The entire set shown in Figure 3.19 provided a way to weather samples with minimum disturbance.

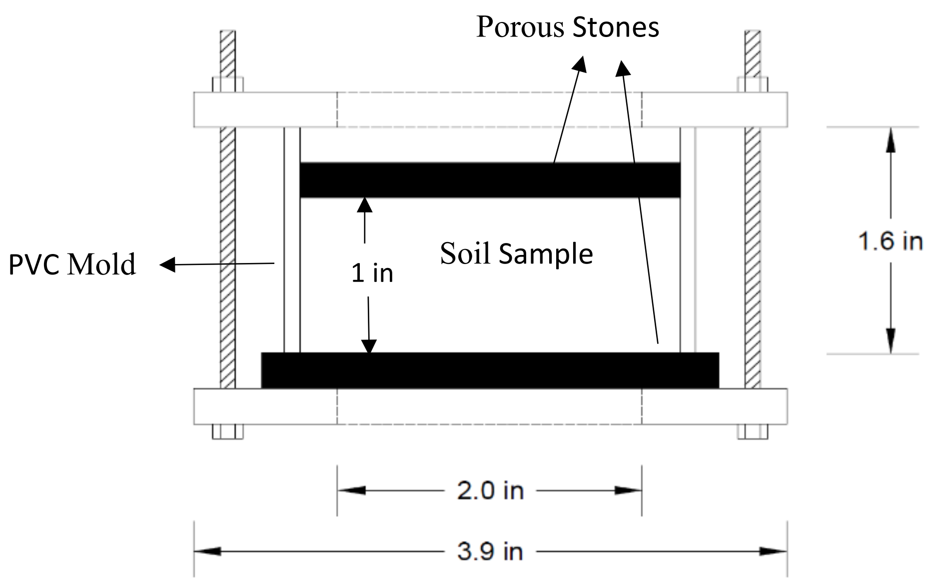


Figure 3.17 The fixture used for weathering soil samples (Song et al., 2018)

Figure 3.18 Preparing samples for weathering (Song et al., 2018)

Figure 3.19 Securing samples in the fixture for weathering

3.5 Application of weathering cycles to soil samples

Wet-freeze-thaw-dry cycles were selected to mimic the weathering conditions in Nebraska. One cycle of weathering was achieved by first placing the samples in the water bath for 24 hours (68 °F), and then keeping them in the freezer at -6 °F for 24 hours, followed by drying and heating the samples in the oven at 167 °F for 24 hours (Figure 3.20). Three different weathering cycles, including 2, 4, and 8 were chosen referring the previous research of Song et al. (2018) to see the effect of weathering cycles on the strength of the soil samples. It should be noted that one set of samples was also included as a control group, samples for this group did not go through any weathering cycles.

Figure 3.20 Water bath and oven used for wetting and drying soil samples, respectively

3.6 Testing

After the required weathering cycles were obtained for each set of samples, the strength of soil samples was determined using the conventional direct shear test. Considering two replicates for each group of samples, a total of 144 specimens were prepared for testing. These included the specimens treated with Xanthan and Gellans plus the original untreated soil specimens. All the samples were prepared for four different weathering cycles (i.e., 0, 2, 4, 8). It should be mentioned that all specimens were tested right after the last wet cycle. For the samples with no weathering cycles, they were placed in the water bath before testing just to reach a similar level of moisture content to other samples. The moisture content of samples was determined before testing, and the results are summarized in Table 3.2 and Table 3.3.

800 psf normal pressure was selected and maintained during the test. This much magnitude of the normal pressure was selected to simulate the behavior of soil in shallow depth (≈ 7 ft). A constant shear displacement of 0.01 in/min (0.25 mm/min) was then applied until the sample failed.

Table 3.2 Moisture content of weathered shales (Verdigre, NE) samples

Biopolymer	Concentration %	Weathering condition	No of cycles	w %
NA	-	W-F-T-D	0	36.26
NA	-	W-F-T-D	2	36.97
NA	-	W-F-T-D	4	37.13
NA	-	W-F-T-D	8	37.34
Xanthan	0.5	W-F-T-D	0	36.84
Xanthan	0.5	W-F-T-D	2	37.17
Xanthan	1.5	W-F-T-D	0	37.28
Xanthan	1.5	W-F-T-D	2	38.66
Xanthan	1.5	W-F-T-D	4	38.78
Xanthan	1.5	W-F-T-D	8	39.33
Xanthan	2.5	W-F-T-D	0	37.82
Xanthan	2.5	W-F-T-D	2	38.34
Xanthan	2.5	W-F-T-D	4	38.77
Xanthan	2.5	W-F-T-D	8	39.52
Gellan	0.5	W-F-T-D	0	36.38
Gellan	0.5	W-F-T-D	2	37.54
Gellan	1.5	W-F-T-D	0	36.82
Gellan	1.5	W-F-T-D	2	37.79
Gellan	1.5	W-F-T-D	4	38.23
Gellan	1.5	W-F-T-D	8	38.46
Gellan	2.5	W-F-T-D	0	37.28
Gellan	2.5	W-F-T-D	2	38.17
Gellan	2.5	W-F-T-D	4	38.63
Gellan	2.5	W-F-T-D	8	39.34

Table 3.3 Moisture content of glacial tills (Lincoln, NE) samples

Biopolymer	Concentration %	Weathering condition	No of cycles	w %
NA	-	W-F-T-D	0	30.26
NA	-	W-F-T-D	2	30.81
NA	-	W-F-T-D	4	31.20
NA	-	W-F-T-D	8	31.33
Xanthan	0.5	W-F-T-D	0	30.72
Xanthan	0.5	W-F-T-D	2	31.64
Xanthan	1.5	W-F-T-D	0	31.43
Xanthan	1.5	W-F-T-D	2	32.56
Xanthan	1.5	W-F-T-D	4	32.40
Xanthan	1.5	W-F-T-D	8	32.61
Xanthan	2.5	W-F-T-D	0	31.89
Xanthan	2.5	W-F-T-D	2	32.78
Xanthan	2.5	W-F-T-D	4	32.97
Xanthan	2.5	W-F-T-D	8	32.89
Gellan	0.5	W-F-T-D	0	30.66
Gellan	0.5	W-F-T-D	2	31.24
Gellan	1.5	W-F-T-D	0	31.19
Gellan	1.5	W-F-T-D	2	32.29
Gellan	1.5	W-F-T-D	4	32.53
Gellan	1.5	W-F-T-D	8	32.34
Gellan	2.5	W-F-T-D	0	31.61
Gellan	2.5	W-F-T-D	2	32.52
Gellan	2.5	W-F-T-D	4	32.89
Gellan	2.5	W-F-T-D	8	33.18

Chapter 4

Results and Discussion

4.1 Direct shear test on glacial tills from Lincoln

4.1.1 Weathered strength of untreated glacial tills

Figure 4.1 shows that the yield stress is decreased as the number of weathering cycles is increased. Figure 4.2, on the other hand, shows that the effect of the number of weathering cycles is decreased on the shear strength is gradually diminished at a higher number of weathering cycles. The shear strength reduction from 4 cycles (2.8 psi) to 8 cycles (2.6 psi) is only 7 %. While the highest decrease in the shear strength occurs from zero weathering cycles (4.65 psi) to 2 weathering cycles (3.3 psi), indicating 30% reduction in the shear strength, indicating a hyperbolical weathering effect of number of weathering cycles on the shear strength of soils.

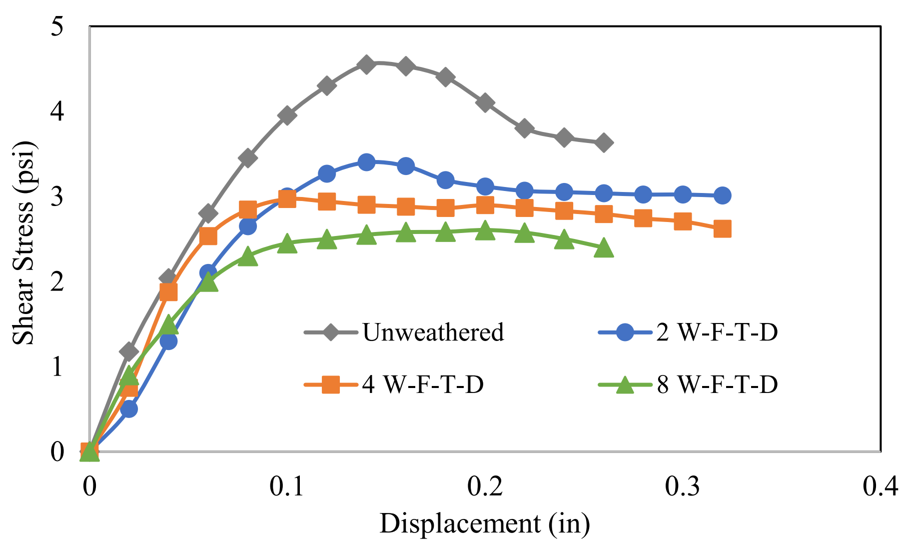


Figure 4.1 Direct shear test results on untreated glacial tills subjected to different weathering cycles

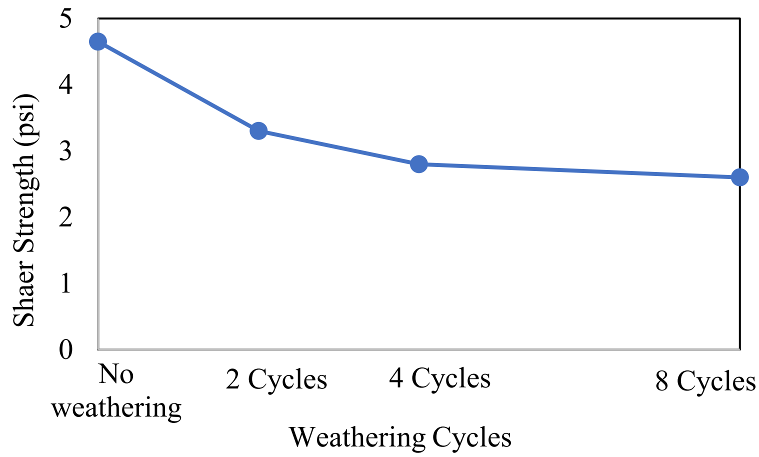


Figure 4.2 Shear strength of untreated glacial tills under different weathering cycles

4.1.2 Unweathered strength of Xanthan treated glacial tills

Glacial tills were treated with three different concentrations of Xanthan (0.5%, 1.5%, and 2.5%) to evaluate the effect of biopolymer contents on the shear strength of the soils. As shown in Figure 4.3, specimens with higher Xanthan content showed higher peak shear strength. There was 31%, 80%, and 108% enhancement in the shear strength by adding 0.5%, 1.5%, and 2.5% of Xanthan, respectively. The increased strength in higher Xanthan content is believed to be due to the enhanced cation bridging and hydrogen bonding between the electrically charged clay surface and the hydroxy and carboxylic acid in the biopolymer, as reported by Chang et al. (2016). For granular soils, it is mentioned that Xanthan is believed to works as a cementation agent in the voids between the particles of the granular soils, as reported by Chang et al. (2016).

Moreover, Figure 4.3 shows that Xanthan treated soils tend to have higher strength and ductile behavior while untreated soils tend to have lower strength and brittle behavior, which is the desired behavior of soils in the slope.

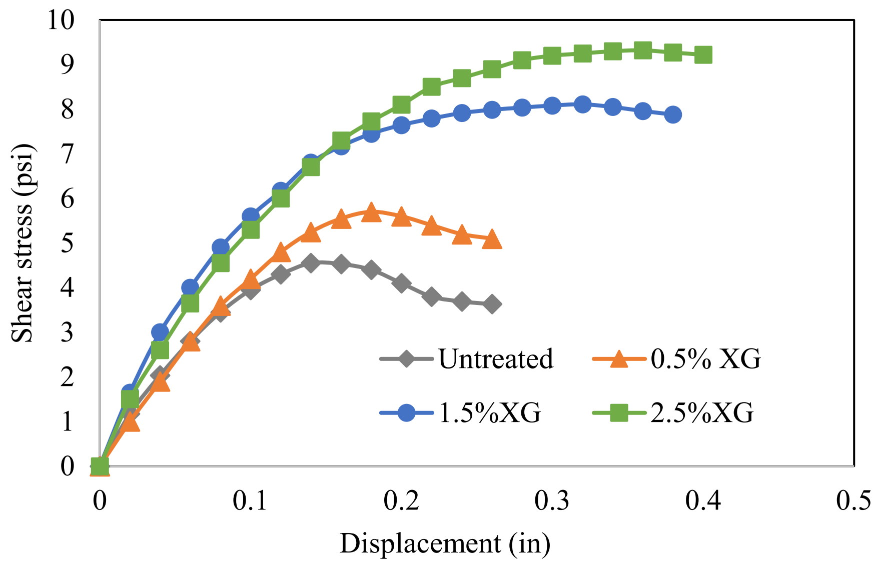


Figure 4.3 The effect of Xanthan content on the shear strength of the glacial tills

Figure 4.4 shows that the improvement in the shear strength of the unweathered glacial tills gradually decreased as the Xanthan concentration is increased from 1.5% to 2.5%. Based on Chang et al. (2015), this behavior is likely due to the hydrophilic property of the biopolymer; the surplus Xanthan molecules will absorb water and remain unbonded with the surface of the soil particles resulting in a lower increment in the shear strength. The non-linear asymptotic enhancement in the shear strength due to increasing the percentage of the biopolymer suggests that the shear strength might stabilize at higher Xanthan content.

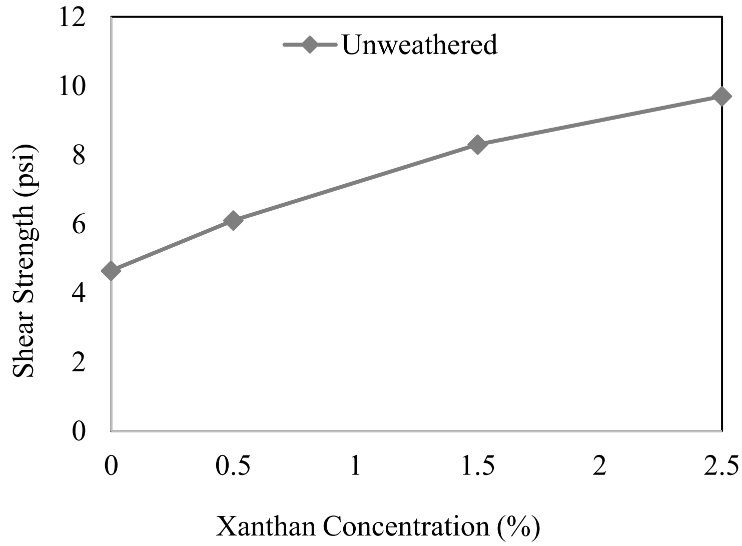


Figure 4.4 The effect of Xanthan content on the shear strength of the glacial tills

4.1.3 Weathered strength of Xanthan treated glacial tills

The durability of the glacial tills treated with Xanthan was tested to evaluate the weathering resistance. The glacial tills mixed with various concentrations of Xanthan (i.e. 0.5%, 1.5%, and 2.5%) were subjected to two wet-freeze-thaw-dry cycles. Figure 4.5 shows that the strength of the Xanthan treated glacial tills mixed is much higher than that of untreated glacial till samples, which is consistent with the result in 4.1.2 for unweathered strength of Xanthan treated glacial tills.

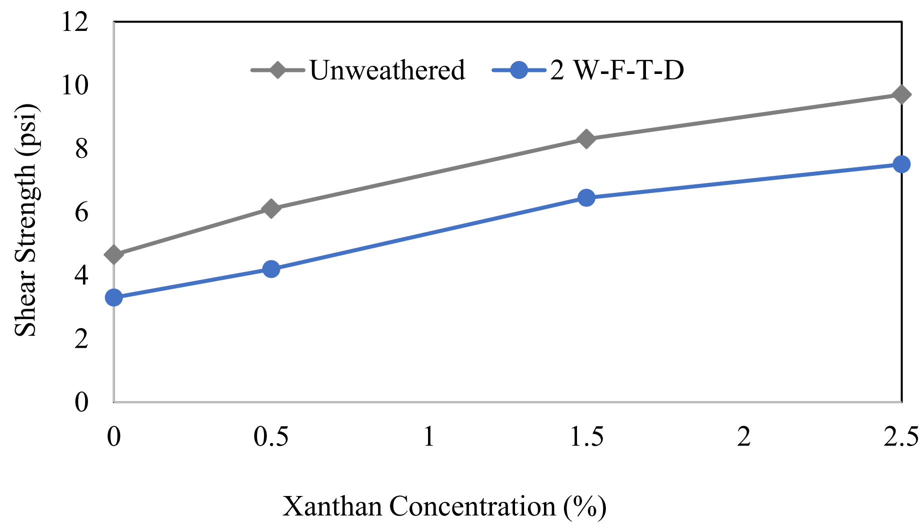


Figure 4.5 Direct shear test results of the glacial tills mixed with 0.5%, 1.5%, and 2.5% of Xanthan under no weathering cycles and two weathering cycles

Since the glacial tills treated with higher concentrations of Xanthan showed higher shear strength, the 1.5% and 2.5% Xanthan treated soils were subjected to 4 and 8 weathering cycles to further evaluate the behavior of stabilized glacial tills under several wet-freeze-thaw-dry cycles.

Figure 4.6 shows there is a decrease in the shear strength of the Xanthan treated soils as the number of the weathering cycles increases. Based on Chang et al. (2017), additional weathering cycles might affect the structure of the Xanthan attached to the surface of the soils, causing a disturbance in the soil structure. However, the reduction rate in the shear strengths is reduced compared to that for untreated soils. A notable result is that the magnitude of weathered strength after 8 cycles is still close to the initial strength of untreated samples.

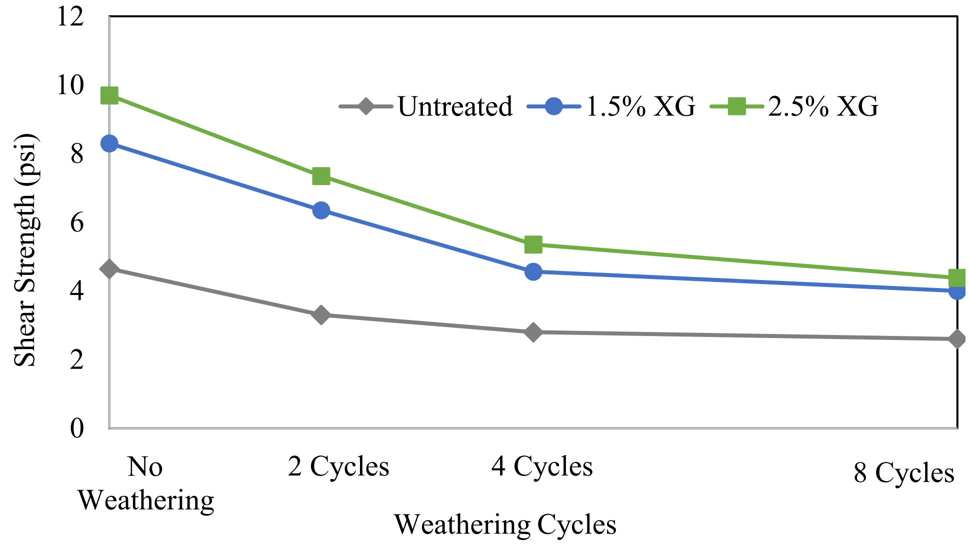


Figure 4.6 Shear strength of glacial tills mixed with 1.5% and 2.5% of Xanthan and subjected to different weathering cycles

4.1.4 Unweathered strength of Gellan treated glacial tills

Gellan was also used in this study to evaluate the effect of this biopolymer on the shear strength of the glacial tills. Figure 4.7 shows the direct shear test results of the glacial tills treated with different concentrations of Gellan (i.e. 0.5%, 1.5%, and 2.5%) under no weathering cycles. As shown in the figure, higher shear strength is obtained at higher Gellan content. There are about 8%, 27%, and 41% increase in the shear strength of the unweathered soils by using 0.5%, 1.5%, and 2.5% of Gellan, respectively. However, the overall strength-enhancing characteristic of Gellan was slightly lower than that of Xanthan.

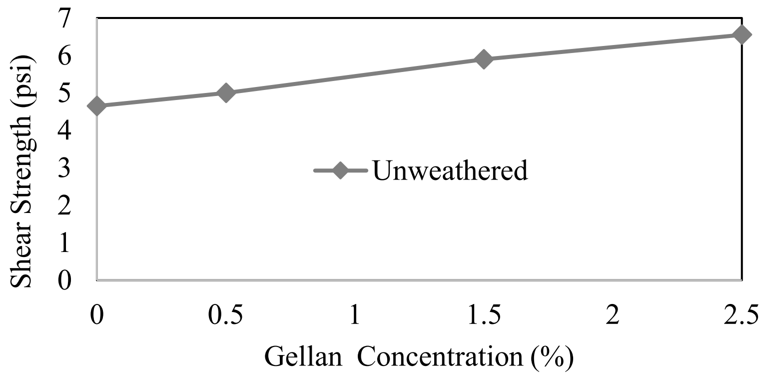


Figure 4.7 The effect of Gellan content on the shear strength of the glacial tills

4.1.5 Weathered strength of Gellan treated glacial tills

The treated glacial tills mixed with different concentrations of Gellan (i.e. 0.5%, 1.5%, and 2.5%) were subjected to two wet-freeze-thaw-dry cycles. Figure 4.8 shows a reduced shear strength of the glacial tills treated with Gellan samples under two weathering cycles. The decreasing percentage in the shear strength due to weathering is 25%, 24%, and 26% for the samples mixed with 0.5%, 1.5%, and 2.5% of Gellan, respectively. However, the shear strength of the glacial tills mixed with 1.5% and 2.5% of Gellan at 2 weathering cycles (4.5 psi, 4.85 psi, respectively) is similar to the initial shear strength of the unweathered samples (4.65 psi).

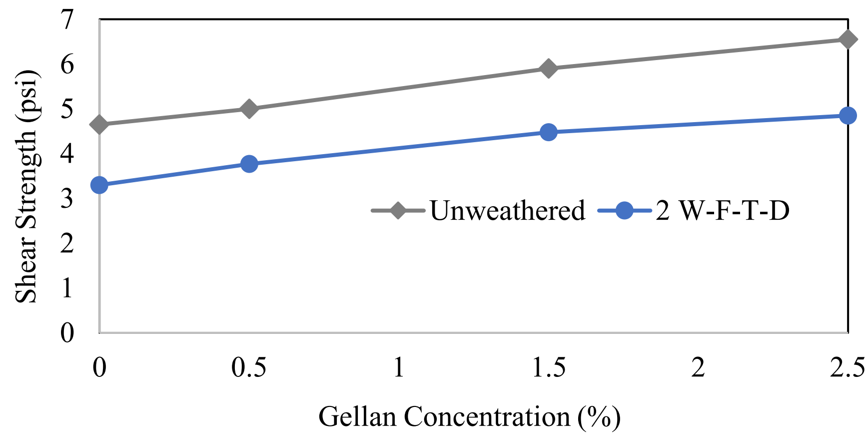


Figure 4.8 Direct shear test results of the glacial tills mixed with 0.5%,1.5%, and 2.5% of Gellan under no weathering cycles and two weathering cycles

Figure 4.9 presents the effect of weathering cycles up to 8 on the shear strength of the treated soils mixed with 1.5% and 2.5% of Gellan. From the figure, the shear strength of the treated soils decreases as the weathering cycles increase. However, the convergence in the shear strength of the treated soils is observed at 4 and 8 weathering cycles. The figure also shows that the shear strengths of the glacial tills treated with Gellan treated samples and the untreated soils are comparable at 8 weathering cycles. This might point out that the effect of Gellan in improving the shear strength of glacial tills is practically vanished after applying 4 to 8 weathering cycles, while the Xanthan treated samples showed sustained strength even at high weathering cycles.

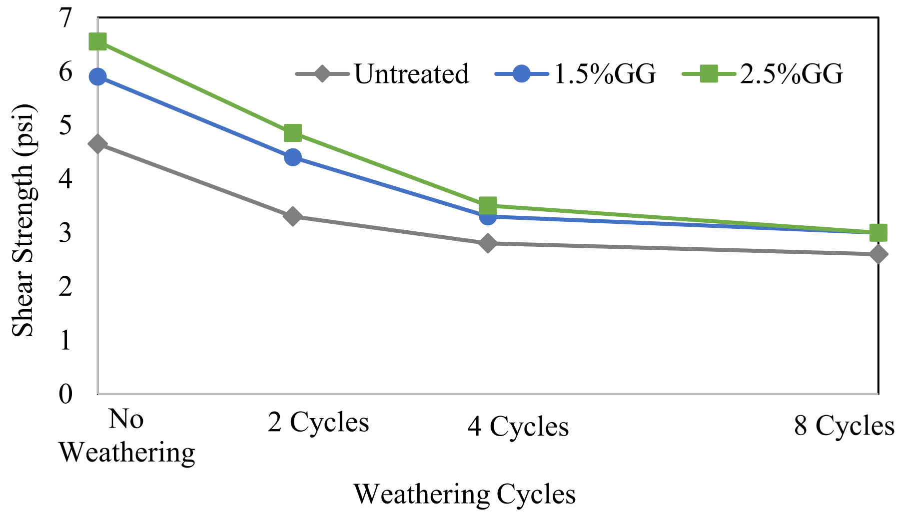


Figure 4.9 Shear strength of glacial tills mixed with 1.5% and 2.5% of Gellan and subjected to different weathering cycles

4.1.6 Cross comparison of Xanthan and Gellan for glacial tills

Figures 4.10, 4.11, 4.12, and 4.13 show the cross-comparison of the strengthening effect of different concentrations of Xanthan and Gellan (i.e. 0.5%, 1.5%, and 2.5%) on the glacial tills under different wet-freeze-thaw-dry cycles up to 8 cycles. While both biopolymers are effective in improving the strength of the glacial tills, Xanthan appears to be more effective in all cases. According to Ayeldeen et al. (2016), this is due to the fact that biopolymers have different chemical compositions that play a major role in forming the structure of the biopolymer. The chemical interaction between biopolymers and soil particles depends on microscale forces existing on the interface between soils and biopolymers. Those bonding forces include van der Waals force that provides the weak bonding and covalent bonding that provides a stronger one.

