

Weathering durability of biopolymerized shales and glacial tills

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Abstract. The glacial tills and shales in Midwestern states of the USA often show strength degradation after construction. They are often in need of applying soil modification techniques to remediate their strength degradation with weathering process. This study investigated the weathering durability of these natural soils and biopolymer treated soils by comparing direct shear test results for wet-dry and wet-freeze-thaw-dry cycled specimens. The tests showed that untreated glacial tills maintained only 62% and 50% initial shear strength after eight wet-dry cycles and eight wet-freeze-thaw-dry cycles, respectively. These untreated