Figure 4.10 shows 31%, 80%, and 108% enhancement in the unweathered shear strength of the glacial tills by adding 0.5%, 1.5%, and 2.5% of Xanthan, respectively. In comparison, it shows 8%, 27%, and 41% enhancement in the unweathered shear strength of the glacial tills by adding 0.5%, 1.5%, and 2.5% of Gellan.

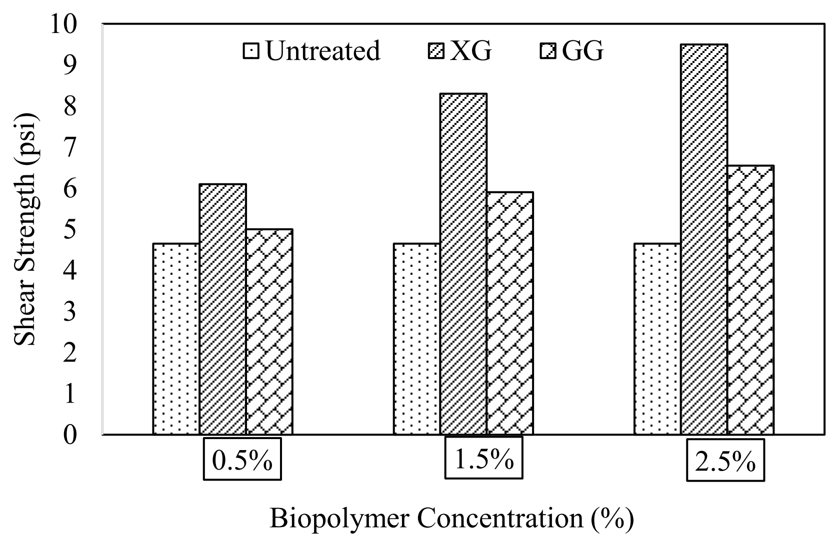


Figure 4.10 Direct shear test results for glacial tills mixed with different concentrations of Xanthan and Gellan (i.e., 0.5%,1.5%, and 2.5%) under no weathering cycles

Figure 4.11 shows that the treated glacial tills exhibit higher shear strength than the untreated ones under 2 weathering cycles. Glacial tills treated with higher concentrations of Xanthan or Gellan present higher shear strength. Moreover, the glacial tills mixed with Xanthan show higher shear strength than the glacial tills mixed with Gellan at the same biopolymer content.

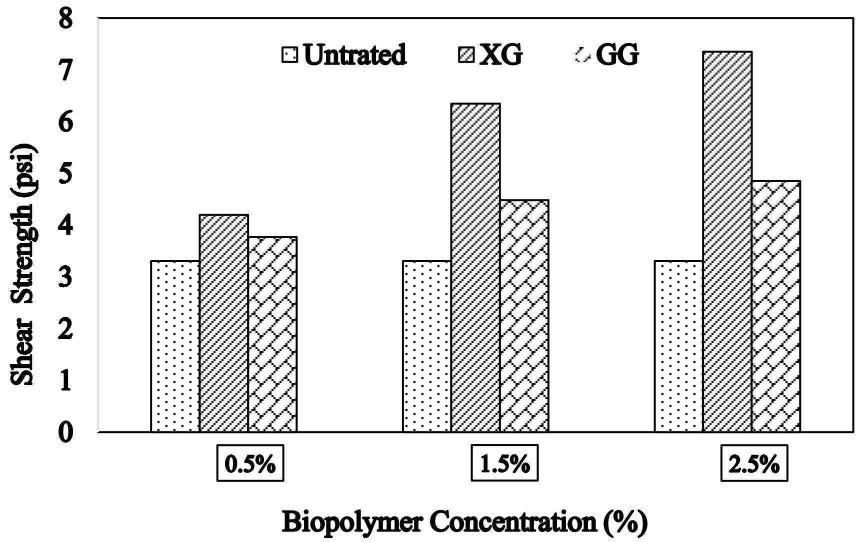


Figure 4.11 Direct shear test results for glacial tills mixed with different concentrations of Xanthan and Gellan (i.e., 0.5%,1.5%, and 2.5%) under 2 W-F-T-D weathering cycles

Figure 4.12 shows that soil samples treated with glacial tills exhibit higher shear strength than the untreated ones under 4 weathering cycles. But glacial tills treated with 2.5% Xanthan show higher shear strength than the glacial tills treated with 1.5% of Xanthan. Moreover, the glacial tills treated with 1.5% and 2.5% of Gellan show did not show a noticeable difference.

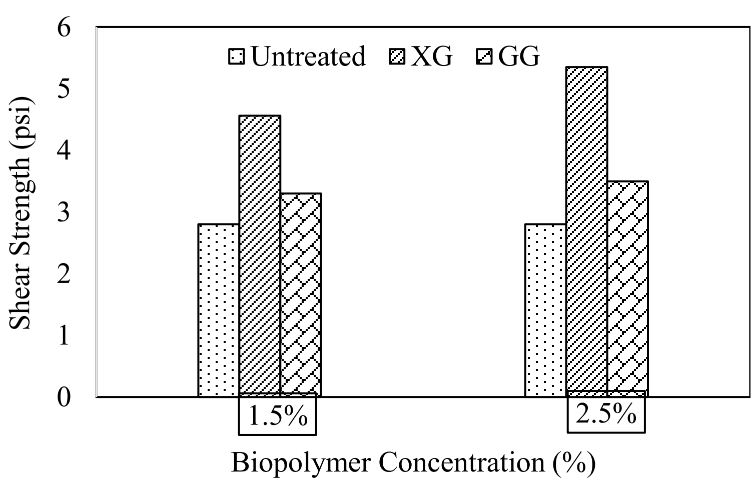


Figure 4.12 Direct shear test results for glacial tills mixed with different concentrations of Xanthan and Gellan (i.e., 1.5% and 2.5%) under 4 W-F-T-D weathering cycles

Figure 4.13 shows that the treated glacial tills exhibit higher shear strength than the untreated ones under 8 weathering cycles. The shear strength of the glacial tills treated with 1.5% or 2.5% of Xanthan or Gellan does not show a noticeable difference.

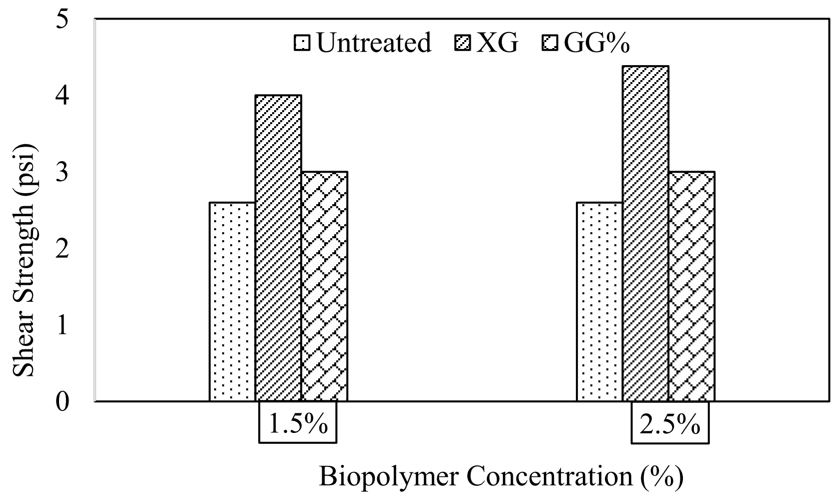


Figure 4.13 Direct shear test results for glacial tills mixed with different concentrations of Xanthan and Gellan (i.e. 1.5% and 2.5%) under 8 W-F-T-D weathering cycles

Table 4.1 shows the summary result of the direct shear tests conducted on the untreated and treated glacial tills mixed with 0.5%, 1.5%, and 2.5% of Xanthan and Gellan and subjected to different weathering cycles (i.e., 0, 2, 4, 8 cycles). In overall, Xanthan showed a slightly better performance compared to Gellan for glacial tills.

Table 4.1 Direct shear test results for untreated and treated glacial tills from Lincoln

Biopolymer	Concen-tration (%)	Weathering cycles	No of cycles	No of sample	Shear strength (psi)	Avg. shear strength (psi)	w (%)	G (psi)
NA	-	W-F-T-D	0	1	4.53	4.65	30.26	50
NA	-	W-F-T-D	0	2	4.77			
NA	-	W-F-T-D	2	1	3.3	3.3	30.81	33.33
NA	-	W-F-T-D	4	1	2.97	2.8	31.2	37.2
NA	-	W-F-T-D	4	2	2.63			
NA	-	W-F-T-D	8	1	2.6	2.6	31.33	33.33
Xanthan	0.5	W-F-T-D	0	1	5.7	6.1	30.66	52.63
Xanthan	0.5	W-F-T-D	0	2	6.5			
Xanthan	0.5	W-F-T-D	2	1	4.42	4.2	31.24	50
Xanthan	1.5	W-F-T-D	0	1	8	8.3	31.19	70
Xanthan	1.5	W-F-T-D	0	2	8.6			
Xanthan	1.5	W-F-T-D	2	1	6.48	6.35	32.29	57.14
Xanthan	1.5	W-F-T-D	2	2	6.22			
Xanthan	1.5	W-F-T-D	4	1	4.56	4.56	32.53	40
Xanthan	1.5	W-F-T-D	8	1	4.1	4.1	32.34	26.67
Xanthan	2.5	W-F-T-D	0	1	9.3	9.7	31.61	74.07
Xanthan	2.5	W-F-T-D	0	2	10.1			
Xanthan	2.5	W-F-T-D	2	1	7.73	7.35	32.52	47.05
Xanthan	2.5	W-F-T-D	2	2	6.97			
Xanthan	2.5	W-F-T-D	4	1	5.35	5.35	32.89	45.45
Xanthan	2.5	W-F-T-D	8	1	4.5	4.38	33.18	28.57
Xanthan	2.5	W-F-T-D	8	2	4.26			
Gellan	0.5	W-F-T-D	0	1	5	5	30.72	40
Gellan	0.5	W-F-T-D	2	1	3.55	3.77	31.64	30
Gellan	0.5	W-F-T-D	2	2	4			
Gellan	1.5	W-F-T-D	0	1	5.6	5.9	31.43	47.06
Gellan	1.5	W-F-T-D	0	2	6.2			
Gellan	1.5	W-F-T-D	2	1	4.17	4.4	32.56	42.86
Gellan	1.5	W-F-T-D	2	2	4.63			
Gellan	1.5	W-F-T-D	4	1	3.68	3.5	32.4	33.33
Gellan	1.5	W-F-T-D	4	2	3.32			
Gellan	1.5	W-F-T-D	8	1	3	3	32.61	30.76
Gellan	2.5	W-F-T-D	0	1	6.67	6.55	31.89	66.7
Gellan	2.5	W-F-T-D	0	2	6.43			
Gellan	2.5	W-F-T-D	2	1	5	4.85	32.78	57.14
Gellan	2.5	W-F-T-D	2	2	4.7			
Gellan	2.5	W-F-T-D	4	1	3.5	3.5	32.97	37.5
Gellan	2.5	W-F-T-D	8	1	3	3	32.89	32.26

4.2 Direct shear test on weathered shales from Verdigre

4.2.1 Weathered strength of weathered shales from Veridigre with no biopolymer treatment

The direct shear test was conducted on the untreated weathered shales from Verdigre, applying 4 different wet-freeze-thaw-dry cycles (i.e., 0, 2, 4, and 8 cycles) to investigate the effect of weathering on the shear strength of the untreated soils. Figure 4.14 shows the reduced yield stress at the higher number of the weathering cycles. However, Figure 4.15 shows the loss in shear strength from 4 cycles (2.66 psi) to 8 cycles (2.56 psi) is insignificant. This trend implies that the reduction in shear strength might stabilize at a higher number of weathering cycles.

The highest drop in the shear strength occurs from no weathering cycles (3.9 psi) to 2 weathering cycles (2.9 psi) (25% reduction in the shear strength). This behavior may indicate that a significant drop in shear strength may occur at the earlier weathering cycles right after the construction.

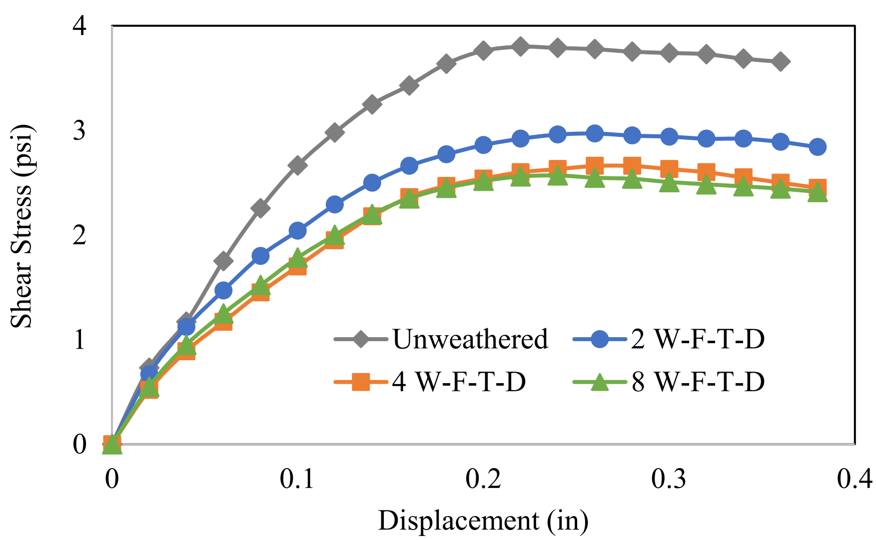


Figure 4.14 Direct shear test results on untreated Verdigre tills subjected to different weathering cycles

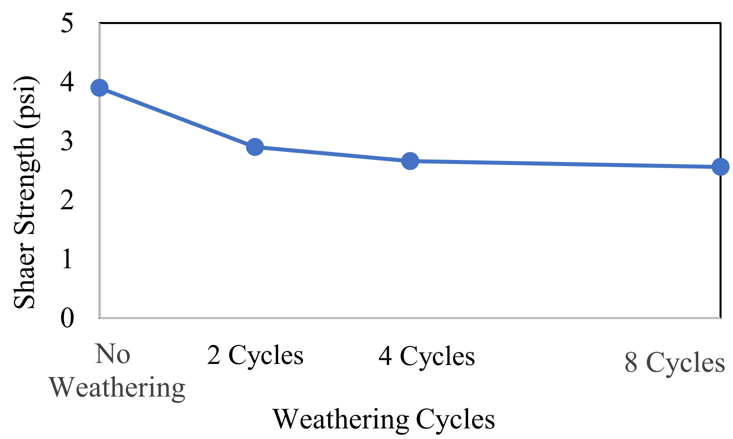


Figure 4.15 Shear strength of untreated weathered shales from Verdigre samples under different weathering cycles

4.2.2 Unweathered strength of weathered whales from Verdigre treated with Xanthan

Weathered shales from Verdigre were treated with different concentrations of Xanthan (0.5%, 1.5%, and 2.5%) to evaluate the effect of the Xanthan content on the shear strength of the soils. As shown in Figure 4.16, increasing Xanthan contents increased the shear strength of the soils. There is about 20%, 30%, and 40% increase in the shear strength by mixing 0.5%, 1.5%, and 2.5% of Xanthan, respectively. The difference between 1.5% and 2.5% Xanthan is slightly controversial; it showed higher resistance for 1.5% at the lower strain level but lower resistance at the higher strain level. In overall, it appears that increasing the amount of Xanthan mixed with the weathered shales from Verdigre effectively enhanced the chemical interaction between the Xanthan and the electrically charged surface of the clay soils producing higher shear strength.

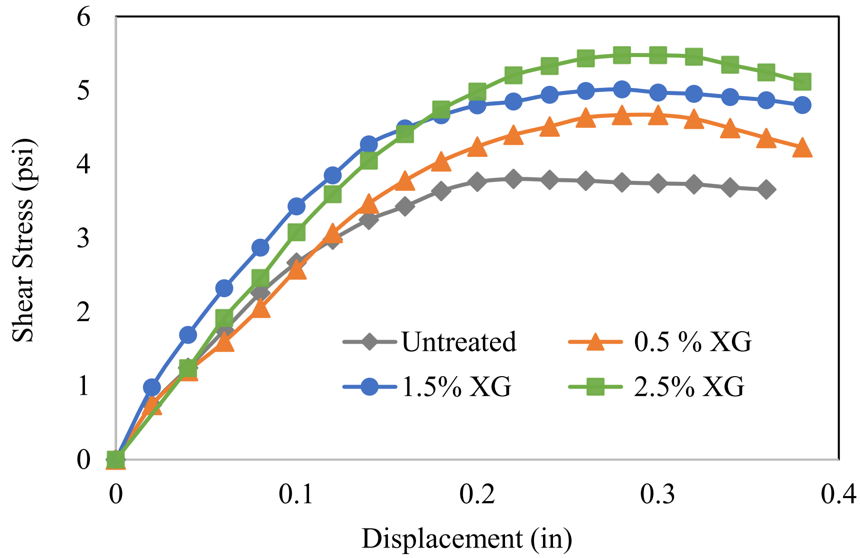


Figure 4.16 The effect of Xanthan content on the shear strength of the weathered shales from Verdigre

Moreover, Figure 4.1 shows that the displacement at peak stresses appears higher at higher Xanthan content, implying that the soils of higher Xanthan content become more ductile than those of lower Xanthan content. This behavior suggests that treating soils with Xanthan modifies the structure of soils, resulting in the enhanced shearing and cracking resistance of the weathered shales, similar to the behavior of glacial tills as discussed in 4.1.

4.2.3 Weathered strength of weathered shales from Verdigre treated with Xanthan

Weathered shales from Verdigre treated with Xanthan samples were subjected to two wet-freeze-thaw-dry weathering cycles to assess the behavior and the durability of the soils mixed with different concentrations of Xanthan (i.e. 0.5%, 1.5%, and 2.5%). Figure 4.17 shows the weathered shales stabilized with higher Xanthan contents exhibit higher shear strength. Also, there is a reduction in the shear strength of the treated soils when subjected to two weathering cycles. The decreasing percentage in the shear strength is 26%, 23%, and 24% for the samples mixed with 0.5%, 1.5%, and 2.5% of Xanthan, respectively. Based on Chang et al. (2016), Xanthan-fines matrices will absorb water leading to a decrease in the stiffness of the Xanthan gel when the treated soils are subjected higher moisture content. This behavior causes a reduction in the shear strength. By re-drying the soils, the hydrogel will dehydrate, and the shear strength increases. But the current shear strength is lower than the previous one. However, the strength of the weathered shales from Verdigre mixed with 1.5% and 2.5% of Xanthan at 2 weathering cycles (3.85 psi, 4.15 psi, respectively) is similar to the strength of the untreated unweathered ones (3.9 psi).

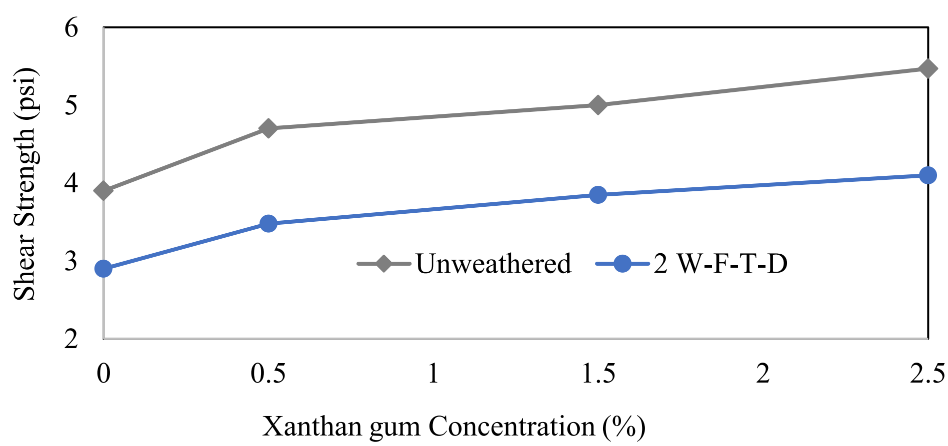


Figure 4.17 Direct shear test results of the weathered shales from Verdigre mixed with 0.5%,1.5%, and 2.5% of Xanthan under no weathering cycles and two weathering cycles

Soils treated with 1.5% and 2.5% of Xanthan were subjected to 4 and 8 weathering cycles to demonstrate the behavior of the weathered shales from Verdigre treated with higher contents of Xanthan under several weathering cycles. Figure 4.18 shows that the shear strength of the stabilized soils decreases as the number of weathering cycles increases. However, the decrease in the shear strength is insignificant from 4 cycles to 8 weathering cycles. Weathered shales from Verdigre treated with 1.5% and 2.5% of

Xanthan show similar shear strength at 4 cycles (3.5 psi) and 8 weathering cycles (3.25 psi). It may be inferred that the effect of mixing weathered shales from Verdigre with Xanthan concentrations greater than 1.5% on the shear strength is not obvious at higher weathering cycles. The shear strength of the treated soils at 8 weathering cycles is 83% of the untreated unweathered ones (3.9 psi). That might indicate the appropriate use of Xanthan to stabilize the weathered shales from Verdigre in the Verdigre slope.

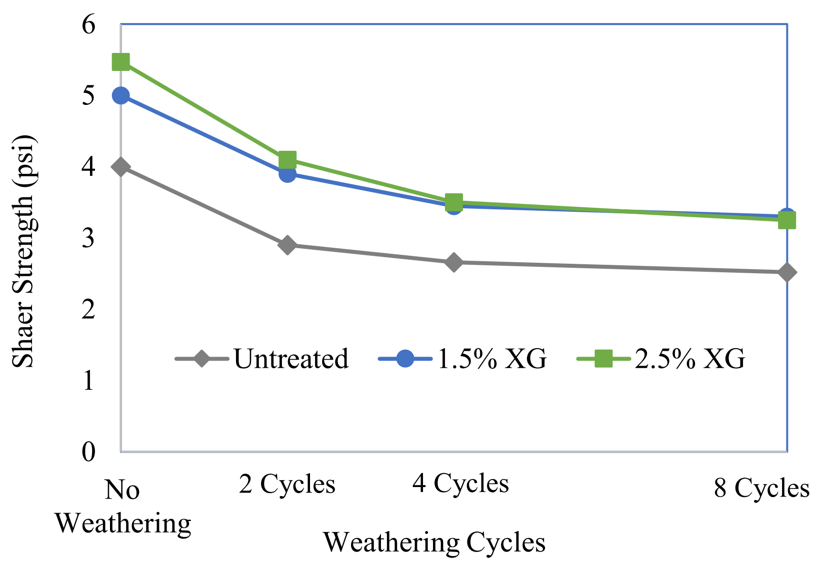


Figure 4.18 Shear strength of weathered shales from Verdigre mixed with 1.5% and 2.5% of Xanthan and subjected to different weathering cycles

4.2.4 Behavior of unweathered shales treated with Gellan

Weathered shales from Verdigre were also treated with Gellan to evaluate the effect of using this biopolymer on the shear strength of the weathered shales from Verdigre. Figure 4.19 shows the direct shear test results of the weathered shales from Verdigre treated with different concentrations of Gellan (i.e. 0.5%, 1.5%, and 2.5%). As shown in this figure, higher shear strength is attained by using higher contents of Gellan. There are about

5%, 10%, and 17% increments in the shear strength of the weathered shales from Verdigre by using 0.5%, 1.5%, and 2.5% of Gellan, respectively.

It is noted that Xanthan and Gellan are more effective in glacial tills compared to weathered shales from Verdigre. Based on Chang et al. (2015), this is likely due to the coupled effect between the biopolymer-fine soil matrices and the granular particles in glacial tills. The biopolymer-fine soil matrices work as a cementation agent in the voids between the coarse particles and improve the inter-particle properties.

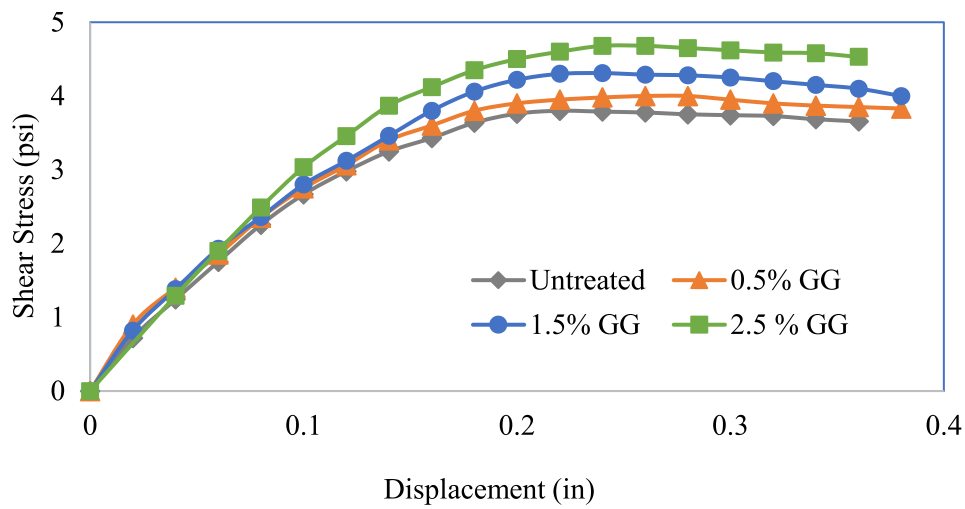


Figure 4.19 The effect of Gellan content on the shear strength of the weathered shales from Verdigre

4.2.5 Behavior of weathered shales reated with Gellan

Two weathering cycles (wet-freeze-thaw-dry) were conducted on the stabilized weathered shales from Verdigre mixed with different concentrations of Gellan (i.e. 0.5%, 1.5%, and 2.5%). Figure 4.20 shows there is a reduction in the shear strength of the weathered shales from Verdigre treated with Gellan samples under two weathering cycles. The reduction percentage in the shear strength is 23% for the samples mixed with 0.5%, 1.5%, and 2.5% of Gellan.

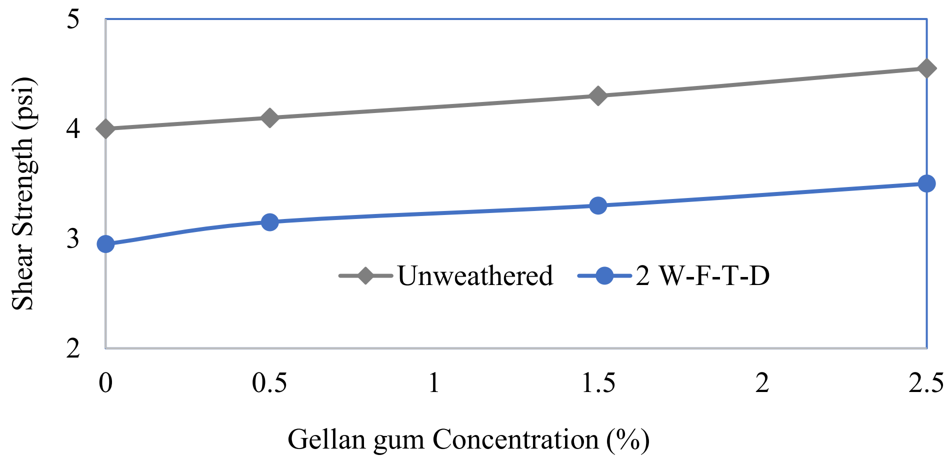


Figure 4.20 Direct shear stress results of the Verdigre tills mixed with 0.5%,1.5%, and 2.5% of Gellan under no weathering cycles and two weathering cycles

Figure 4.21 presents the effect of applying several weathering cycles up to 8 on the shear strength of the treated soils using 1.5% and 2.5% of Gellan. From the figure, the shear strength of the treated weathered shales from Verdigre decreases as the number of the weathering cycles increases. There is a stabilization in the shear strength of the treated soils at 4 and 8 weathering cycles for both cases (1.5% and 2.5% of Gellan). Also, the soil samples treated with 1.5% and 2.5% of Gellan have the same shear strength at 4 cycles (2.85 psi) and 8 weathering cycles (2.63 psi). Additionally, the shear strengths of the weathered shales from Verdigre treated with Gellan samples and the untreated soils are comparable at 8 weathering cycles (2.63 psi). That may imply the effectiveness of Gellan in improving the shear strength of the weathered shales from Verdigre disappears at higher weathering cycles.

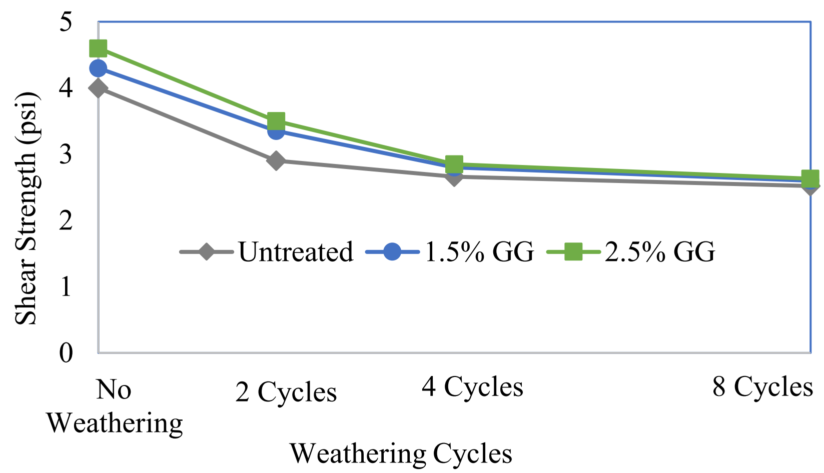


Figure 4.21 Shear strength of weathered shales from Verdigre mixed with 1.5% and 2.5% of Gellan and subjected to different weathering cycles

4.2.6 Cross comparison of Xanthan and Gellan for weathered shales from Verdigre

Figures 4.22, 4.23, 4.24, and 4.25 show the visual comparison of the strengthening effect of Xanthan and Gellan under no weathering cycles and 2, 4, and 8 wet-freeze-thaw-dry cycles. From those figures, Xanthan is more effective compared to Gellan in increasing the shear strength of the weathered shales from Verdigre in all cases. This observation is also recognized in the glacial tills. As was mentioned earlier and based on Ayeldeen et al. (2016), biopolymers have different chemical compositions that control the interaction between the biopolymers and the negatively charged surface of the clay causing them to generate different types of forces on the surface of the soil particles. Those bonding forces include van der Waals force, which presents the weakest bonding, and covalent bonding which is responsible for a stronger one.

Figure 4.22 shows there is a 20%, 30%, and 40% enhancement in the unweathered shear strength of the weathered shale samples by adding 0.5%, 1.5%, and 2.5% of Xanthan, respectively. While there are 5%, 10%, and 17% increments in the unweathered shear strength of the weathered shales by adding 0.5%, 1.5%, and 2.5% of Gellan.

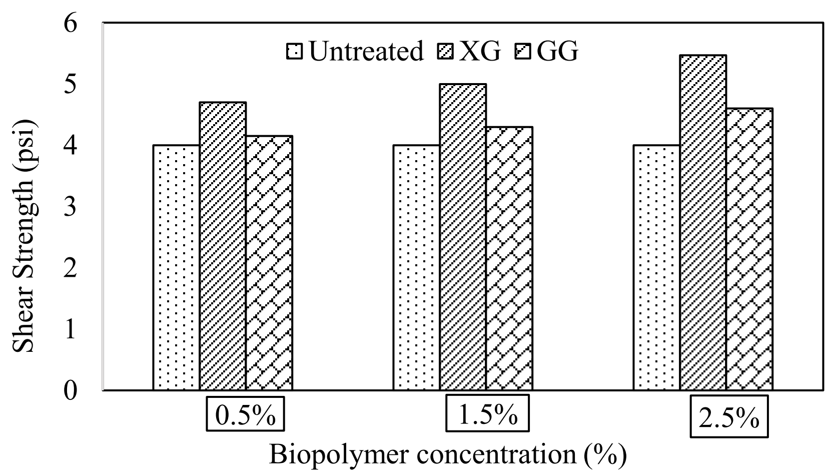


Figure 4.22 Direct shear test results for weathered shales from Verdigre mixed with different concentrations of Xanthan and Gellan (i.e. 0.5%,1.5%, and 2.5%) under no weathering cycles

Figure 4.23 shows that the treated weathered shales from Verdigre exhibit higher shear strength than the untreated ones under 2 weathering cycles. Weathered shale samples treated with higher concentrations of Xanthan and Gellan present higher shear strength. Moreover, the weathered shales mixed with Xanthan show higher shear strength than the weathered shale mixed with Gellan at the same content of the biopolymers.

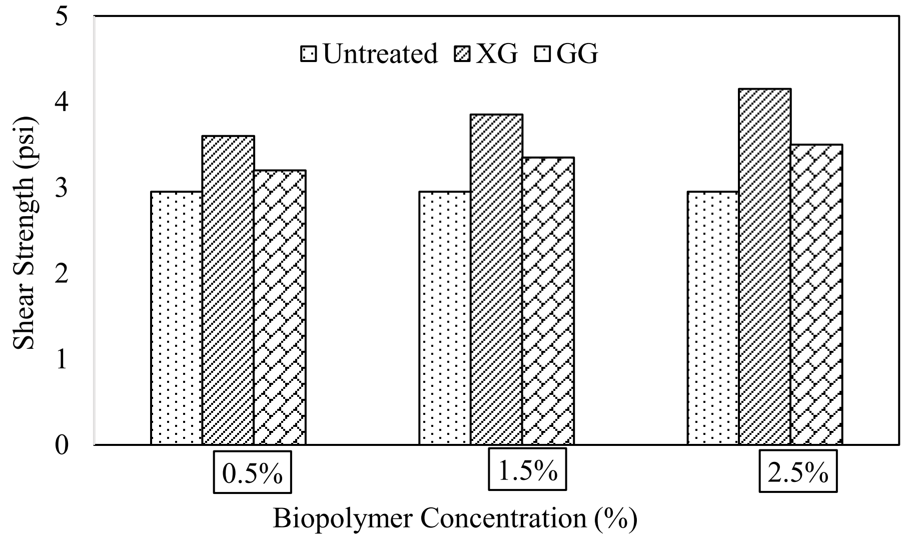


Figure 4.23 Direct shear test results for weathered shales from Verdigre mixed with different concentrations of Xanthan and Gellan (i.e. 0.5%,1.5%, and 2.5%) under 2 W-F-T-D weathering cycles

Figure 4.24 shows the weathered shales mixed with 1.5% and 2.5% of Xanthan have the same shear strength under 4 weathering cycles. Also, the shear strengths of the weathered shales mixed with 1.5% and 2.5% of Gellan are similar. Weathered shales from Verdigre treated with Xanthan show higher shear strength than the weathered shales from Verdigre treated with Gellan at the same content of the biopolymer.

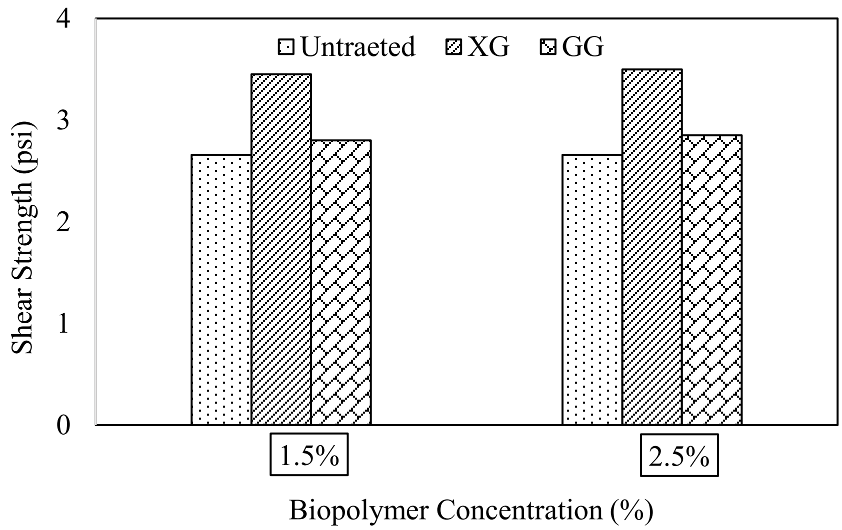


Figure 4.24 Direct shear test results for weathered shales from Verdigre mixed with different concentrations of Xanthan and Gellan (i.e. 1.5% and 2.5%) under 4 W-F-T-D weathering cycles

Figure 4.25 shows the weathered shales from Verdigre treated with Xanthan exhibit higher shear strength than the untreated ones under 8 weathering cycles. Weathered shales samples mixed with 1.5% and 2.5% of Xanthan have the same shear strength. The shear strength of the weathered shales treated with 1.5% and 2.5% of Gellan is similar to the shear strength of the untreated ones.

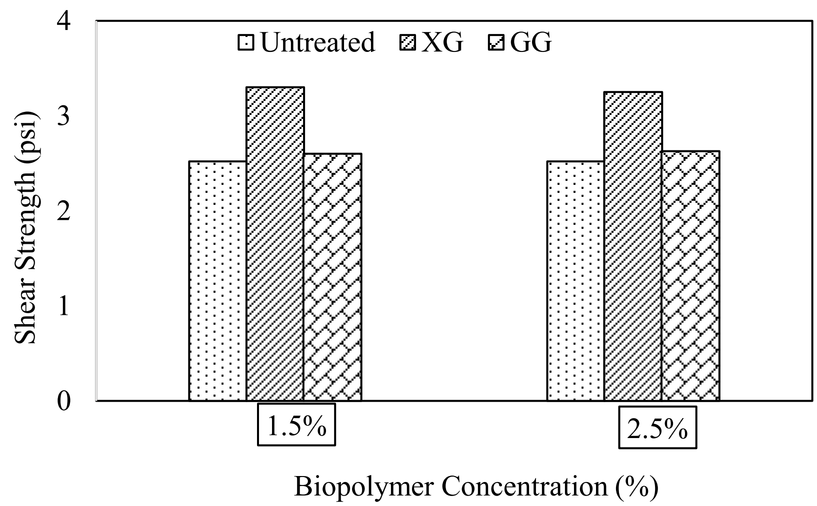


Figure 4.25 Direct shear test results for weathered shales from Verdigre mixed with different concentrations of Xanthan and Gellan (i.e. 1.5% and 2.5%) under 8 W-F-T-D weathering cycles

Table 4.2 shows the results of the direct shear tests conducted on the untreated and treated weathered shales from Verdigre mixed with 0.5%, 1.5%, and 2.5% of Xanthan and Gellan and subjected to different weathering cycles (i.e. 0, 2, 4, 8 cycles).

Table 4.2 Direct shear test results for untreated and treated weathered shales from Verdigre

Bio Polymer Name	Concentration (%)	Weathering cycles	No. of cycles	No. of samples	Shear strength (psi)	Avg. shear strength (psi)	w (%)	G (psi)
NA	-	W-F-T-D	0	1	4.5	4	36.26	36.3
NA	-	W-F-T-D	0	2	3.5			
NA	-	W-F-T-D	2	1	3.1	2.96	36.97	31.58
NA	-	W-F-T-D	2	2	2.82			
NA	-	W-F-T-D	4	1	2.66	2.66	37.13	22.3
NA	-	W-F-T-D	8	1	2.56	2.56	37.34	25
Xanthan	0.5	W-F-T-D	0	1	4.7	4.7	36.84	33.33
Xanthan	0.5	W-F-T-D	2	1	3.08	2.9	37.17	23.41
Xanthan	0.5	W-F-T-D	2	2	2.72			
Xanthan	1.5	W-F-T-D	0	1	5	5	37.28	50
Xanthan	1.5	W-F-T-D	2	1	4.15	3.85	38.66	33.33
Xanthan	1.5	W-F-T-D	2	2	3.55			
Xanthan	1.5	W-F-T-D	4	1	3.18	3.5	38.78	31.5
Xanthan	1.5	W-F-T-D	4	2	3.82			
Xanthan	1.5	W-F-T-D	8	1	2.87	3.25	39.33	25
Xanthan	1.5	W-F-T-D	8	2	3.63			
Xanthan	2.5	W-F-T-D	0	1	5.47	5.47	37.82	35.4
Xanthan	2.5	W-F-T-D	2	1	4.31	4	38.34	34.78
Xanthan	2.5	W-F-T-D	2	2	3.72			
Xanthan	2.5	W-F-T-D	4	1	3.24	3.5	38.77	30.7
Xanthan	2.5	W-F-T-D	4	2	3.76			
Xanthan	2.5	W-F-T-D	8	1	3.25	3.25	39.52	23.07
Gellan	0.5	W-F-T-D	0	1	4.1	4.1	36.38	40
Gellan	0.5	W-F-T-D	2	1	2.79	3.15	37.54	22.22
Gellan	0.5	W-F-T-D	2	2	3.51			
Gellan	1.5	W-F-T-D	0	1	4.3	4.3	36.82	42.1
Gellan	1.5	W-F-T-D	2	1	3.58	3.3	37.79	30.77
Gellan	1.5	W-F-T-D	2	2	3			
Gellan	1.5	W-F-T-D	4	1	3.1	2.85	38.23	21.05
Gellan	1.5	W-F-T-D	4	2	2.6			
Gellan	2.5	W-F-T-D	0	1	4.55	4.55	37.28	33.4
Gellan	2.5	W-F-T-D	2	1	3.7	3.5	38.17	30.7
Gellan	2.5	W-F-T-D	2	2	3.32			
Gellan	2.5	W-F-T-D	4	1	3.1	2.85	38.63	27.3
Gellan	2.5	W-F-T-D	4	2	2.6			
Gellan	2.5	W-F-T-D	8	1	2.63	2.63	39.34	24.37

4.2.7 Further analysis of the effects of biopolymers based on gradation analysis and Atterberg Limits

Atterberg limit tests are conducted to check the particle level adhesive property of biopolymers and soil grains, gradation. Gradation in Figure 4.26 shows that there is no substantial change in gradation curves for biopolymer treated soils and untreated soils, implying that biopolymer bonding may be almost completely broken down during crushing or water bathing period for sieve analysis and hydrometer analysis. Similar test results are obtained for crushed shales.

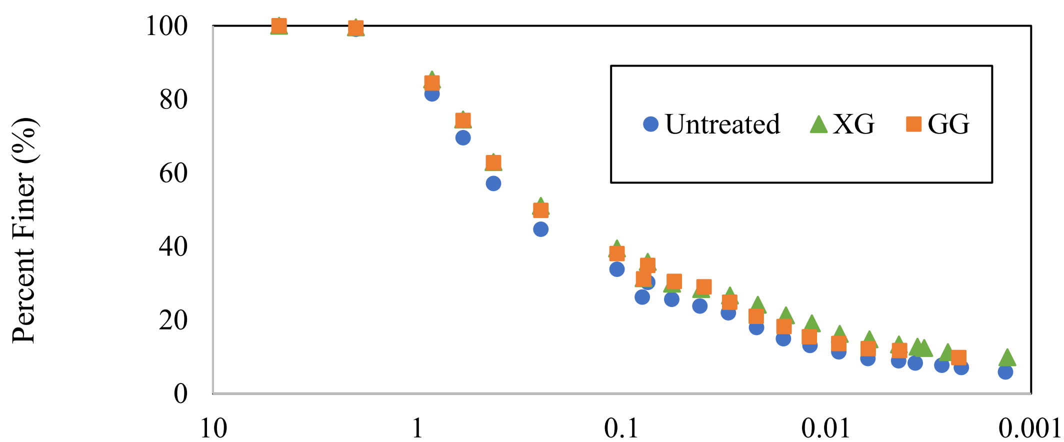


Figure 4.26 Comparison of gradation for glacial tills from Lincoln, Xanthan treated one and Gellan treated one

Contrary to the gradation test results, Atterberg limit test results in Table 2 showed that all three parameters, liquid limit, plastic limit, and plasticity index are substantially increased. The increased numbers in Atterberg limits indicates that the biopolymer treated soils could maintain the same consistency even at much higher moisture content. In another aspect, biopolymerized soils can maintain tighter bonding than untreated soils at the same moisture content, resulting in higher strength supporting the strength test results.

A notable result in Table 4.3 is that the Atterberg limits for 1.5% Gellan content samples showed substantially higher numbers than those for 1.5% Xanthan content samples. These numbers are even higher than those for crushed shales with much higher fine content (≈70%) compared to those for glacial tills (≈26%). Secondary tests for 1.5% Gellan content samples resulted in practically identical results. Recalling that the strength increase for 1.5% Gellan content glacial tills was strangely low in Table 4.3, the behavior of glacial tills with 1.5% Gellan is an outlier with reasons needing further research.

Table 4.3 Atterberg limits of glacial tills and weathered shales

Mixture		LL (%)	PL (%)	PI (%)
Glacial tills from Lincoln	Untreated	44.7	22.82	21.88
	1.5% Xanthan	65.89	31.2	34.69
	1.5% Gellan	93.84	44.16	49.68
Verdigre weathered shales	Untreated	52.8	28.6	24.2
	1.5% Xanthan	87.93	36.21	51.72
	1.5% Gellan	84.27	37.25	47.02

Combining Figure 4.26 and Table 4.3, it is said that a small amount of biopolymer mixed in soils will greatly enhance the consistency of soils and increase the shear strength. At the same time, the bonds between soil grains and biopolymer are not irreversible bonds but reversible ones. Supplying enough water may wash out biopolymers. The latter result is a desirable characteristic because that means the biopolymers can improve the soil strength when they stay in the pore space and interact with pore water, but they can be removed by water-flushing nullifying hydrophilic potential when needed.

Chapter 5

Performance Evaluation of Field Applied Xanthan

5.1 Site – general

The field-testing site is located on Nebraska Highway 84, about 1.6 miles from Verdigre, NE as shown in Figure 5.1. The initial slope is a 3:1 (H:V) compacted fill slope with geogrid placed in-between the compacted layers. This site used to show the slow downward movement of the slope, and NDOT decided to remove and replace the materials from the slope.

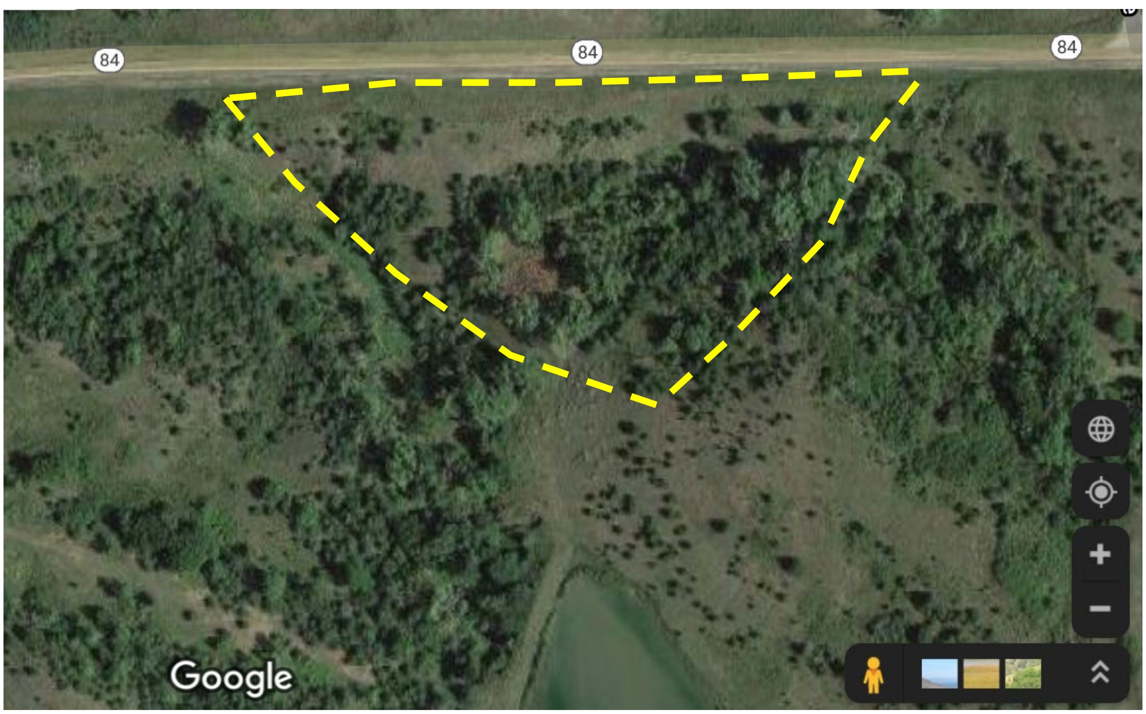


Figure 5.1 Aerial view of the field-testing site (Note that the cracks are not seen due to vegetation.)

The scene of the slope with failed materials removed, and prepared to apply compacted geogrid reinforced soil, is as shown in Figure 5.2.

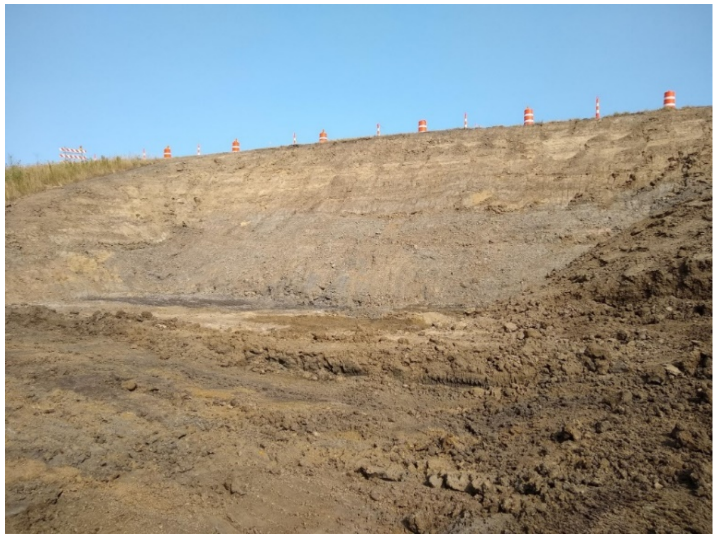


Figure 5.2 View of the slope with loose materials removed (Note: The total height is about 30 ft.)

In the design stage of the new slope, the geogrid layers are included. Besides, the Biopolymer (Xanthan) was designed to be applied to a small section of the new slope as shown in Figures 5.3 and 5.4.

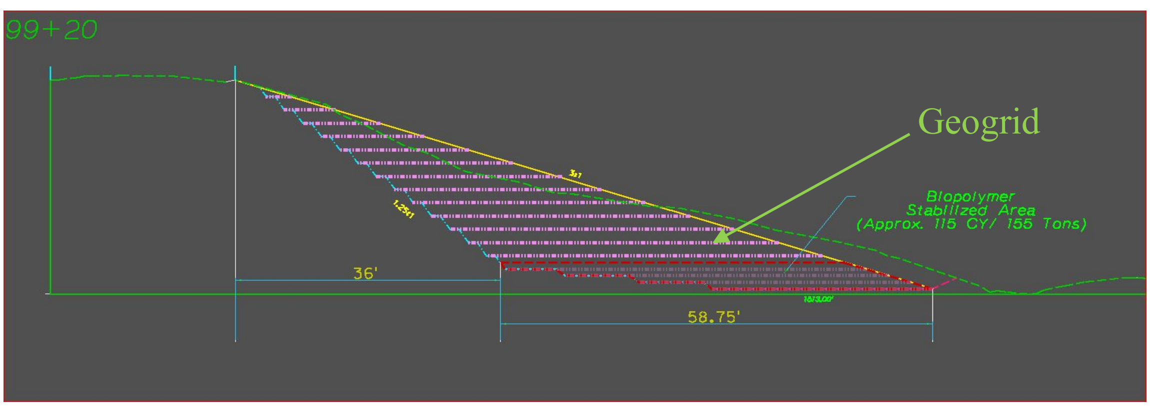


Figure 5.3 Cross-section of the new slope and location of Biopolymer(Xanthan) applied area

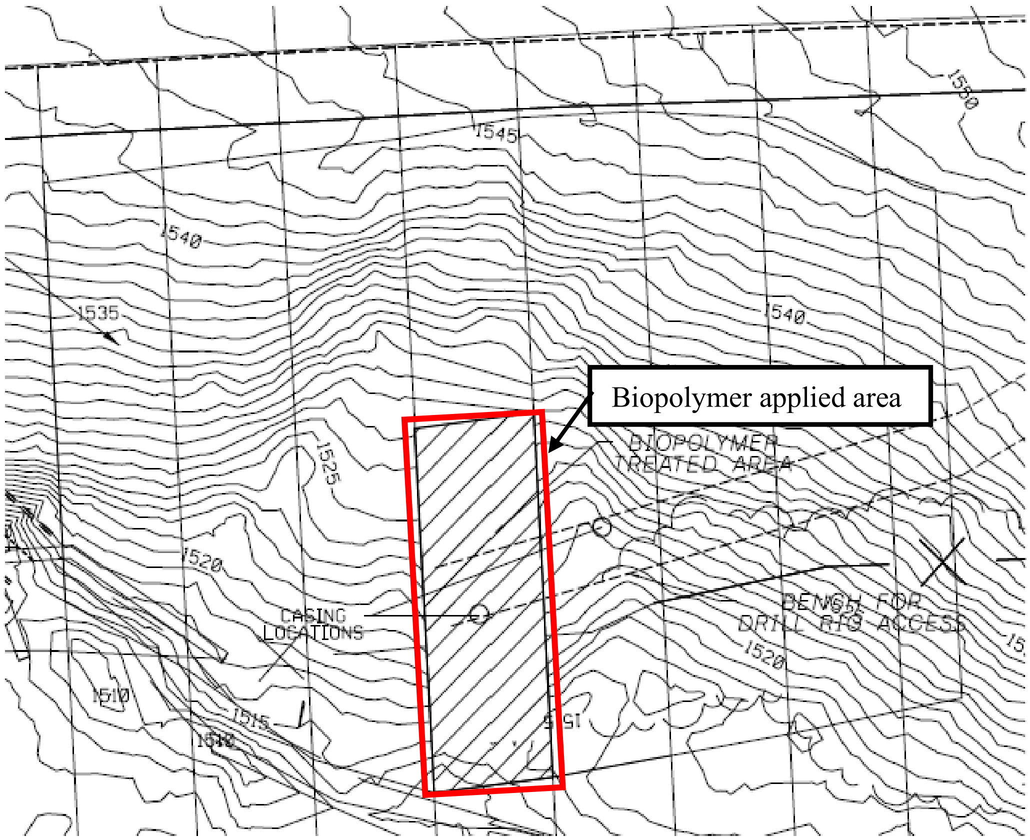


Figure 5.4 Plan view of Biopolymer applied area

5.2 Field specification for biopolymer application

Xanthan content 1.5% was recommended based on the laboratory test results. Field specification for biopolymer application was recommended as follows. The device used in the field (BOMAG) and scene of Xanthan spreading are shown in Figure 5.5.

% finer = 39%, LL = 51%, PI = 30%
Highly Compressible Clay (USCS).
OMC=20.1%, Max. Dry Density = 103.9 pcf

Figure 5.5 Scene of field mixing (White powder is Xanthan)

5.2.1 Construction specification for biopolymerized soil

a. Description

The work of constructing the biopolymer-stabilized soil shall consist of spreading and mixing of the Xanthan by thorough disking and blading of the 8-inch layers of soil as shown in the plans. The percentage of Xanthan used for each 8-inch layer shall be determined in the field. After thoroughly mixing the 8-inch layer of soil and Xanthan, it shall be compacted to the widths shown in the plans, to a maximum Deflection Target Value determined by a rolling pattern.

Material Requirements

b. Materials Characteristics

b.1. Xanthan shall have a minimum purity of 90%. If the Xanthan purity is less than 90%, the Contractor shall obtain approval of the product prior to use.

c. Equipment

c.1. A material spreader capable of spreading the Xanthan a uniform thickness across the surface of soil.

c.2. A disk capable of pulverizing and mixing, to a homogeneous material, the soil with Xanthan and water (if required).

c.3. Distributors used for applying water shall conform to the requirements of Subsection 301.02 in the main specification.

c.4. A minimum of one self-propelled pad foot compactor.

The pad foot compactor shall be vibratory and shall consist of one or more drums with pads or feet projecting no less than 6.5 in. The static load on the individual pads shall be no less than 200 psi exerted on a single row of pads or feet parallel to the axle of the drum.

Example: pad area = 4"x6" =24 in^2, 3 pads in a row make contact at one time, static load on drum is 16000 lbs., 16000 lbs. ÷ (24 in^2x3) = 222 psi.

d. Construction Methods

d.1. The Contractor shall provide adequate protection for the Xanthan against moisture. Xanthan shall be hauled or stored in suitable moisture proof dry bulk trailers or containers. The use of tarpaulins for the protection of the fly ash will not be allowed. Xanthan that has become caked or lumpy shall not be used.

d.2. The work of constructing the stabilized soil shall be accordance to Class III embankments in Section 205 of the NDOT Standard Specifications for Highway Construction.

d.3. The actual project mix design has been pre-determined from previous sampling at the project site. The quantity of Xanthan to be applied shall be approximately 1.3% to 1.5% by dry weight. The Xanthan shall be placed on the surface of the soil and distributed in a layer of uniform thickness over the entire width of the area being treated. A spreading device for distribution of the Xanthan shall be required. The spreading device shall be capable of spreading the additive both laterally and longitudinally in an even and accurate manner. The Xanthan shall not be placed on the soil when the wind is blowing so that the loss of Xanthan cannot be satisfactorily controlled.

d.4. Mixing operations shall begin within 30 minutes after distribution of the Xanthan. Mixing of Xanthan shall be accomplished throughout the scarified material with a machine capable of pulverizing the soil to a minimum depth of 8 inches. The disk shall be capable of blending and mixing, to a homogeneous material, the pulverized soil with the Xanthan and water (if required). Care shall also be taken to avoid mixing the Xanthan with a greater quantity of the soil than is required to build the compacted thickness specified. During the mixing, water shall be added to provide a moisture content in a range from minus 2 to plus 2 percentage points above optimum moisture. The optimum moisture content shall be determined by AASHTO T 99. The optimum moisture shall be determined by Materials and Research Central Lab. Mixing shall be continued until all chunks of soil have been reduced to a maximum of 0.5-inches in size.

d.5. After mixing, the material shall be shaped to the proper cross section and compacted with padfoot rollers. Compaction shall begin immediately after mixing and all shaping and rolling shall be completed within 1.25 hours following the incorporation of Xanthan. Water may be added during the compaction and finishing operations to compensate for evaporation loss.

e. Sampling and Testing

Sampling and testing shall be completed according to Section 10 of the Materials and Research Division Material Sampling Guide.

f. Compaction and Soil Stiffness Requirements

The soil stiffness is an in-place measurement of the deflection of the Stabilized Soil measured by NDOT personnel performing Light Weight Deflectometer measurements on the processed material for acceptance. Refer to NDOT Test Method T 2835 for the proper operation of the Light Weight Deflectometer (LWD). The procedure for conducting Lightweight Deflectometer testing is as follows:

① The Deflection test is defined as the average of the fourth, fifth, and sixth drops of the deflectometer at one location. The first 3 drops are to be used to seat the LWD.

② The deflection value is defined as the average of 3 test locations.

③ The Deflection Target Value (DTV) is the lowest deflection value determined by using a control strip. A single coverage is defined as the compacting of unbound material over a given point a single time.

④ A new control strip shall be constructed when there is an observed change in material or as determined by the Engineer.

A Control Strip shall be constructed for the purpose of determining the Deflection Target Value.

⑤ The control strip dimensions have a minimum length of 200 feet.

⑥ The control strip construction shall be incidental to the pay item Stabilized Soil.

⑦ The optimum moisture content shall be in an acceptable range of optimum moisture to plus 2%. The moisture content shall be determined by AASHTO T99 at the NDOT M&R Central Lab.

⑧ During construction of the control strips, the Contractor shall make repeated compaction coverages. When the material is visibly densified, the engineer will take deflection tests at 3 locations to get an average deflection value. Following each test, additional coverages shall be conducted and deflection tests taken until a Deflection Target Value is established.

⑨ The Deflection Target Value of the control strip shall be determined by compacting the processed material to a point that three consecutive coverages do not change the deflection by more than 1 mm. The DTV shall be based on the lowest average deflection test. The padfoot roller procedure shall have a minimum of 6 consecutive coverages unless an alternate rolling pattern is approved by the Engineer.

⑩ The Deflection Target Value shall be re-evaluated when:

i. Deflection test measurements are consistently less than the DTV. (3 out of 5 consecutive deflection tests are less than 0.8 of the DTV).

ii. Failing test results are consistently occurring and adequate compaction is observed.

Acceptance Testing

⑪ A passing deflection test is defined as a deflection value that is less than 1.10 x DTV.

⑫ The moisture content of soil shall be performed using NDOT's approved equipment and methods. Approved equipment includes: 1) hot plates, stove, or microwave, 2) Speedy Moisture Method, or 3) Laboratory oven method. Moisture content results shall be reported to the nearest tenth of a percent.

⑬ The frequency of testing deflection and moisture content is 1 test at one location for every 1500 cubic yards or less. It should be noted that more tests may be taken for research purpose.

Method of Measurement

① Xanthan shall be measured by the Ton of acceptable material used in the work.

② Water applied, as directed by the Engineer will be measured as provided in paragraph 5. of Subsection 205.04.

Basis of Payment

① Xanthan that is used in the work, measured as provided herein, shall be paid for at the contract unit price per Ton for the item, "Xanthan". This price shall be full compensation for furnishing, delivering, and distributing the Xanthan, and for all equipment, labor, tools, and incidentals necessary to complete the work.

② Water measured as provided herein, shall be paid for at contract unit price per Mgal for the item "Water".

③ Stabilized soil measured as provided herein, shall be paid for at the contract unit price per Cubic Yard for the item, "Stabilized Soil". This price shall be full compensation for shaping and trimming the soil, scarifying and pulverizing the soil, drying, mixing, shaping, and compacting the Xanthan treated soil, and for all equipment, labor, tools, and incidentals necessary to complete the work.

5.3 Testing and field Instrumentation to monitor degradation of soil strength and deformation of the slope

5.3.1 Testing techniques

CPT (PCPT), field vane shear tests and TEXAM pressuremeter tests were adopted both in the biopolymer treated zone and untreated zone to monitor the degradation of strength in two zones. Laboratory techniques were used only to check the gradation. Field test locations of testing are shown as green dots in Figure 5.6.

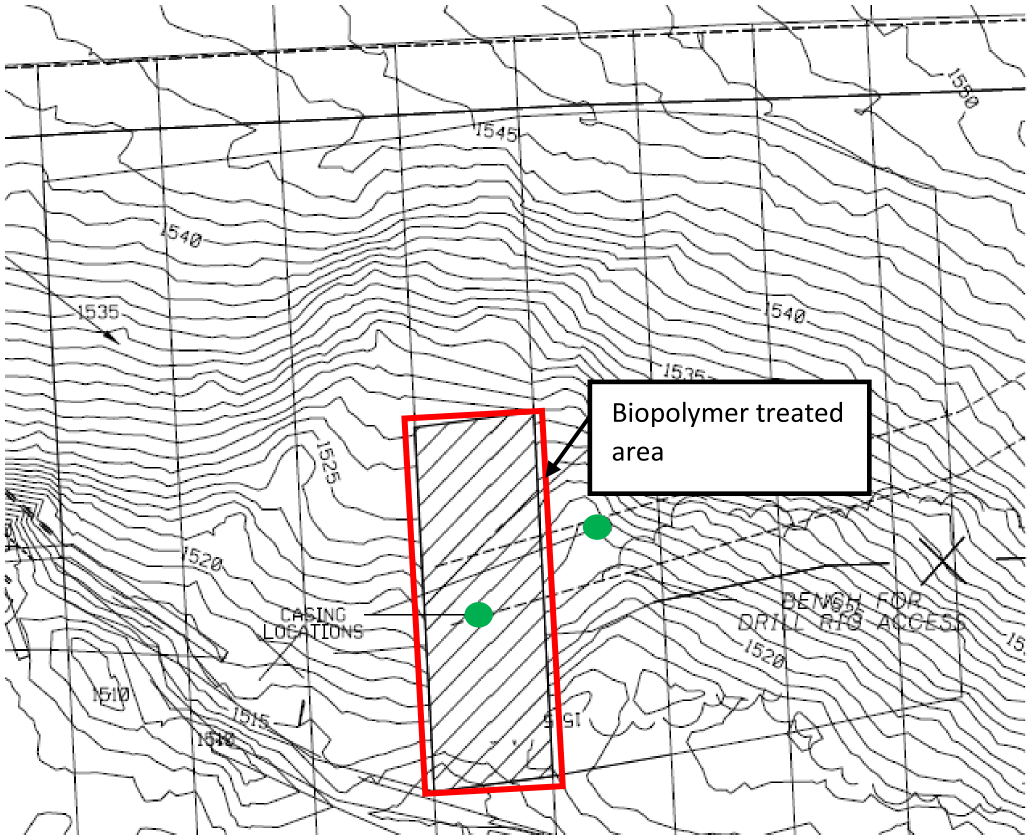


Figure 5.6 Location of field tests

i) CPT (PCPT)

Nova CPT system mounted on Geoprobe 7822DT was used to measure the tip resistance, friction resistance, and pore pressure of soils at every 0.8 in. (2 cm) depth increment during penetration (Figure 5.7). From these three measurements, intact strength, disturbed strength, and modulus of field soils were computed, again at every 0.8 in. depth increment.

Figure 5.7 Scene of CPT(PCPT) testing

ii) Pressuremeter

Pressuremeter is a modern device that can directly obtain the deformation-displacement relationship of soils. The research team utilized TEXAM pressuremeter system as shown in Figure 5.8 and obtained the modulus and yield stress of field soils.

Figure 5.8 Scene of TEXAM pressuremeter deployed to the field

iii) Field Vane Shear Test

A handheld field vane shear testing device (Humboldt) was utilized to double-check the strength of soils in the Xanthan treated zone and untreated zone.

5.3.2 Field Instrumentation System

Field instrumentation system was designed and installed as follows to monitor the overall behavior of the slope.

i) Inclinometer casings

GEOKON 6400 glue-snap ABS inclinometer casings were installed as shown in Figure 5.9, also represented as green dots, one in the biopolymer treated area and another one in the untreated area. A GEOKON GK-604D readout unit with model 6100D digital inclinometer probe and FPC-2 Bluetooth wireless system was used to measure the slope movement.

Figure 5.9 Inclinometer casing

ii) Fiber optic distributed strain sensing system

A series of fiber optic cable was installed at the surface of the slope to monitor the overall deformation of the slope. To measure the localized deformation, anchor poles were used as shown in Figure 5.10. Essentially the tension or compression in fiber optic cable was converted to the strain of fiber optic wires in between while anchors in Figure 5.8. LIOS Pre-vent system was used to take the readings and compute strains between anchors. Deformation was computed by average strain in one segment multiplied by the length of the segment.

Figure 5.10 Anchors for DSS and UAS measuring system

iii) UAS (Unmanned Aerial System) based surface deformation system

Identification of overall deformation of the slope is critically important, therefore UAS was employed as another system to monitor the deformation of the slope. To enhance the accuracy of the UAS surveying results, anchors for DSS system were also used as reference points as shown in Figure 5.10. UAS system essentially takes the 3-D coordinate of point clouds. An example picture of UAS based point clouds is shown in Figure 5.11. Points in this grainy picture contain 3-D coordinates. The difference between the initial point clouds and current point clouds is the movement of the points.

Figure 5.11 A picture of 3-D point clouds

iv) TDR based moisture/temperature measurement system

Temperature variation and moisture variation turned out to be critical factors that govern the shear strength reduction of soils in previous laboratory tests. Therefore, TDR based moisture/temperature sensors (Teros 12, Meter GroupInc.) with solar cell powered data acquisition system (ZL6) shown in

Figure 5.12 were installed to collect data from six different locations at 1 ft depth.

Figure 5.12 Picture of TDR moisture/temperature measurement system

5.4 Results of field Testing and Measurement

5.4.1 CPT based strength of field soils

Figure 5.13 shows the tip resistance (q_c) of soils on the slope. The tip resistance is typically related to the intact strength of soils. It shows the high-frequency fluctuation of the tip resistance. It is, however, noted that this much inhomogeneity of the soils is not an indicator of the workmanship of the compaction. It is believed that this is rather due to a typical variation of soil strength. The predicted OCR at the shallow depth was even higher than 1 million, indicating the soil is heavily compacted.

General analyses of the results can be summarized as follows.

. Depth zero to 4 ft: q_c is increased linearly with depth. This is expected behavior because of the lack of confinement at the shallow depth.

. Depth 4 ft to 9 ft: q_c is nearly constant. This behavior indicates a consistent compaction effect. The undisturbed shear strength of these soils turned out to be about 6 to 15 psi based on Robertson's (2012) correlation

. Depth 9 ft to 22 ft: q_c is nearly constant. Again, the trend indicates a consistent compaction effect. However, the reason why this depth range shows lower strength than the upper layer is not known.

. Depth 22 ft to deeper depth: It seems like the CPT tip hit the bedrock.

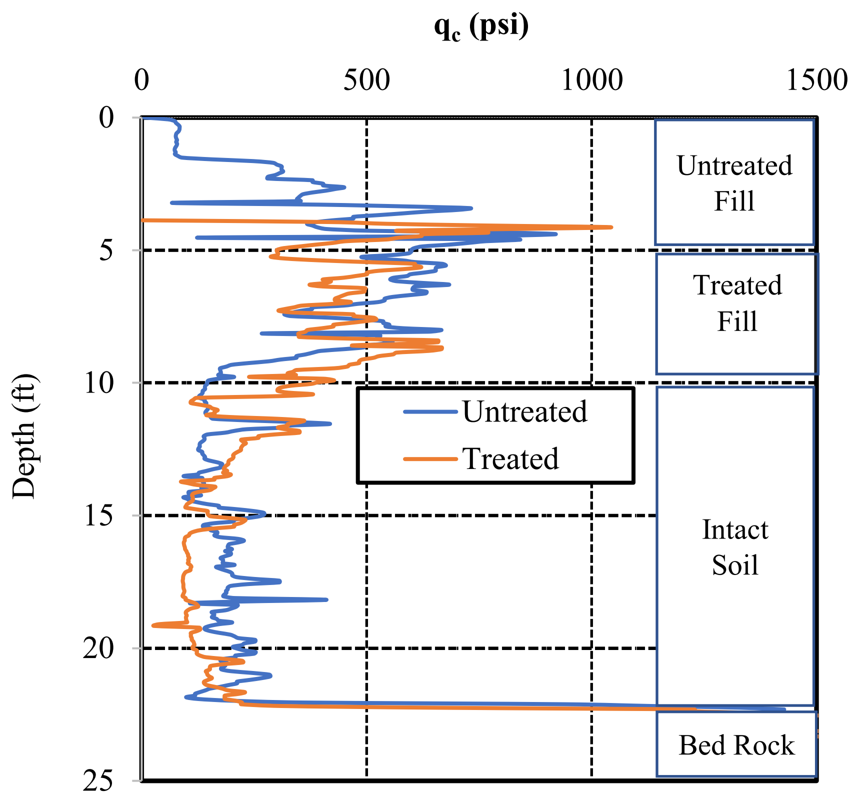


Figure 5.13 Tip resistance at initial condition (Measurement Date: Dec. 01, 2020)

Figure 5.14 shows the friction resistance (f_s) of soils, and that is related to the disturbed shear strength of soils. The overall trend is similar to the tip resistance but the magnitude is lower which is a typical behavior. The computed disturbed shear strength of soil at 4 ft to 9 ft depth is approximately 6 psi with sensitivity 1 to 2.5, which is reasonable as well.

However, the variation of the CPT based parameters with time is not obtained as of Feb. 28th, 2021.

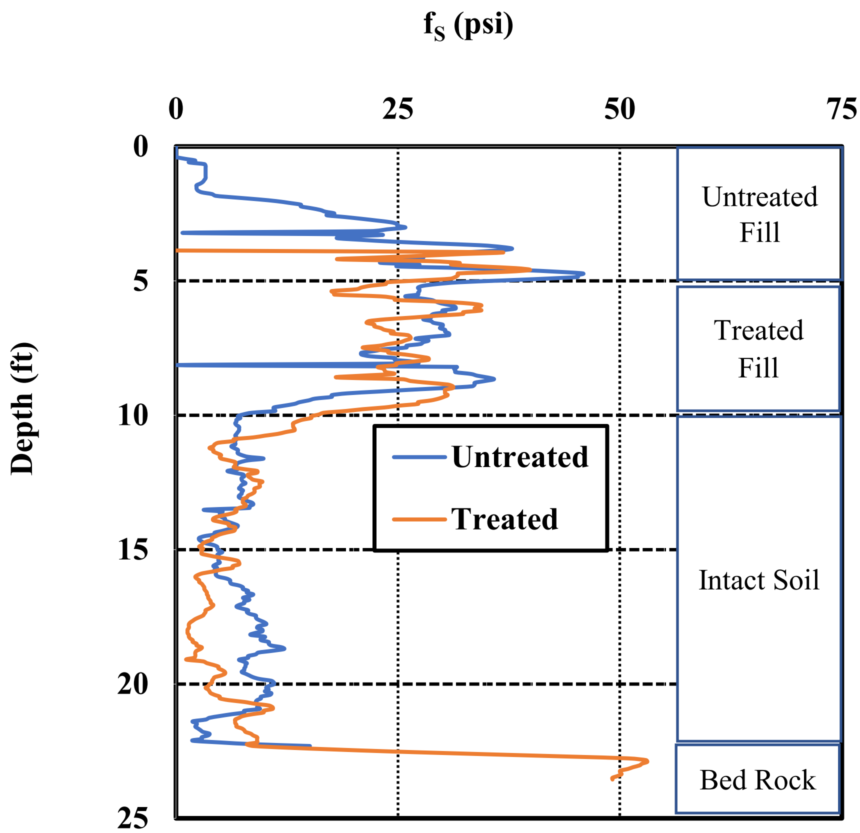


Figure 5.14 Friction resistance at the initial condition (Measurement Date: Dec. 01, 2020)

5.4.2 Pressuremeter based strength and modulus of field soils

Figure 5.15 shows the pressure vs. relative deformation relationship from the pressuremeter test. The analysis of this data showed that the modulus of soils at 4 ft depth is 700 to 980 psi indicating that the soil is medium stiff silty clay based on Briaud (1992). The shear strength is in the range of 7 psi (untreated soils) to 14 psi (treated soils) showing good agreement with CPT(PCPT) results. However, it showed higher shear strength for treated soils. It also indicated that the Ko (in situ earth pressure coefficient) is about 1.7 indicating the highly overconsolidated condition (or highly compacted condition). The variation of the pressuremeter based parameters with time is not obtained as of Feb. 28th, 2021.

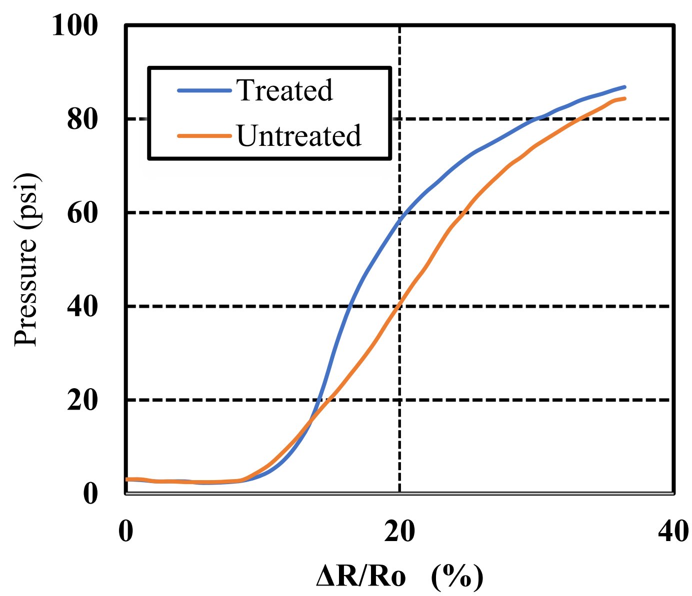


Figure 5.15 Pressuremeter test result (Measurement Date: Nov. 20, 2020)

5.4.3 Vane shear strength of field soils

Figure 5.16 shows the vane shear strength of soils measured after two weeks of snow coverage. Low strength at the surface should be attributed to the wetting effect of melted snow. Only the strength at a deeper depth may represent the field shear strength of soils. The treated area showed about 15 psi and the untreated area showed about 11 psi shear strength, which agrees fairly with pressuremeter data.

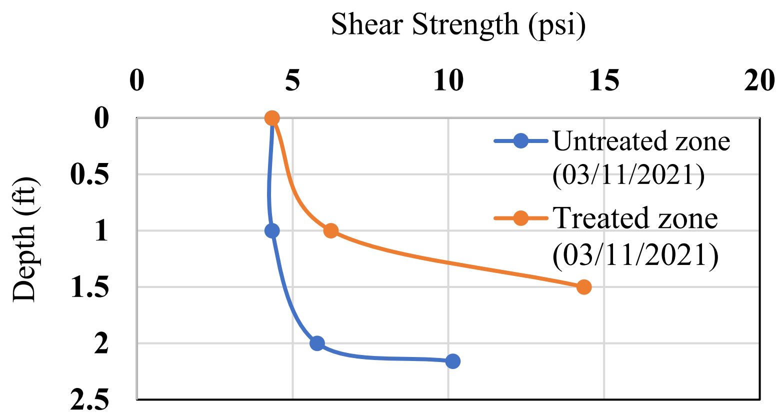


Figure 5.16 Vane shear test result
(Measurement Date: Mar. 11, 2021)

5.4.4 Comparison of CPT(PCPT), pressuremeter, vane shear, and laboratory test results.

Laboratory direct shear tests by Layal (2020) show that the initial shear strength of field soils will be in the range of 4 to 5.5 psi as shown in Figure 5.17. This range of shear strength lower than the initial measurement by CPT(PCPT) and pressuremeter and vane shear test results. It is expected that the higher strength of field soils could be due to the higher compaction by heavier field compaction equipment.

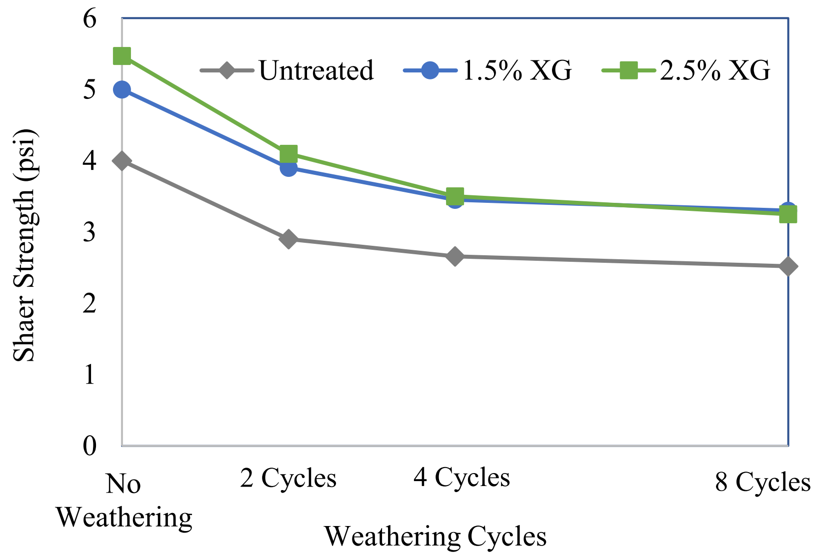


Figure 5.17 Laboratory direct shear test by Layal (2020)

5.4.5 Inclinometer based deformation data

Figure 5.18 shows that the inclinometer based horizontal deformation to upstream-downstream deformation. The peak deformation is at the surface, and it is 0.6 in. and 1.2 in. for the untreated area and the treated area, respectively. This much measurement result does not necessarily indicate the instability of the slope. Further measurement with an extended period of time is required.

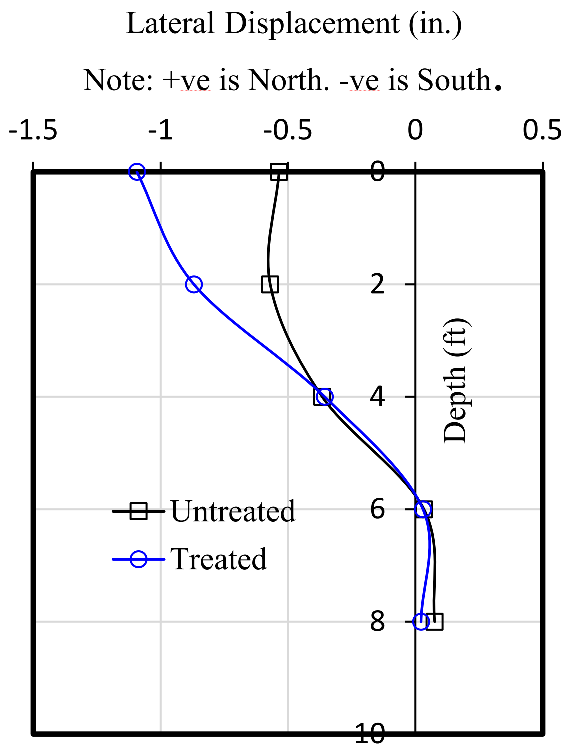
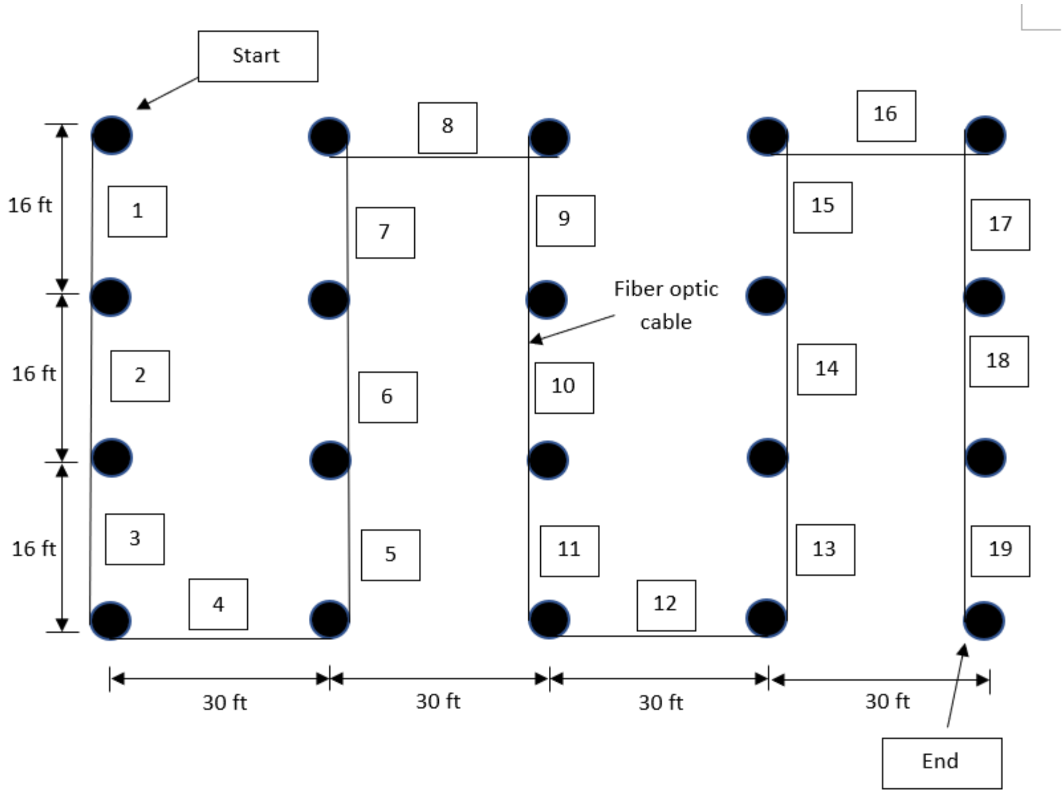


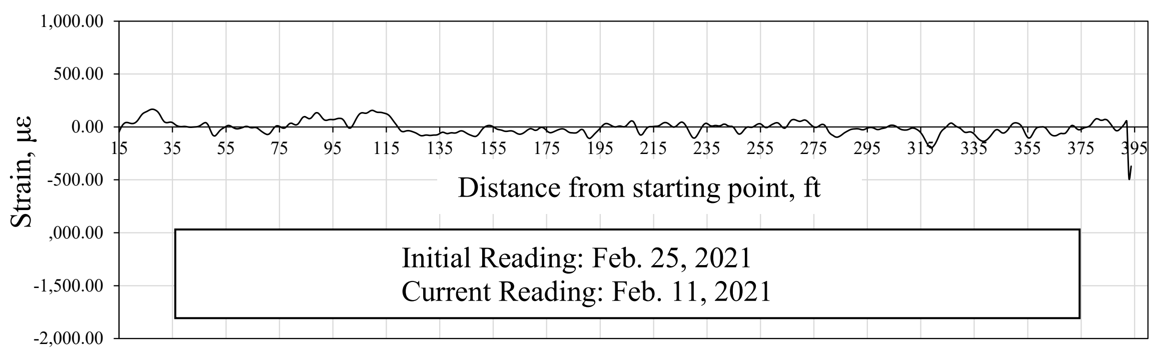
Figure 5.18 Upstream – Downstream deformation from Inclinometer (Initial Reading: Feb. 25, 2021, Second Reading: Mar. 11, 2021)

5.4.6 Fiber optic DSS (Distributed Strain Sensing) based deformation data

Figure 5.19 shows the overall strain profile of the slope based on fiber optic cable based DSS system is quite low (less than 100 μ strain) across the whole slope. It did not indicate a specifically high strain zone that may be a precursor of the localized shear zone.



(a) Arrangement of measuring section (Top Left: Upstream and Westward)



(b) Strain profile from the top left to lower right.

Figure 5.19 Overall deformation profile of the slope based on fiber optic DSS (Discrete Strain Sensing) technique

5.4.7 UAS (Unmanned Aerial System) based surface deformation data

UAS (Unmanned Aerial System) based surface deformation system Identification of overall deformation of the slope is critically important; therefore, a UAS was employed as another system to monitor the deformation of the slope. This provides monitoring of deformation throughout the entire slope and not just at discrete locations. To enhance the accuracy of the UAS surveying results, anchors for the DSS system were also used as reference points, as shown in Fig. 5.10. The UAS system collects a sequence of photos that can be used for the 3-D reconstruction of the slope geometry, using Pix4DMapper. This was accomplished through the use of a dedicated surveying drone, a WingtraOne fixed-wing UAS platform with an onboard Sony 42 MP camera, and a post-processing kinematic (PPK) module for sub-centimeter local accuracy. A temporary static global navigation satellite system base station collected continuous observations during the UAS flights for the PPK processing, where the base station location was determined using the Online Position User Service (OPUS). An example picture of a UAS based point cloud for the slope is shown in Fig. 5.11. Points in this grainy picture contain 3-D coordinates, as this is not a 2-D image. Datasets were collected on two separate days (Nov. 2020 and Feb. 2021) to determine if there are any areas of deformation/slope movement.

UAS data collected was obtained on November 20, 2020, and February 25, 2021. These two data sets allow for a detailed comparison of the full-field displacement of the entire slope area (with and without biopolymer treatment). This type of temporal comparison between the two datasets is known as change detection and was performed using a cloud-to-cloud distance workflow within CloudCompare software platform. Based on these measurements, the vertical changes in the dataset range between 0 and 3 cm. In Fig. 5.20, this is color-coded by the heat map (where the units are in meters). On the left side of the repaired slope, some deformation in excess of 2 cm is observed, but this is primarily due to surface disruption associated with the drill rig. However just above this area, some deformations 1-2 centimeter were observed, indicating some small deformation in this area. In comparison, the untreated soil in the middle of the repaired area experienced much more deformation in the range of 1 to 3 centimeters. This highlights the improved soil response with the biopolymer treatment.

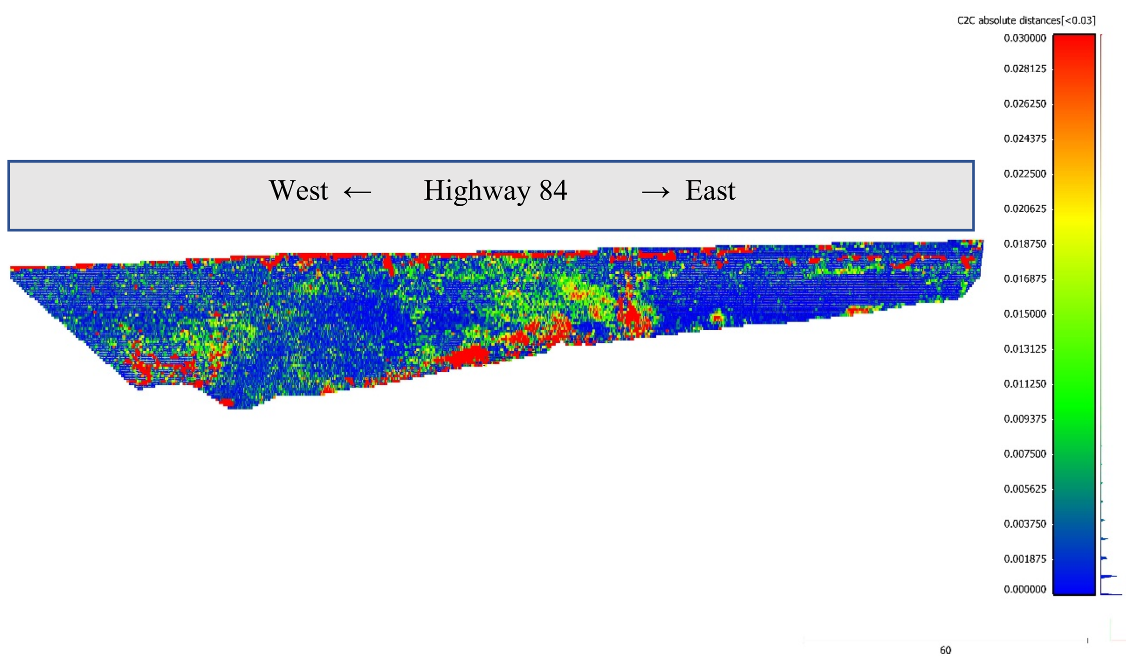


Figure 5.20 UAS – Point Clouds based deformation profile (Note: The unit of color scale is in cm. 1 cm = 0.8 in.) (Measurement Date: Nov. 20, 2020; Feb. 25, 2021)

5.4.8 TDR based temperature and moisture data

The soil moisture probes recorded temperature and volumetric moisture contents at 1 ft depth every 6 hours. Figure 21 shows the location of moisture and temperature probes. Besides, the precipitation data for Knox County was obtained through Nebraska Rainfall Assessment and Information Network website (https://nednr.nebraska.gov/ NeRain/report/Index).

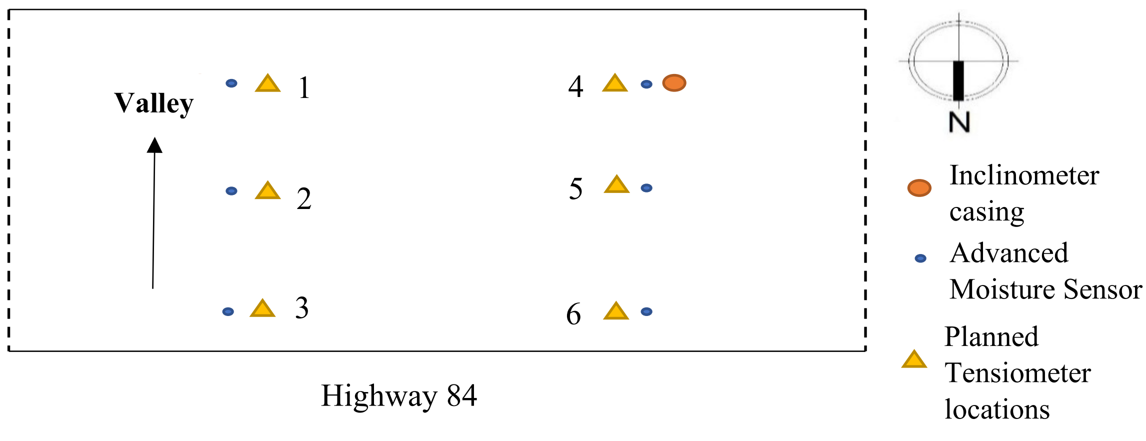
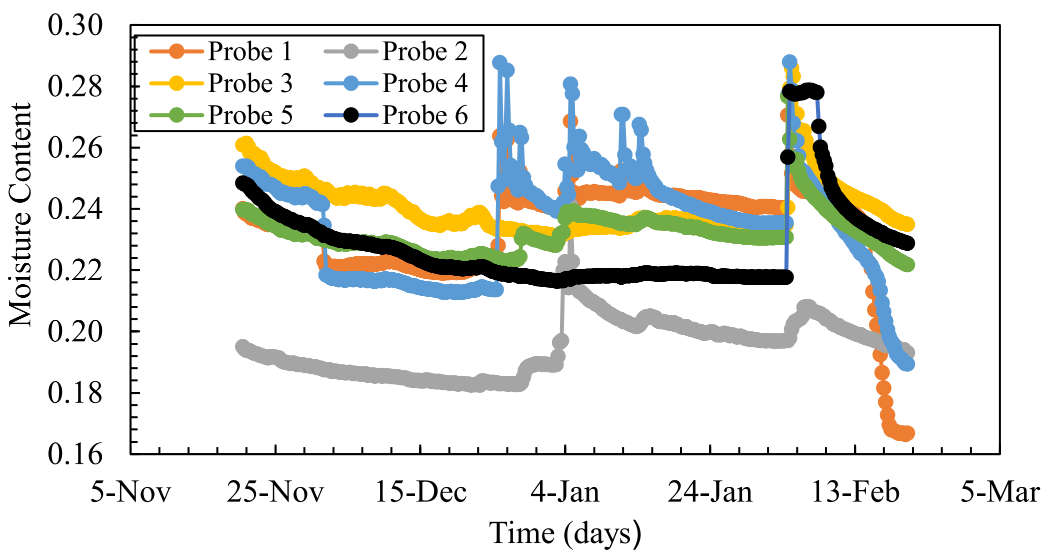


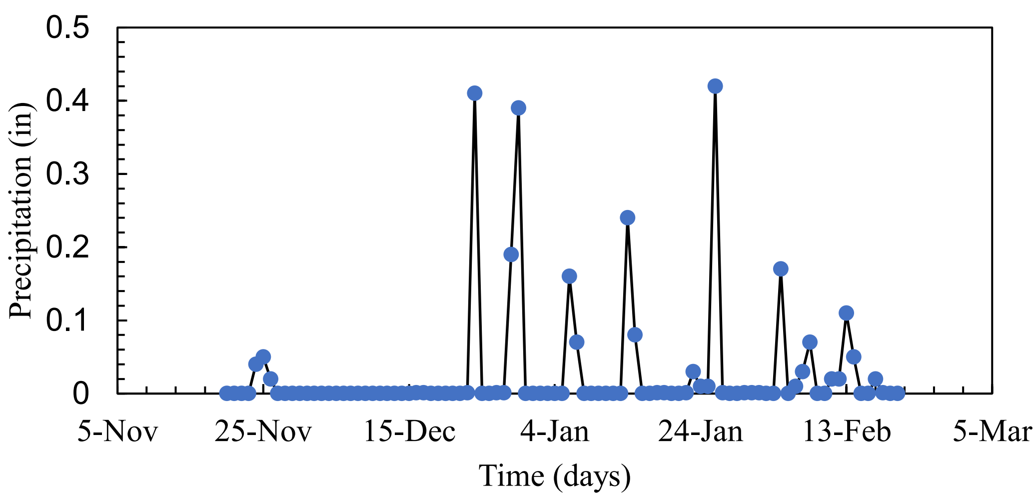
Figure 5.21 Location of moisture and temperature measurement points

Moisture fluctuation at 1 ft depth for six different locations in Fig. 5.22 (a) shows that the moisture content was mostly 24% to 26% range (except Probe 2), and trend lines showed about the same decreasing trend across the measured results. Considering that the moisture content immediately after the construction was 30% to 34% range, and about two weeks of dry days were maintained in the field, the trend appears reasonable. Then the trend lines showed spikes to high water content (as high as 28%) a couple of days after the precipitation as appeared in Fig. 5.22 (b).

Another notable trend is the rapid decrease in moisture during February 2021. During this time, the slope was covered by heavy snow. Temperature plotting in Fig. 5.23 showed that the ambient temperature on the site was extremely cold (as low as -30˚C) and the soil temperature was 0 to -2 ˚C as shown in Fig. 5.24 It is believed that the freezing ground could convert moisture into ice and reduced the moisture. Additional strength measured by CPT(PCPT), pressuremeter, and vane shear equipment may provide the magnitude of strength reduction in these soils.



(a)



(b)

Figure 5.22 (a) Volumetric moisture content of 6 probes; and (b) Precipitation data of Knox county

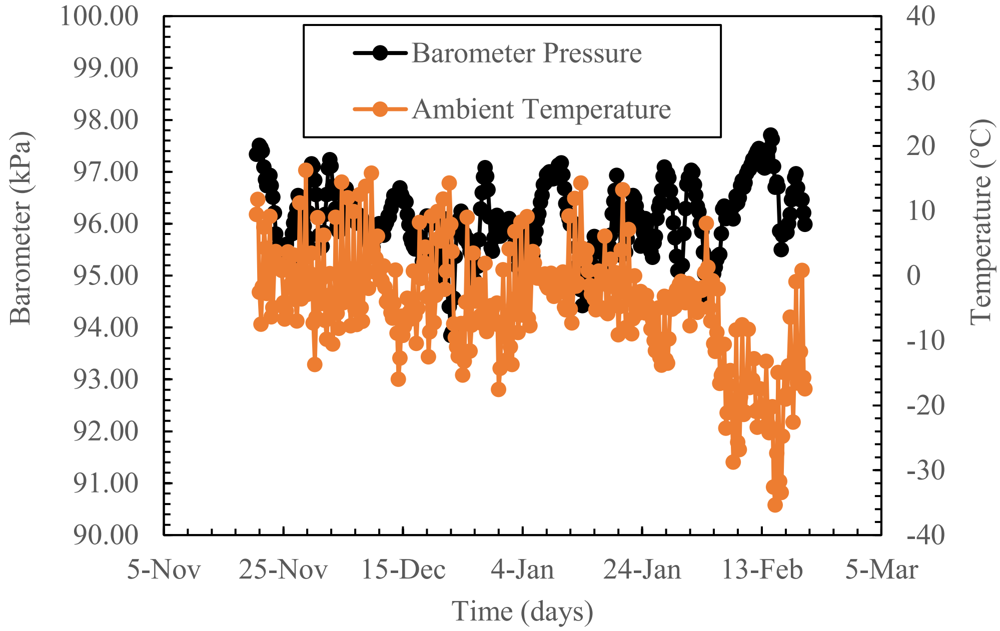


Figure 5.23 Barometric pressure and temperature fluctuation data (1 kPa = 0.145 psi)

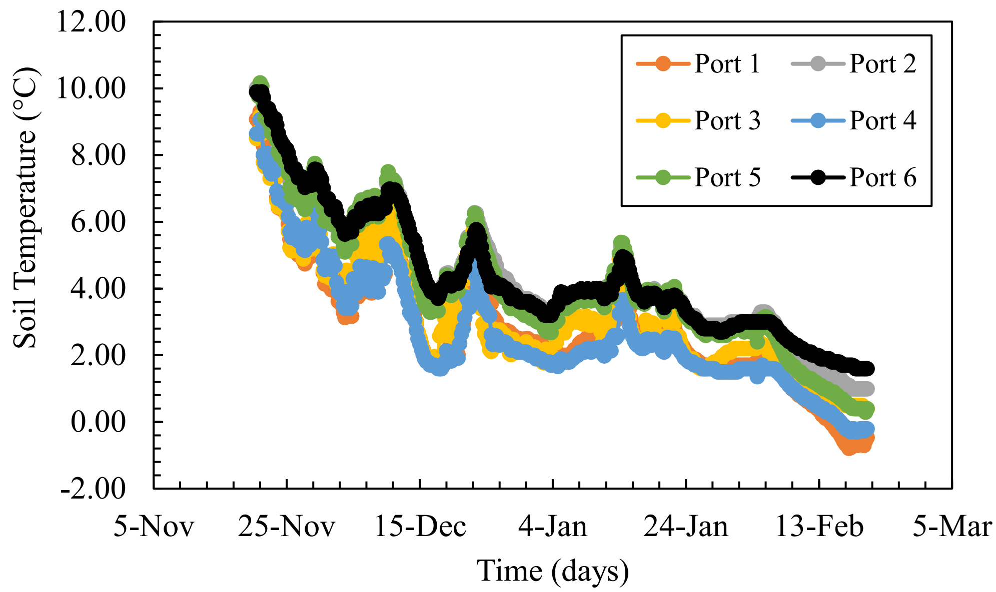


Figure 5.24 Soil temperature profile

Chapter 6

Conclusion and Recommendations for Future Research

6.1 Conclusion from laboratory tests

Xanthan treated glacial tills (Lincoln)

- Increasing Xanthan concentrations increased the shear strength of the glacial tills. There were 31%, 80%, and 108% shear strength increase by adding 0.5%, 1.5%, and 2.5% of Xanthan, respectively. Higher Xanthan is believed to increase the chemical interaction between the biopolymers and the surface of the fine soils. Xanthan-fines matrices worked as a cementation agent in the voids between the granular particles in the glacial tills.
- The shear strength of the treated glacial tills mixed with 1.5% and 2.5% of Xanthan at 8 weathering cycles was 88% and 94% of the untreated unweathered ones (4.65 psi), respectively. That might indicate the sustained long-term stability achieved by stabilizing the soils using Xanthan.

Xanthan Treated Weathered Shales (Verdigre)

- The shear strength of the weathered shales from Verdigre was improved by 20%, 30%, and 40% by adding 0.5%, 1.5%, and 2.5% of Xanthan, respectively.
- The shear strength of the weathered shales from Verdigre treated with 1.5% of Xanthan at 8 wet-freeze-thaw-dry cycles was 83% of that for the untreated and unweathered ones.
- Xanthan was more effective in improving the shear strength of glacial tills from Lincoln and weathered shales from Verdigre compared to Gellan. This behavior

might be because of the type of bonding forces existing at the interface between the soil particles and the biopolymer.

- The effect of using a biopolymer content higher than 1.5% on the shear strength of glacial tills from Lincoln and weathered shales from Verdigre was not significant at higher weathering cycles.
- The strength of the glacial tills mixed with 1.5% and 2.5% of Gellan at 8 weathering cycles (3 psi) was comparable to the strength of the untreated weathered ones (2.6 psi) at the same number of weathering cycles. That suggested the effect of Gellan in improving the shear strength of glacial tills is vanished after applying several weathering cycles.
- Weathered shales stabilized with Gellan showed slight increases in the shear strength. The shear strength was enhanced by 5% (from 3.9 psi to 4.1 psi), 10% (from 3.9 psi to 4.3 psi), and 17% (from 3.9 psi to 4.55 psi) for 0.5%, 1.5%, and 2.5% of Gellan, respectively.
- Xanthan and Gellan were more effective in glacial tills from Lincoln than in weathered shales from Verdigre.

6.2 Conclusion from field tests

- Initial field strength showed 6 to 15 psi shear strength at 4 ft to 9ft depth range both for Xanthan treated soils and untreated soils, which is slightly higher than laboratory test results that showed 4 to 5.5 psi range.
- However, the difference in strength between Xanthan treated area and non treated area was not clearly distinguished from field test results.

- Initial modulus at 4 ft depth was 700 psi for untreated soil to 980 psi for treated soil indicating that the soil is medium stiff silty clay. The shear strength obtained from the pressuremeter is in the range of 7 – 14 psi showing good agreement with CPT(PCPT) results. It also indicated that the Ko (in situ earth pressure coefficient) is about 1.7 indicating the highly overconsolidated condition (induced by compaction).
- The deformation of the slope is low and the slope is stable now. However, continuous monitoring is recommended.
- The moisture of the surface of the slope gradually increased from 20% (initial) to 30% as of mid-Feb. 2021 indicating that the strength degradation is undergoing.
- Vane shear test results showed that the strength of soil at 0.5 ft and 1.0 ft depth is in the range of 10 to 15 psi as of Mar. 1, which is similar in magnitude to the initial measured shear strength by CPT and pressuremeter. However, the higher strength was measured in the Xanthan treated area.

6.3 Suggestion for Future Study

Based on this study, the following suggestions are recommended for future study.

- Biopolymer may be applied for enhancing weathering resistance of weathered shales and glacial tills in Nebraska, which are popular materials for earthworks that include slopes and roadbed materials.
- Field soils did not experience even one full cycle of weathering process at this time. Therefore, it is recommended to monitor the behavior of soils in the test site for a few more years.

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Appendix A Summary of Direct Shear Tests

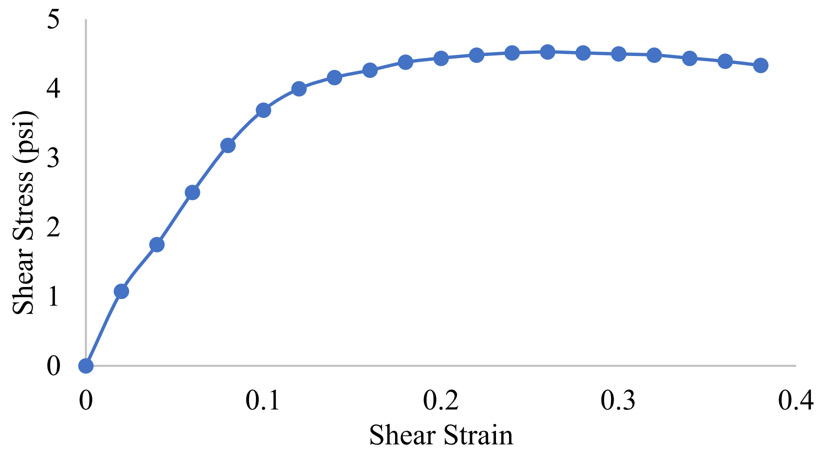

Figure A.1 Direct shear test result on untreated weathered shales from Verdigre subjected to no weathering cycle

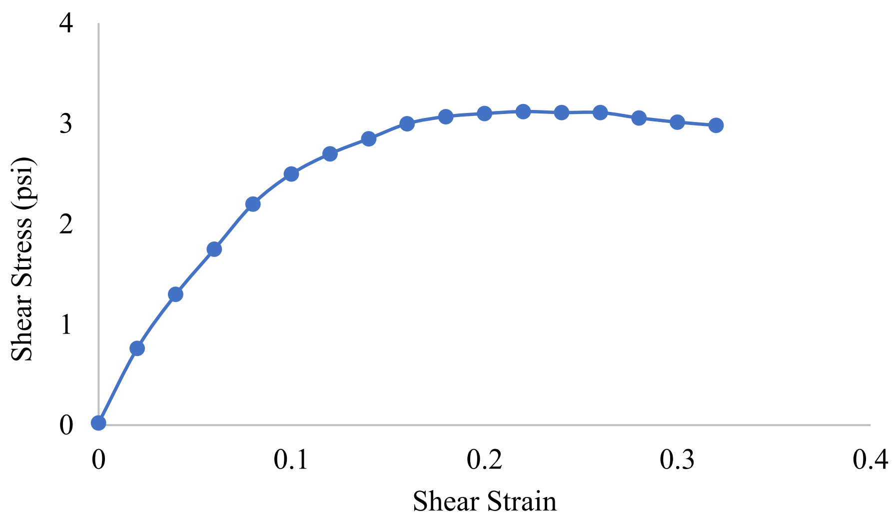

Figure A.2 Direct shear test result on untreated weathered shales from Verdigre subjected to 2 W-F-T-D cycles

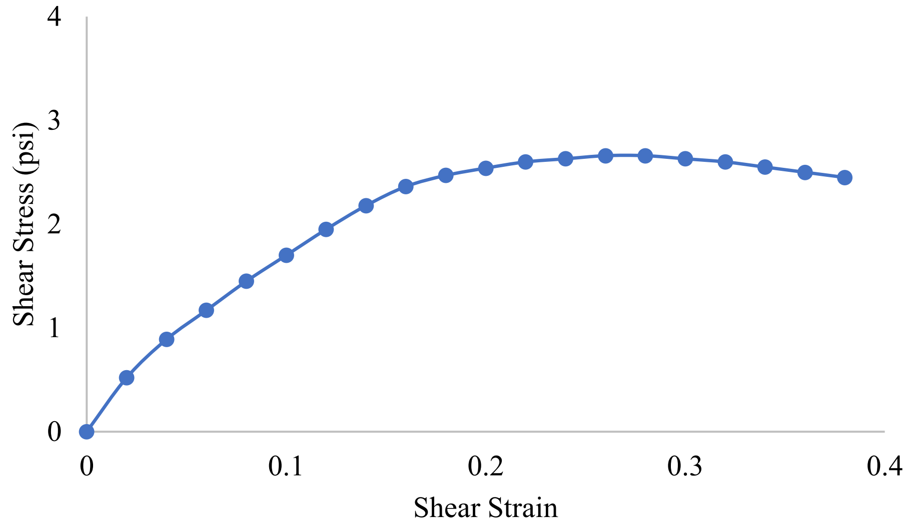

Figure A.3 Direct shear test result on untreated weathered shales from Verdigre subjected to 4 W-F-T-D cycles

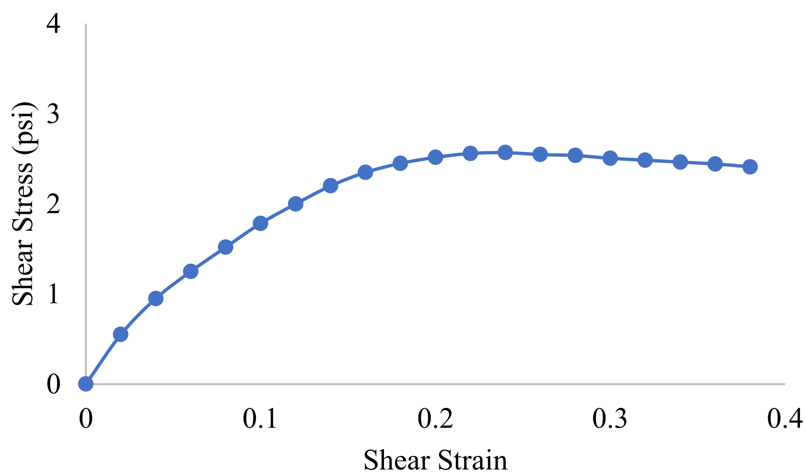

Figure A.4 Direct shear test result on untreated weathered shales from Verdigre subjected to 8 W-F-T-D cycles

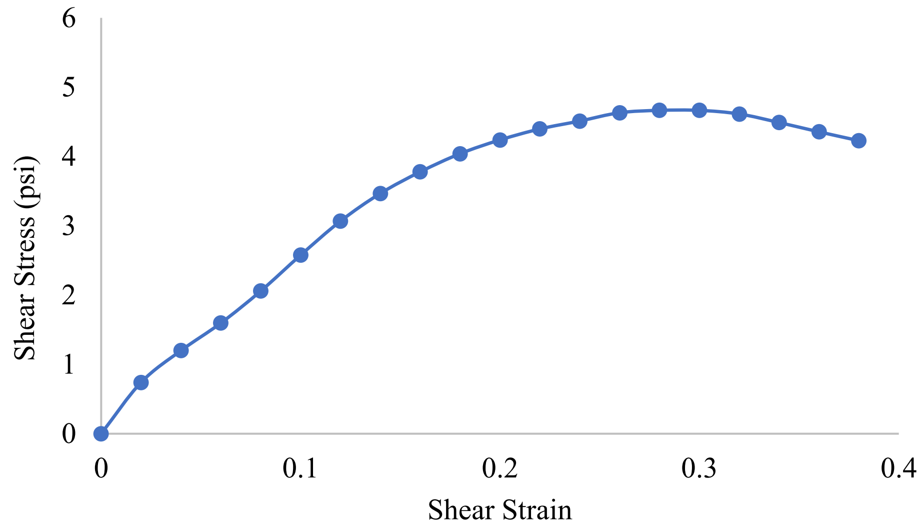

Figure A.5 The effect of using 0.5% of Xanthan gum on the shear strength of the weathered shales from Verdigre

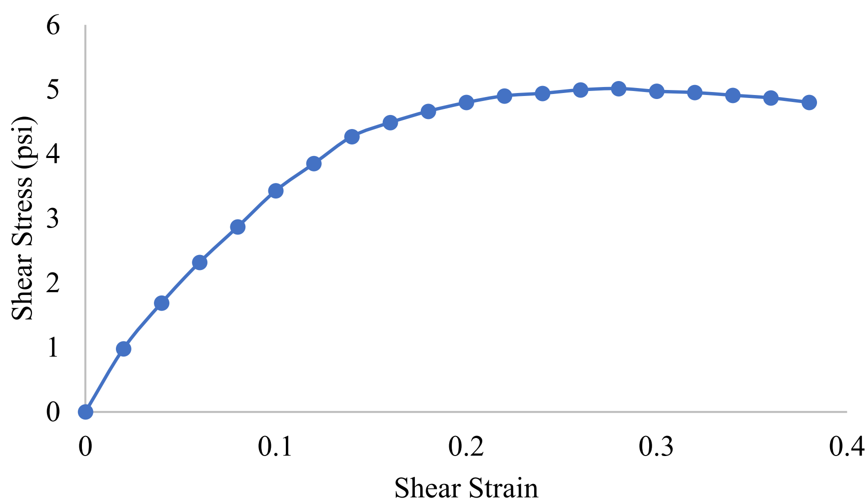

Figure A.6 The effect of using 1.5% of Xanthan gum on the shear strength of the weathered shales from Verdigre

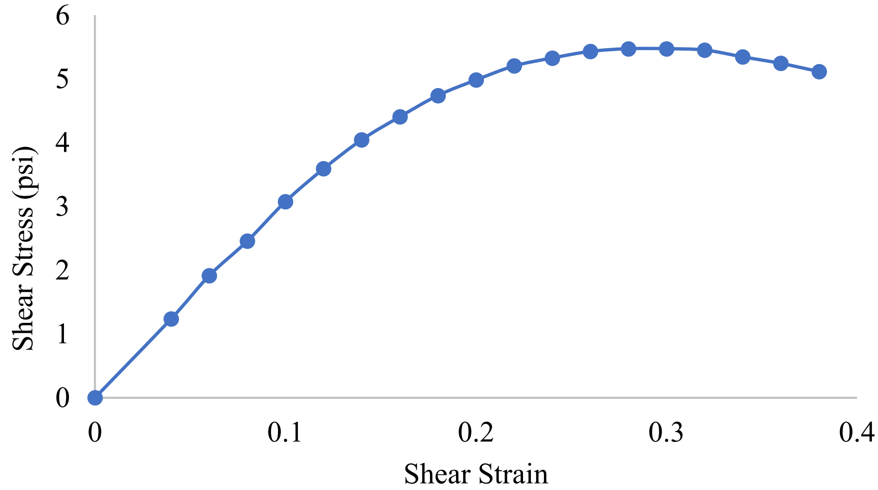

Figure A.7 The effect of using 2.5% of Xanthan gum on the shear strength of the weathered shales from Verdigre

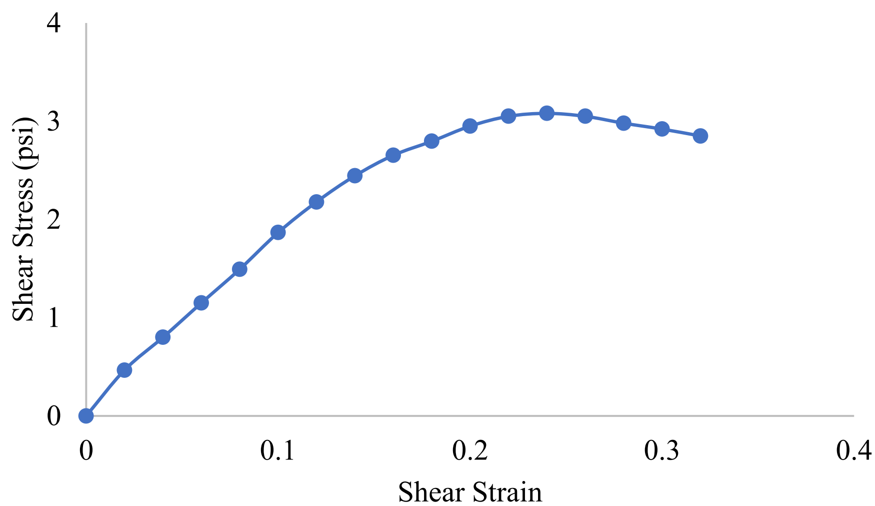

Figure A.8 Direct shear test result on weathered shale treated with 0.5% XG and subjected to 2 W-F-T-D cycles

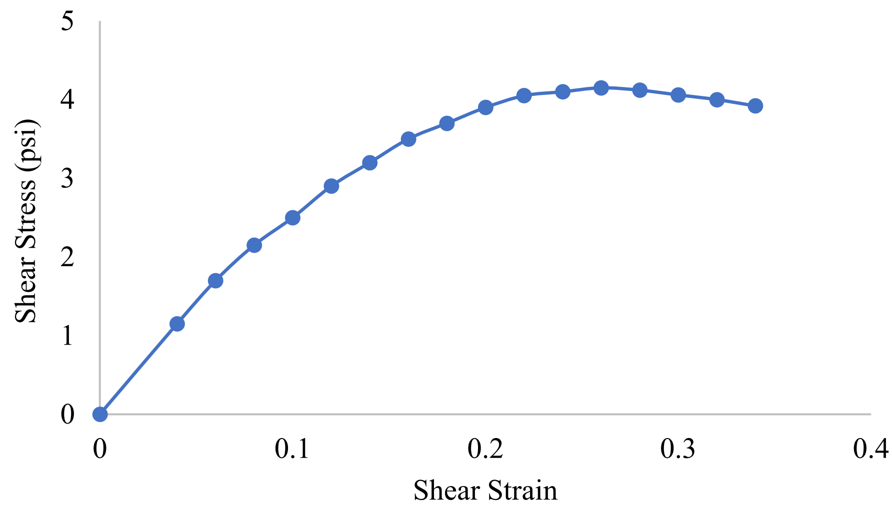

Figure A.9 Direct shear test result on weathered shales from Verdigre treated with 1.5% XG and subjected to 2 W-F-T-D cycles

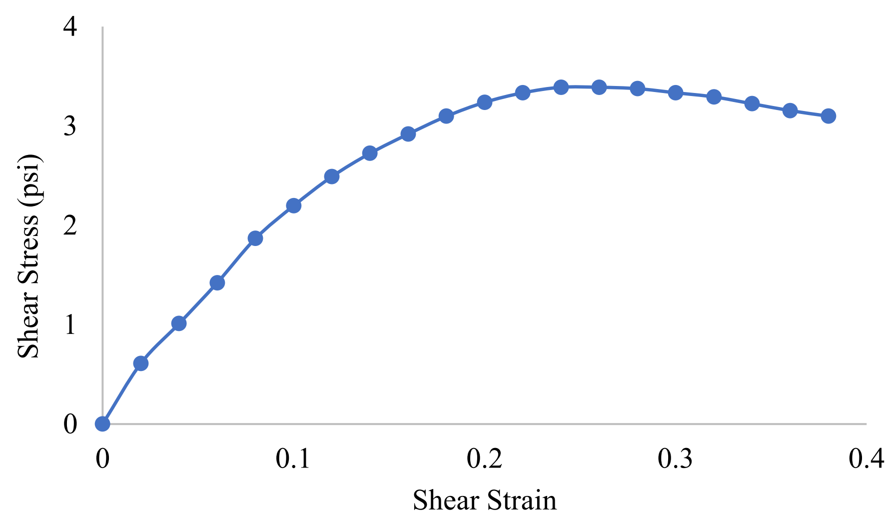

Figure A.10 Direct shear test result on weathered shales from Verdigre treated with 1.5% XG and subjected to 4 W-F-T-D cycles

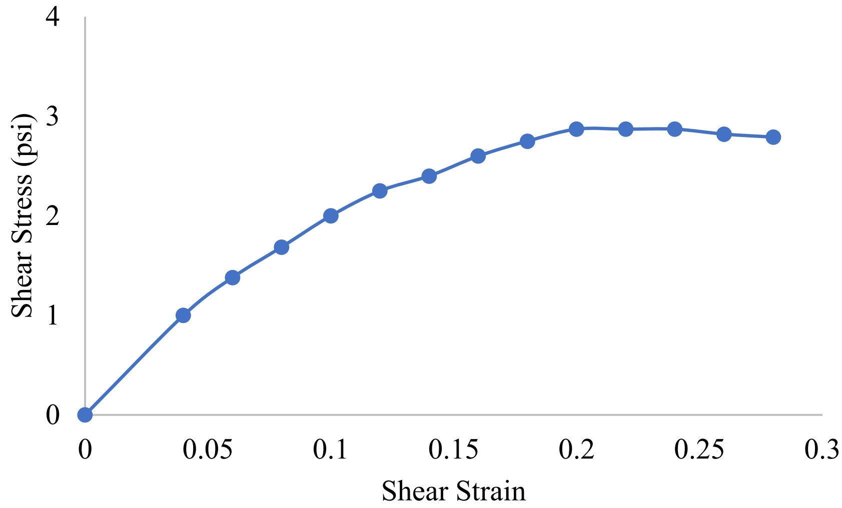

Figure A.11 Direct shear test result on weathered shales from Verdigre treated with 1.5% XG and subjected to 8 W-F-T-D cycles

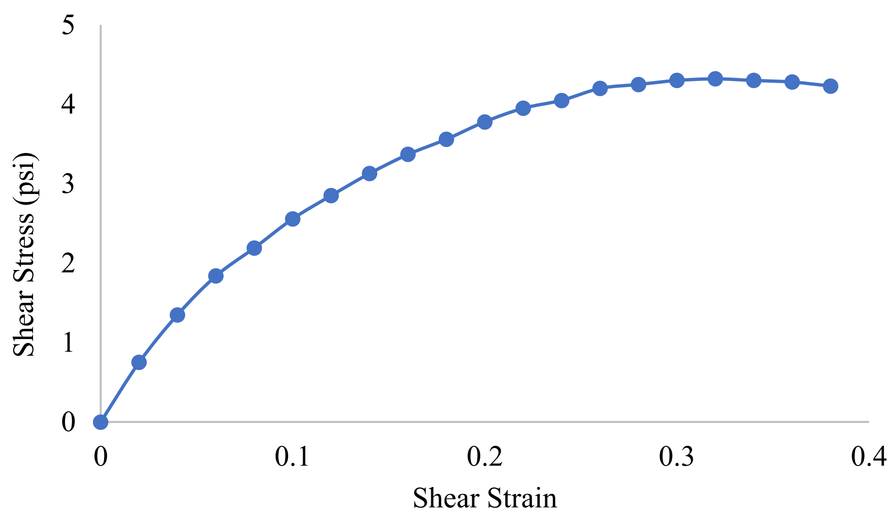

Figure A.12 Direct shear test result on weathered shales from Verdigre treated with 2.5% XG and subjected to 2 W-F-T-D cycles

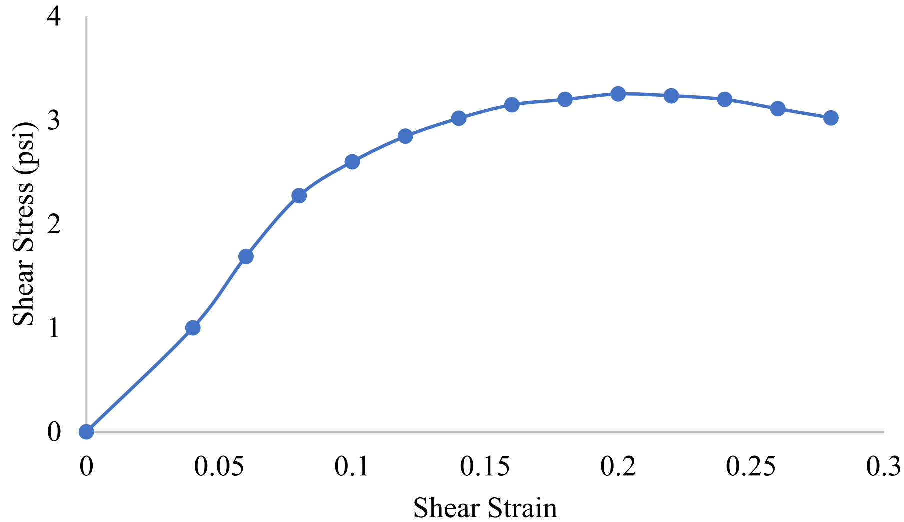

Figure A.13Direct shear test result on weathered shales from Verdigre treated with 2.5% XG and subjected to 4 W-F-T-D cycles

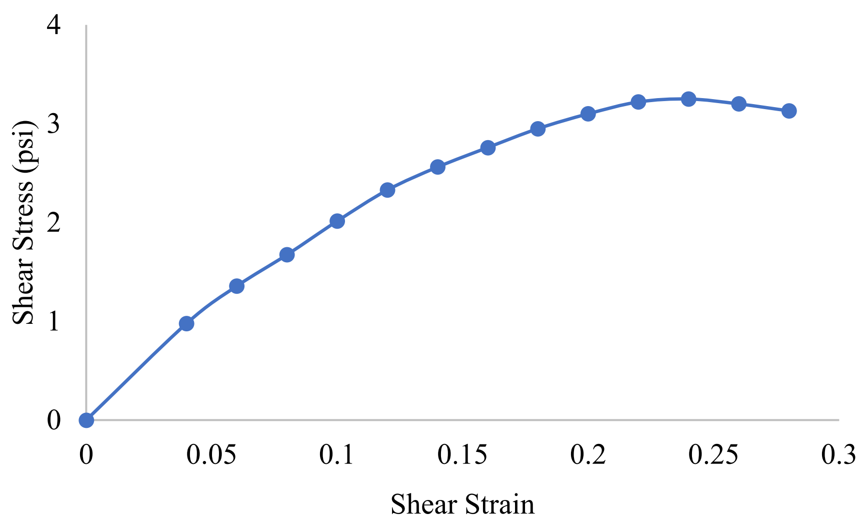

Figure A.14 Direct shear test result on weathered shales from Verdigre treated with 2.5% XG and subjected to 8 W-F-T-D cycles

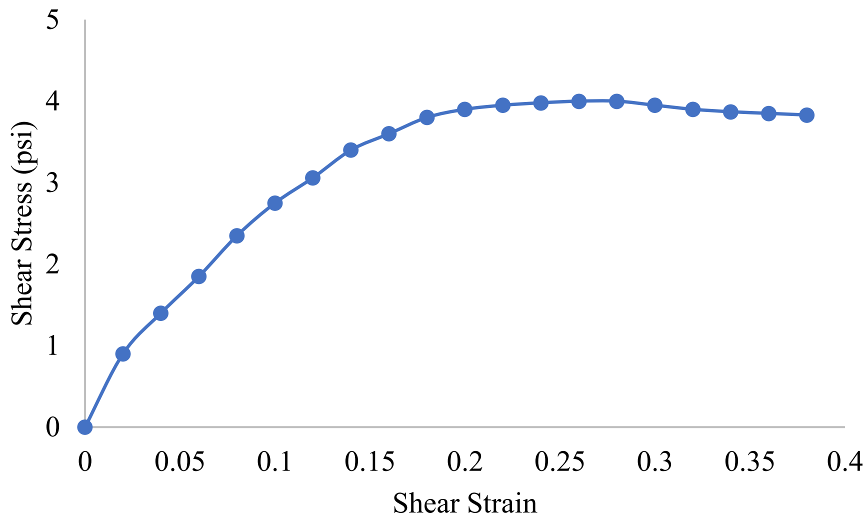

Figure A.15 The effect of using 0.5% of Gellan on the shear strength of the weathered shales from Verdigre

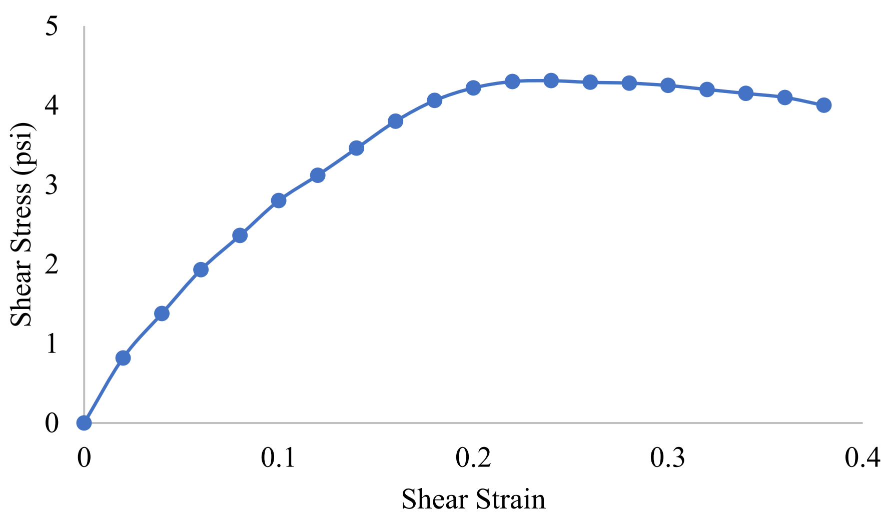

Figure A.16 The effect of using 1.5% of Gellan on the shear strength of the weathered shales from Verdigre

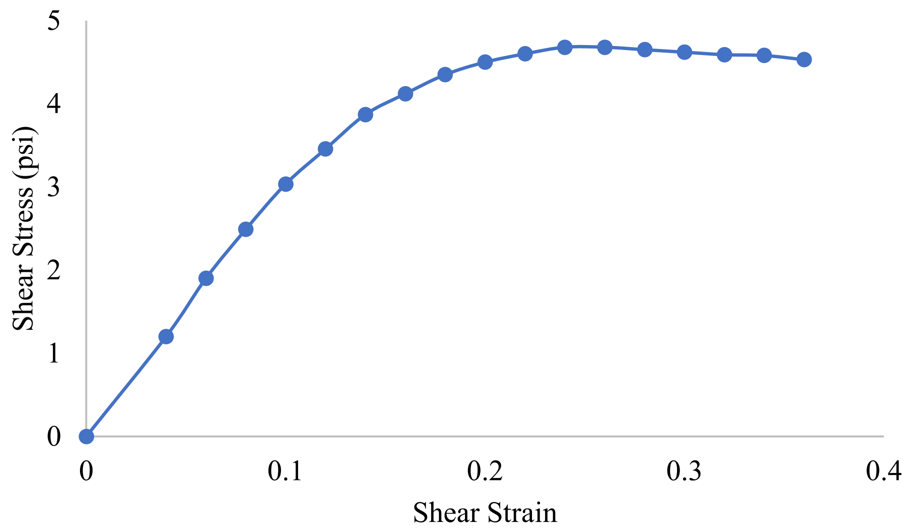

Figure A.17 The effect of using 2.5% of Gellan on the shear strength of the weathered shales from Verdigre

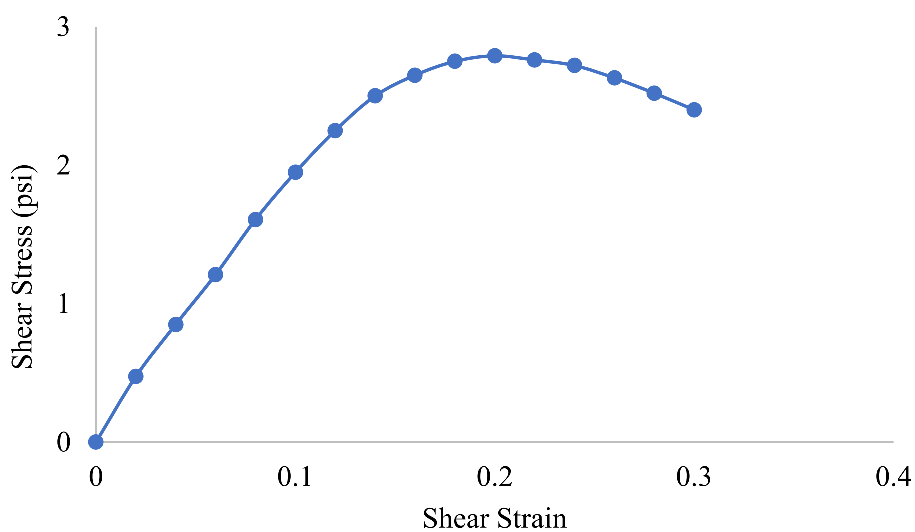

Figure A.18 Direct shear test result on weathered shales from Verdigre treated with 0.5% GG and subjected to 2 W-F-T-D cycles

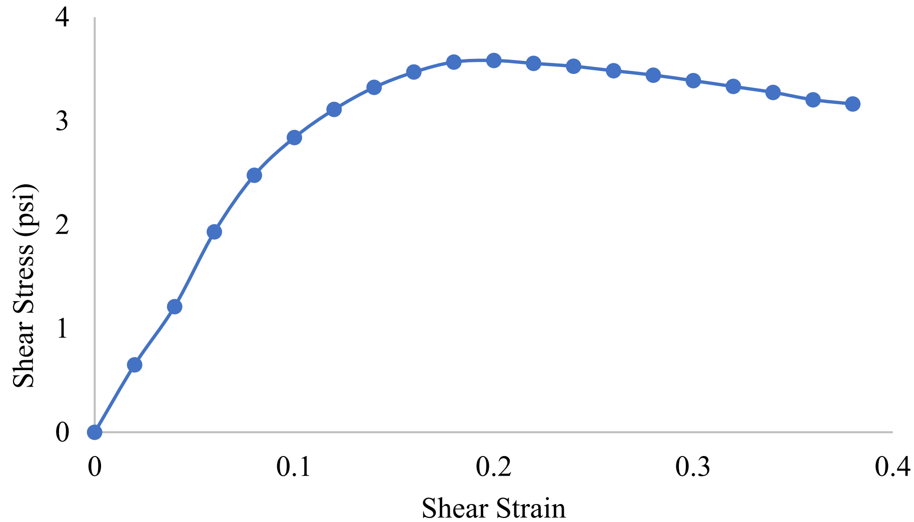

Figure A.19 Direct shear test result on weathered shales from Verdigre treated with 1.5% GG and subjected to 2 W-F-T-D cycles

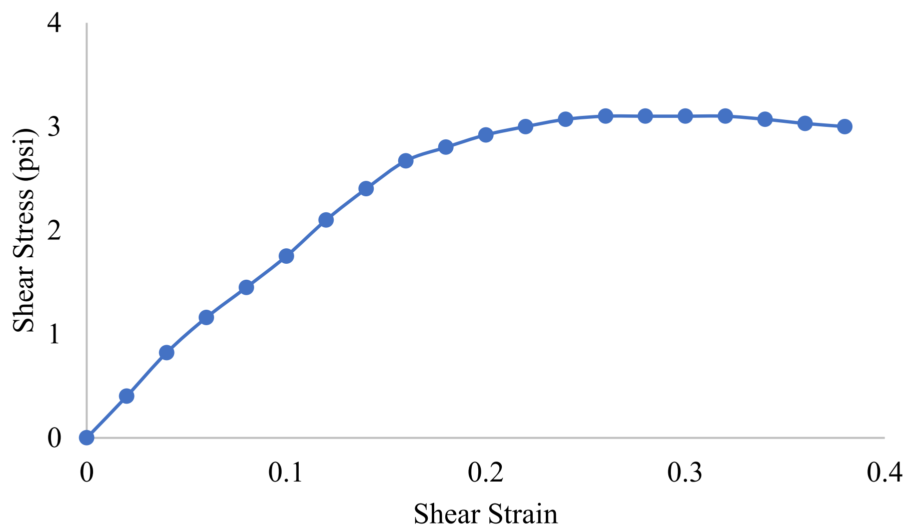

Figure A.20Direct shear test result on weathered shales from Verdigre treated with 1.5% GG and subjected to 4 W-F-T-D cycles

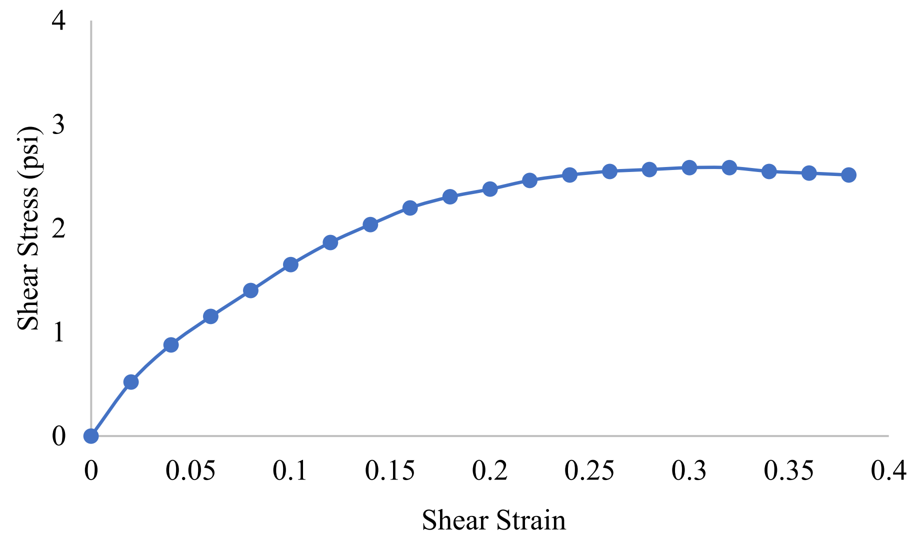

Figure A.21Direct shear test result on weathered shales from Verdigre treated with 1.5% GG and subjected to 8 W-F-T-D cycles

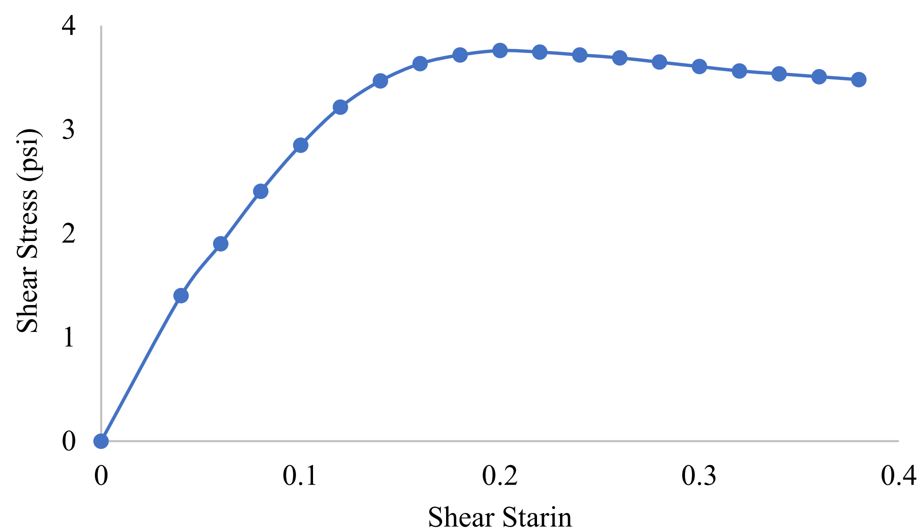

Figure A.22 Direct shear test result on weathered shales from Verdigre treated with 2.5% GG and subjected to 2 W-F-T-D cycles

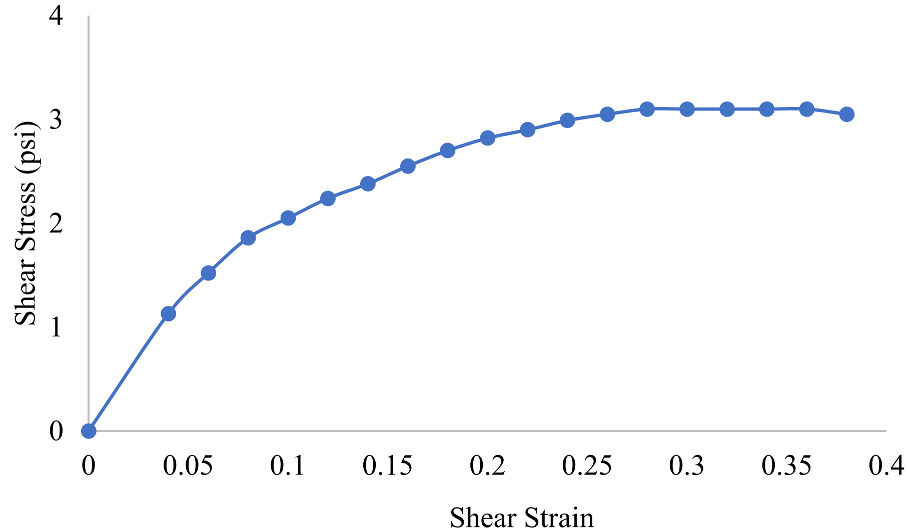

Figure A.23Direct shear test result on weathered shales from Verdigre treated with 2.5% GG and subjected to 4 W-F-T-D cycles

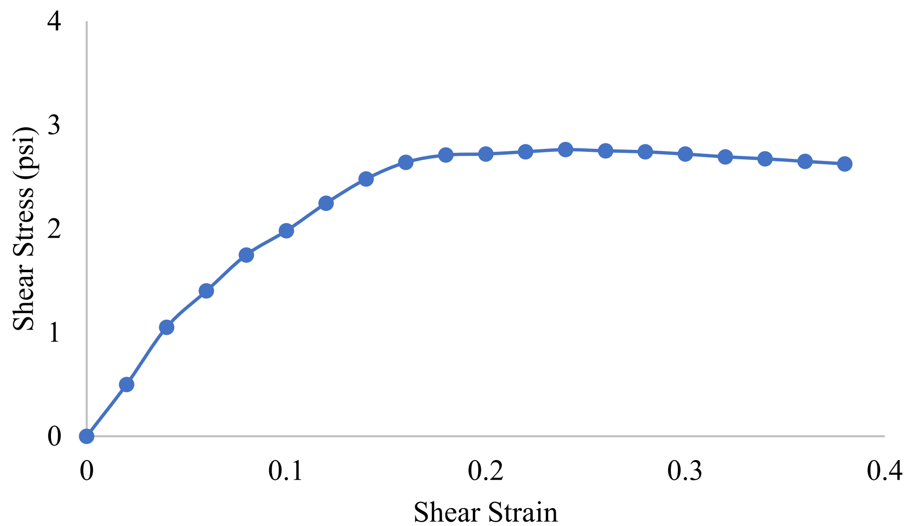

Figure A.24 Direct shear test result on weathered shales from Verdigre treated with 2.5% GG and subjected to 8 W-F-T-D cycles

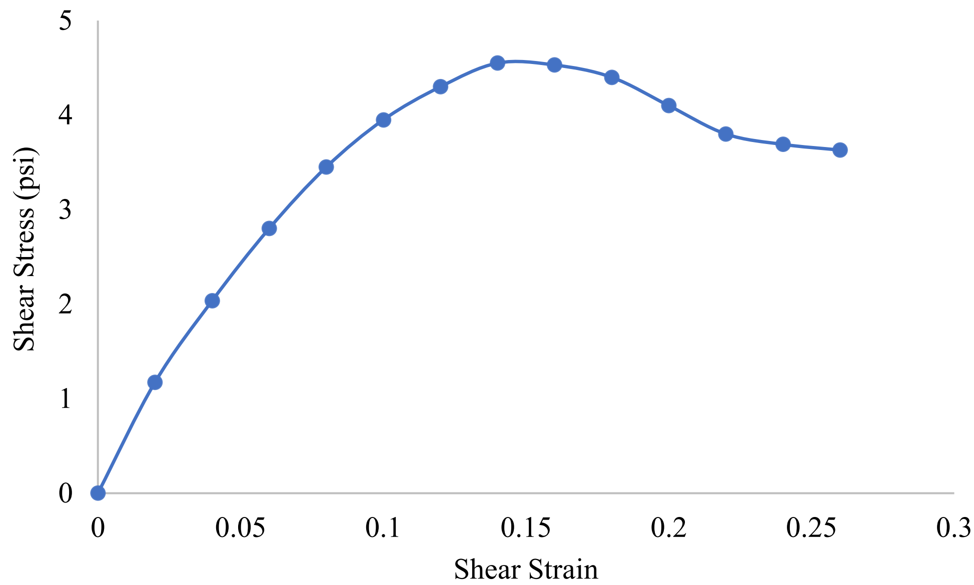

Figure A.25 Direct shear test result on untreated glacial tills and subjected to no weathering cycle

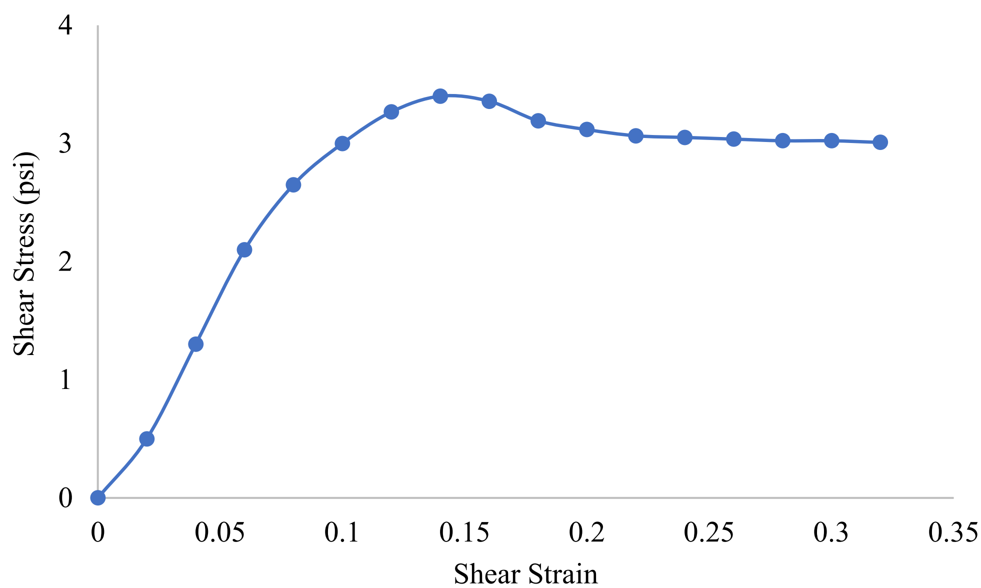

Figure A.26 Direct shear test result on untreated glacial tills subjected to 2 W-F-T-D cycles

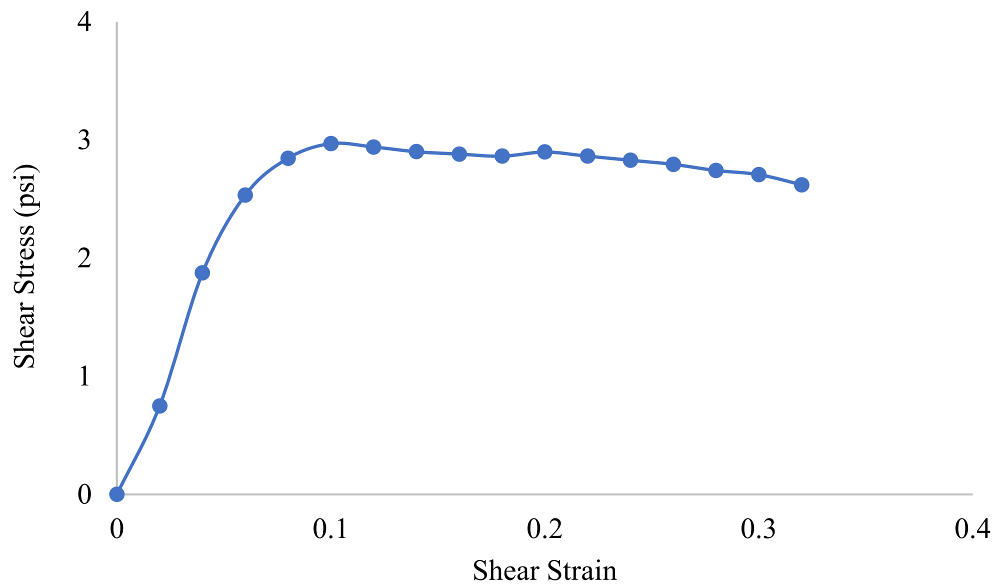

Figure A.27 Direct shear test result on untreated glacial tills subjected to 4 W-F-T-D cycles

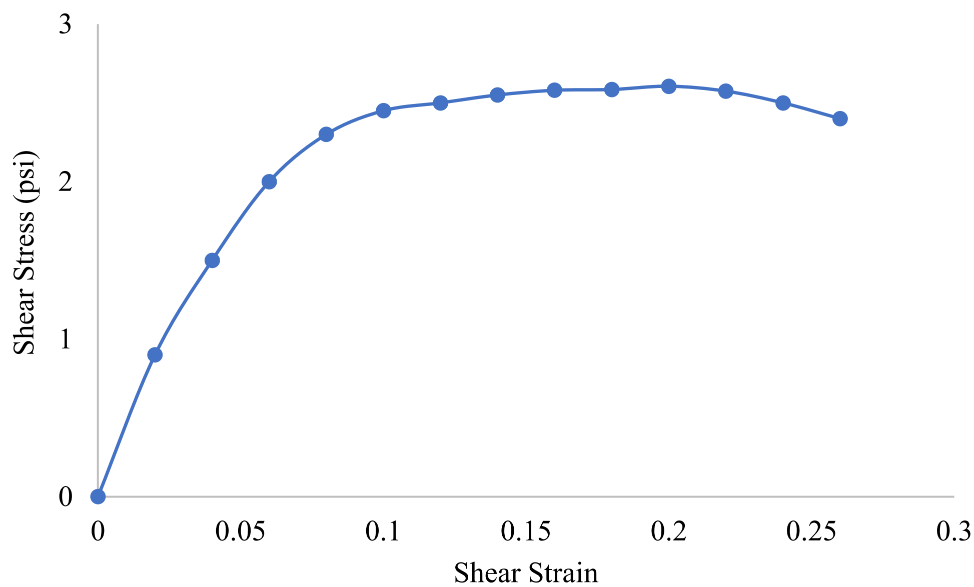

Figure A.28 Direct shear test result on untreated glacial tills subjected to 8 W-F-T-D cycles

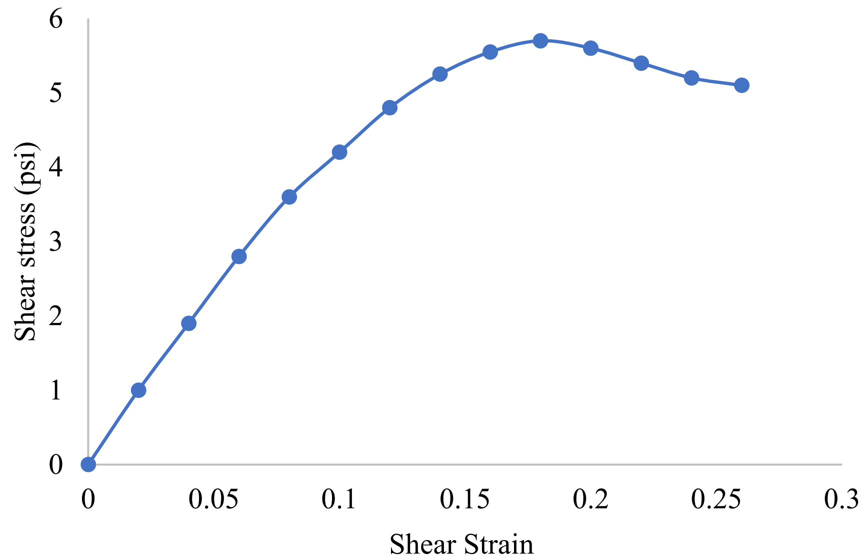

Figure A.29 The effect of using 0.5% of Xanthan gum on the shear strength of the glacial tills

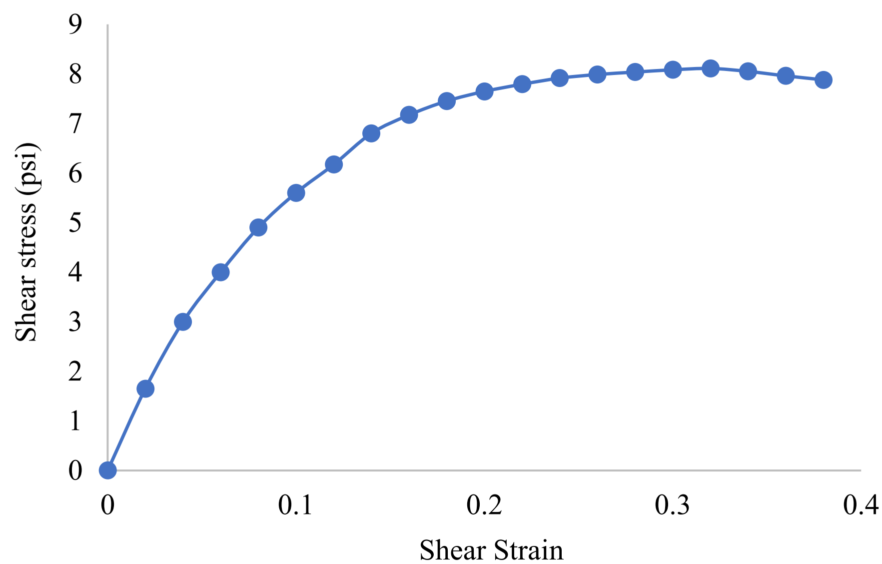

Figure A.30 The effect of using 1.5% of Xanthan gum on the shear strength of the glacial tills

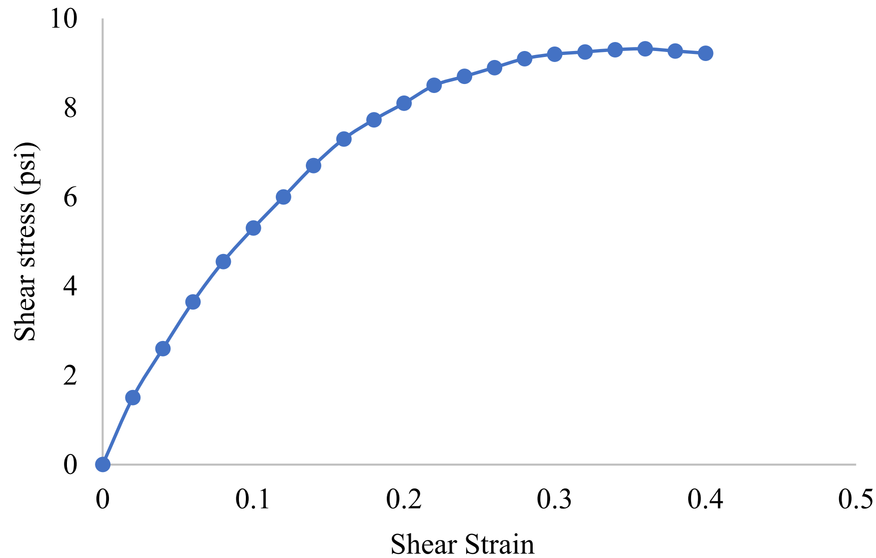

Figure A.31 The effect of using 2.5% of Xanthan gum content on the shear strength of the glacial tills

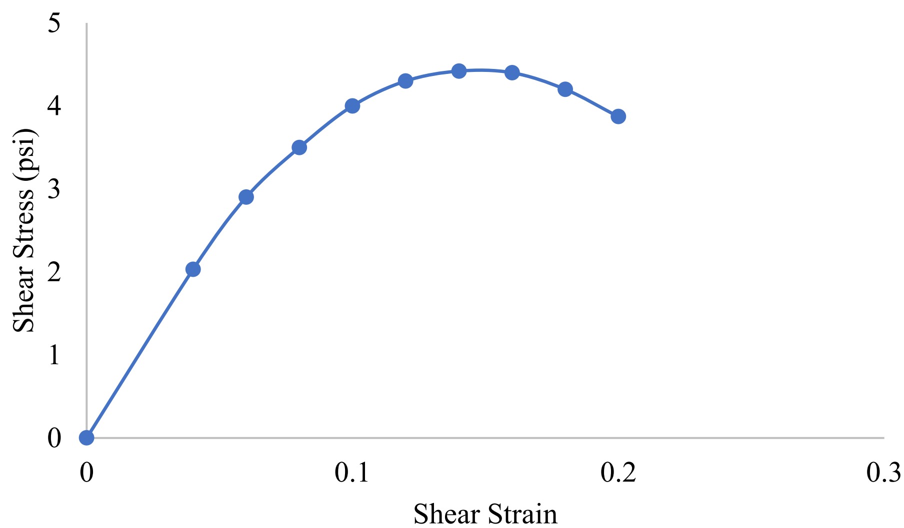

Figure A.32 Direct shear test result on glacial tills treated with 0.5% XG and subjected to 2 W-F-T-D cycles

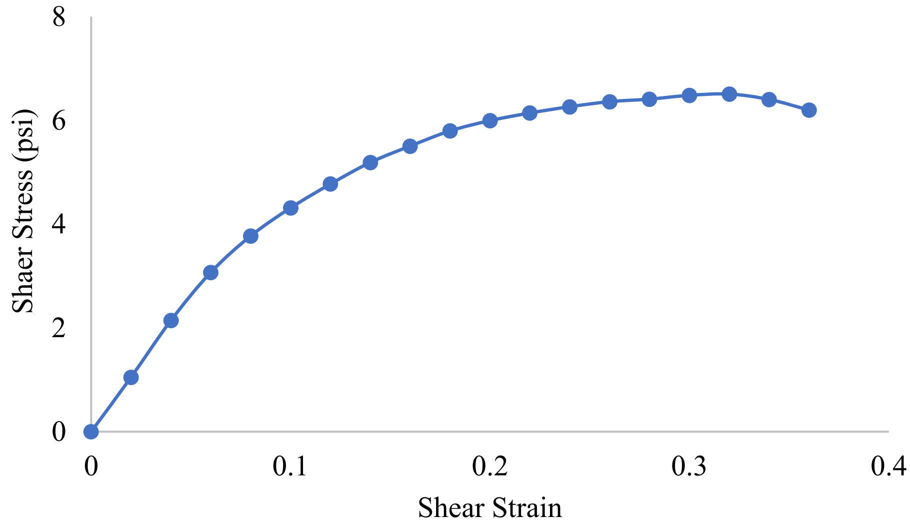

Figure A.33 Direct shear test result on glacial tills treated with 1.5% XG and subjected to 2 W-F-T-D cycle

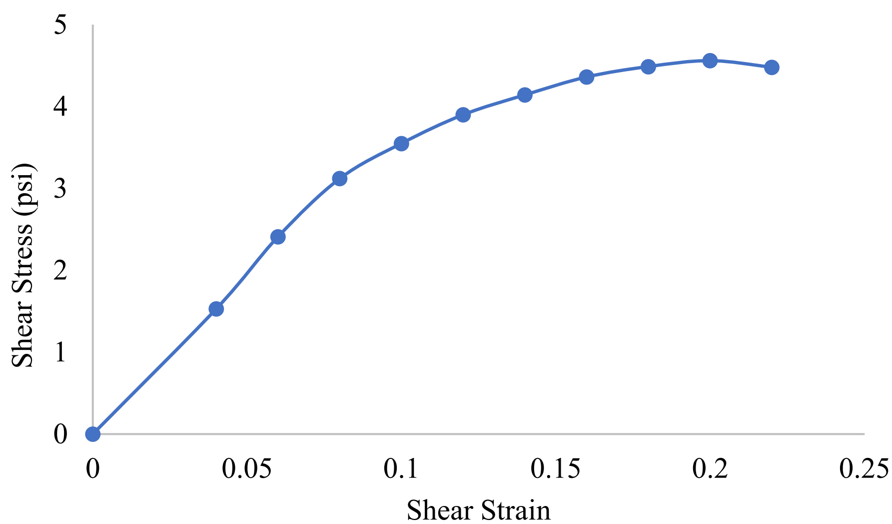

Figure A.34 Direct shear test result on glacial tills treated with 1.5% XG and subjected to 4 W-F-T-D cycles

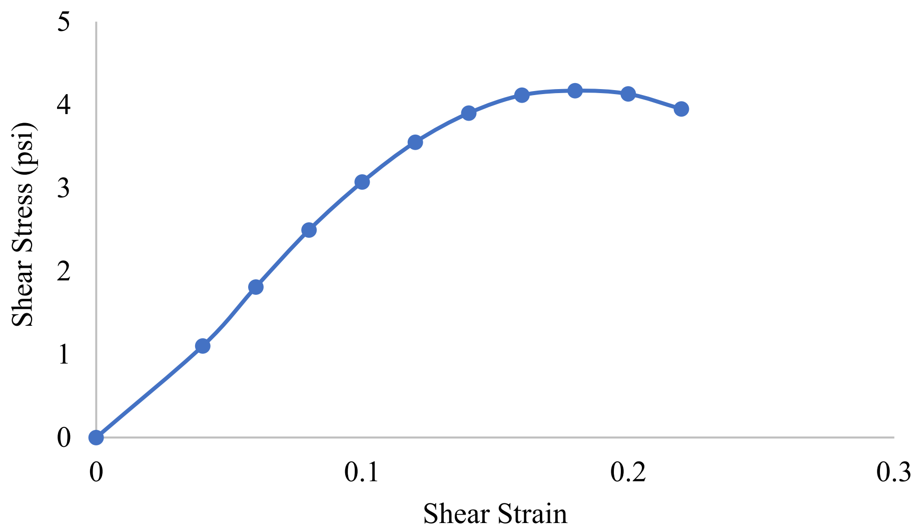

Figure A.35 Direct shear test result on glacial tills treated with 1.5% XG and subjected to 8 W-F-T-D cycles

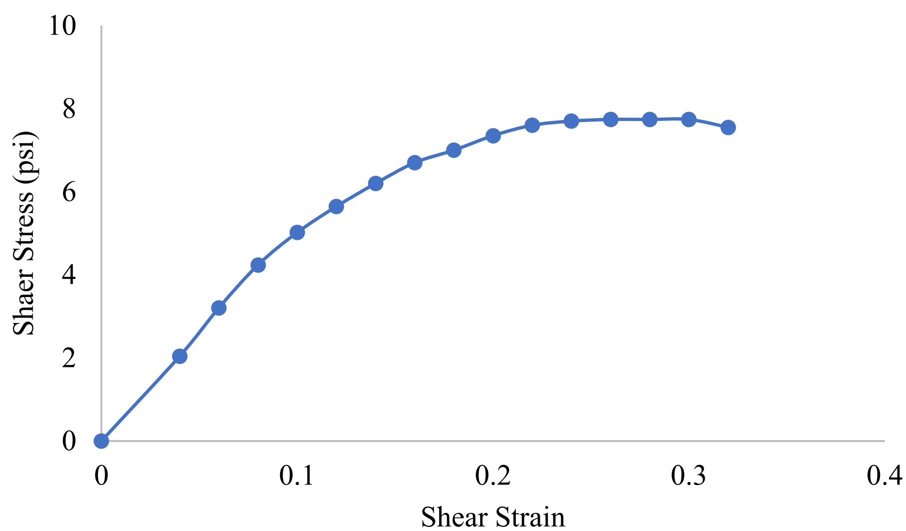

Figure A.36 Direct shear test result on glacial tills treated with 2.5% XG and subjected to 2 W-F-T-D cycles

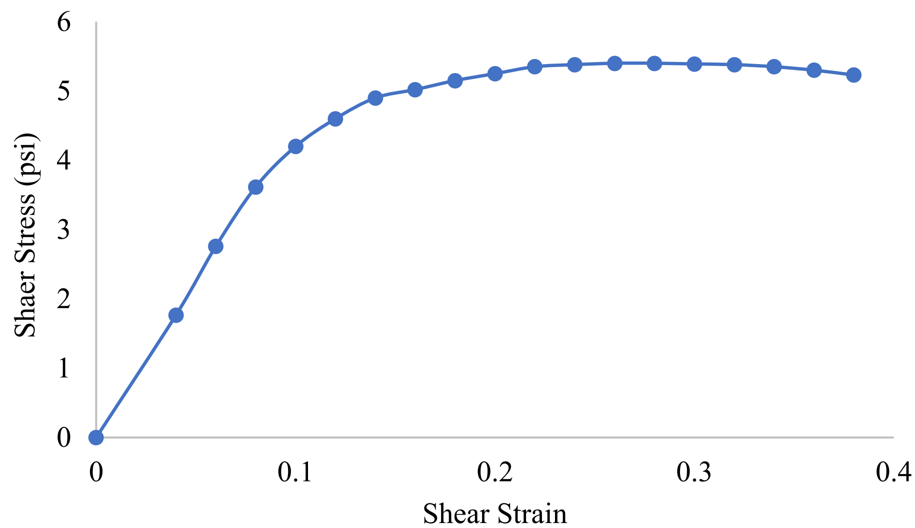

Figure A. 37 Direct shear test result on glacial tills treated with 2.5% XG and subjected to 4 W-F-T-D cycles

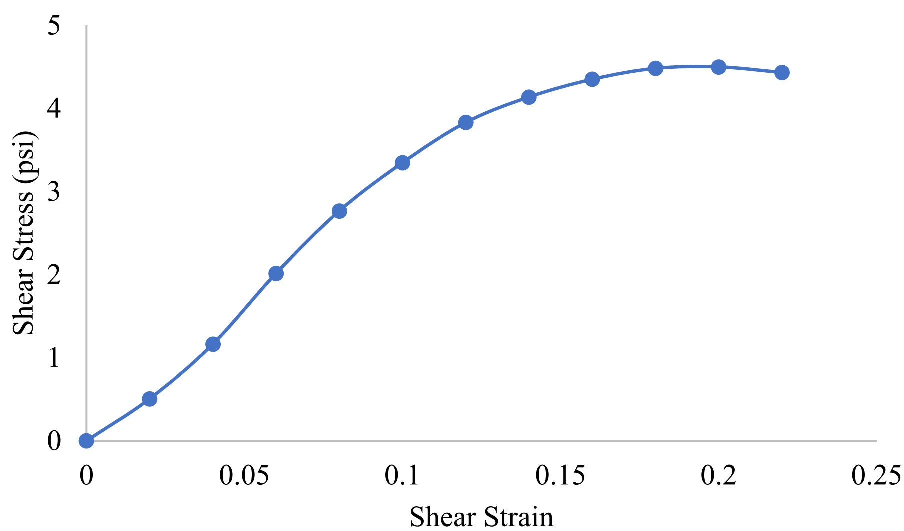

Figure A.38 Direct shear test result on glacial tills treated with 2.5% XG and subjected to 8 W-F-T-D cycles

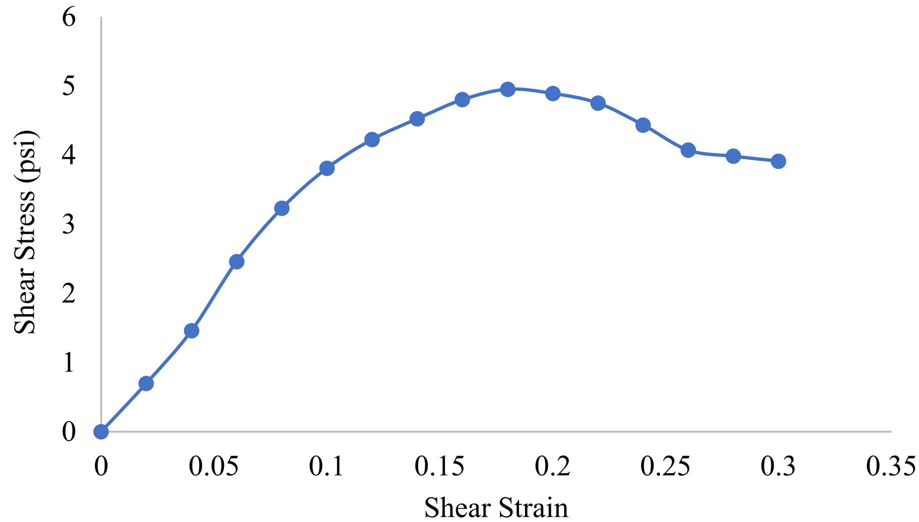

Figure A.39 The effect of using 0.5% of Gellan content on the shear strength of the glacial tills

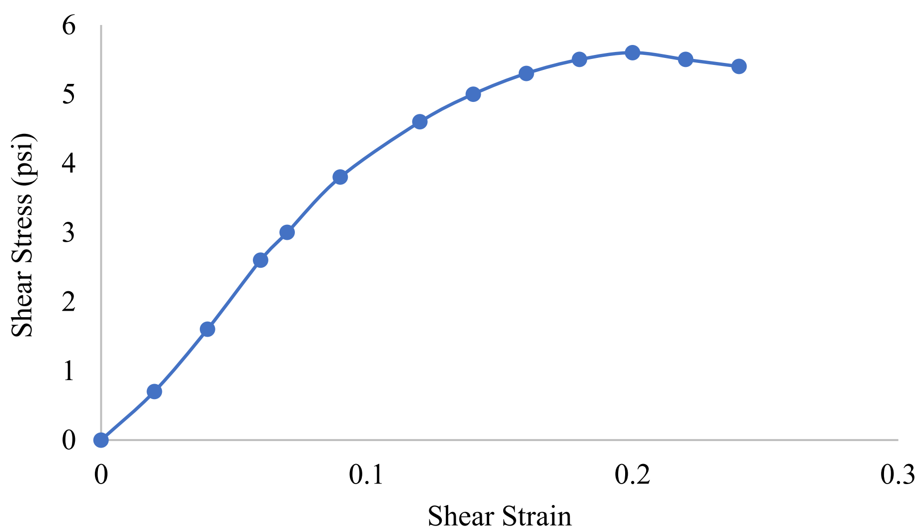

Figure A.40 The effect of using 1.5% of Gellan content on the shear strength of the glacial tills

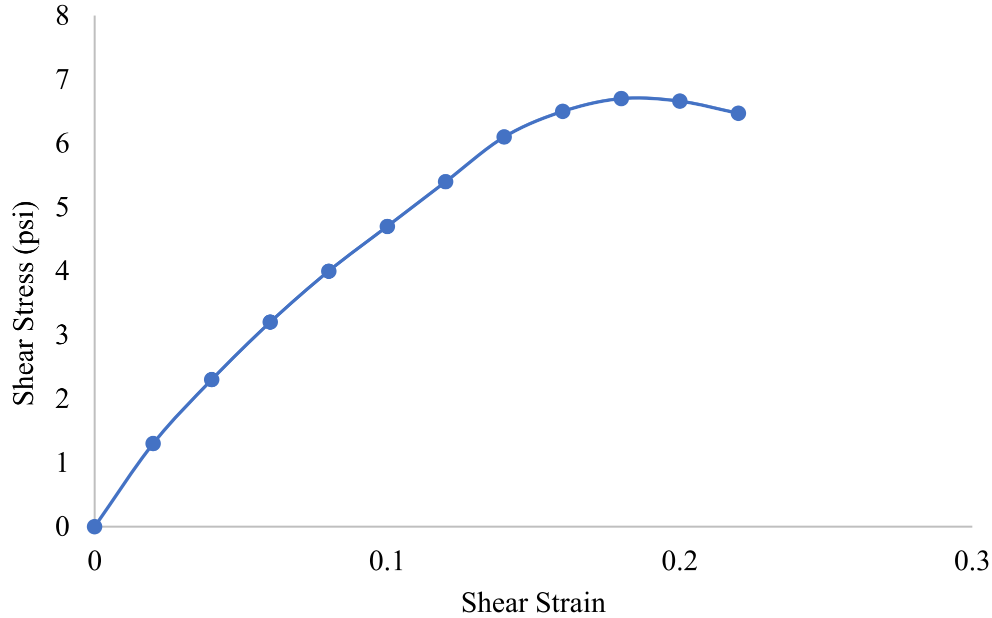

Figure A.41 The effect of using 2.5% of Gellan content on the shear strength of the glacial tills

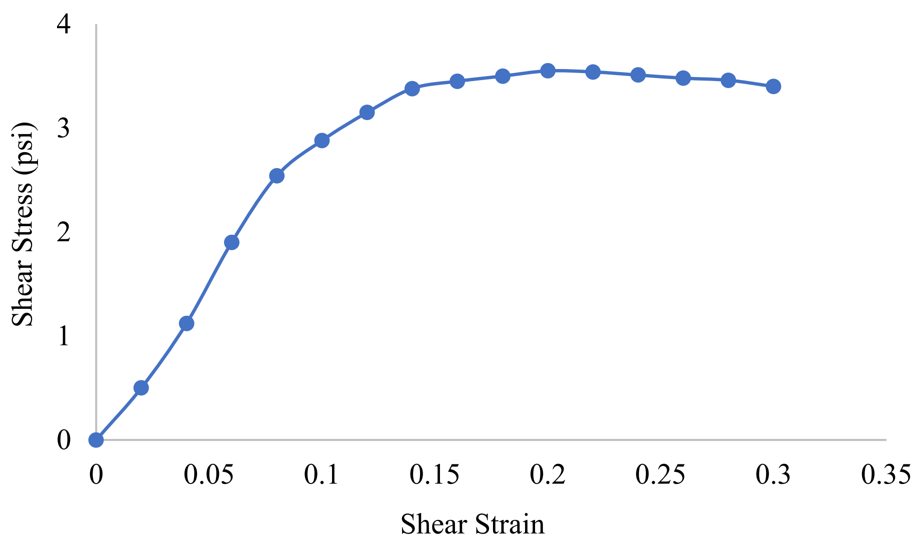

Figure A.42 Direct shear test result on glacial tills treated with 0.5% GG and subjected to 2 W-F-T-D cycles

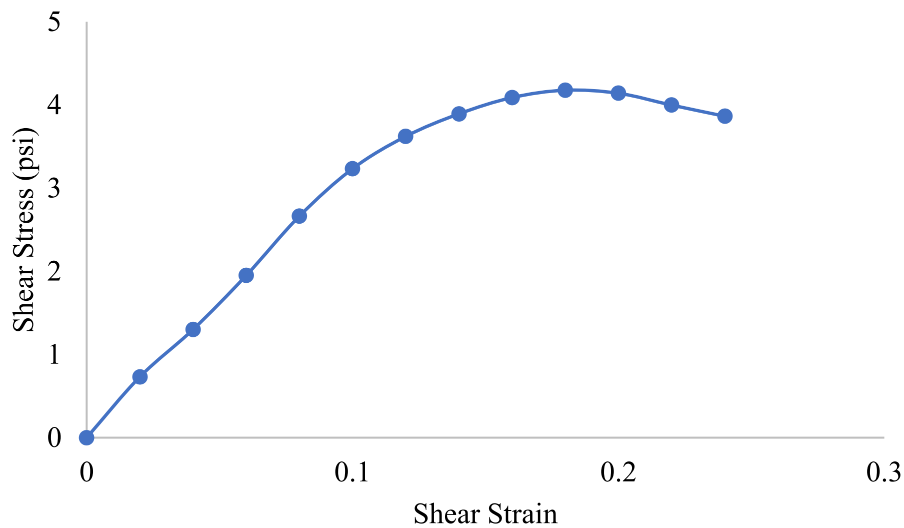

Figure A.43 Direct shear test result on glacial tills treated with 1.5% GG and subjected to 2 W-F-T-D cycles

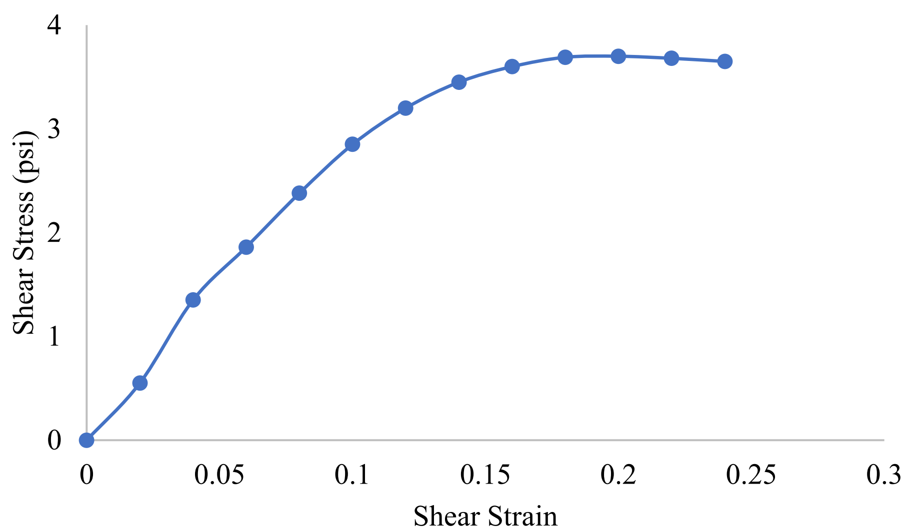

Figure A.44 Direct shear test result on glacial tills treated with 1.5% GG and subjected to 4 W-F-T-D cycles

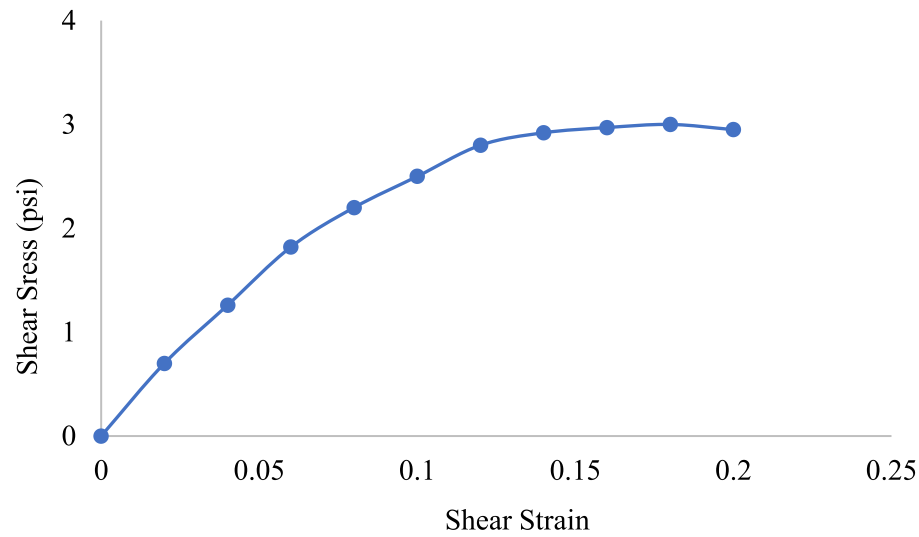

Figure A.45 Direct shear test result on glacial tills treated with 1.5% GG and subjected to 8 W-F-T-D cycles

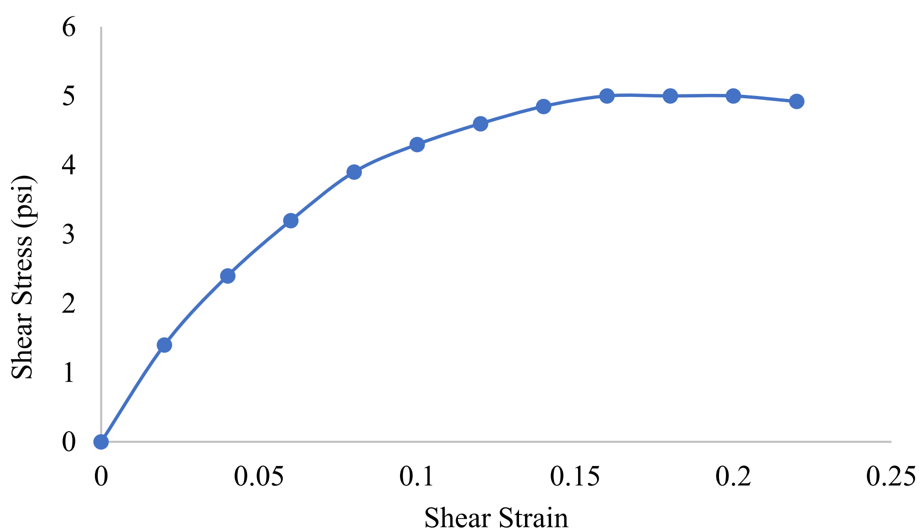

Figure A.46 Direct shear test result on glacial tills treated with 2.5% GG and subjected to 2 W-F-T-D cycles

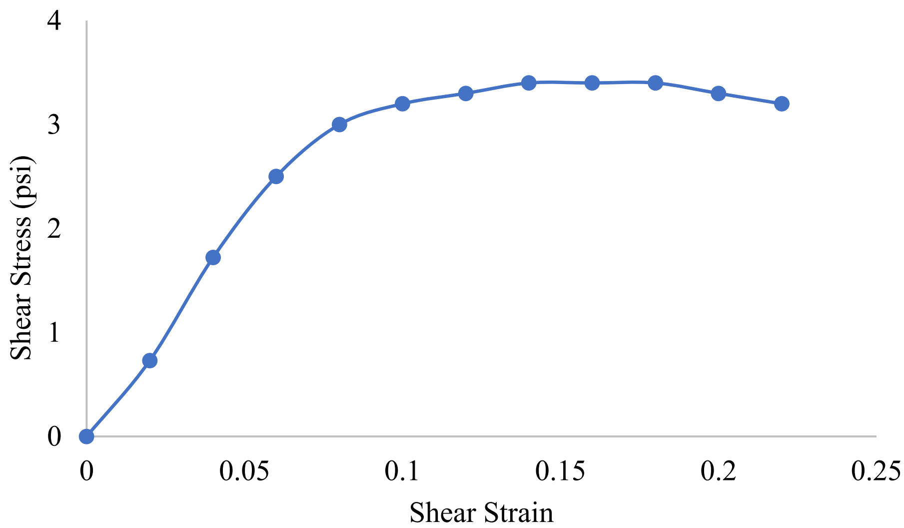

Figure A.47 Direct shear test result on glacial tills treated with 2.5% GG and subjected to 4 W-F-T-D cycles

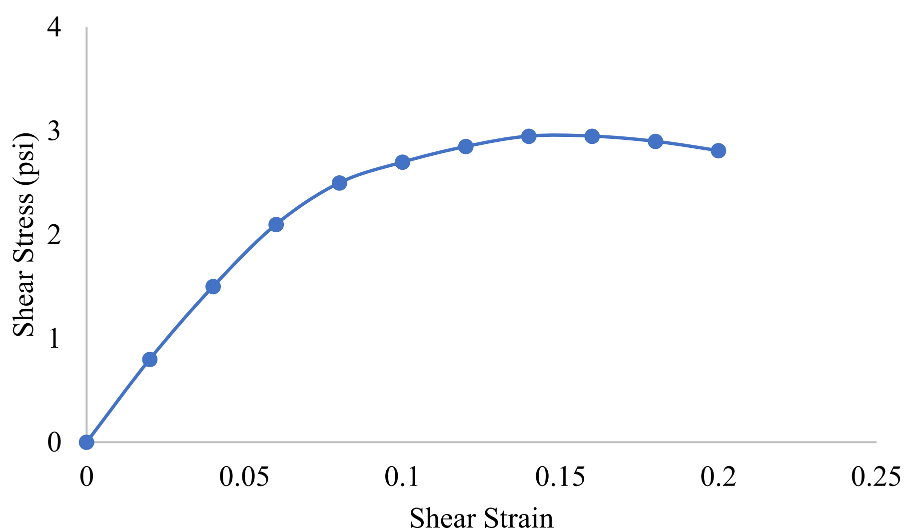

Figure A.48 Direct shear test result on glacial tills treated with 2.5% GG and subjected to 8 W-F-T-D cycles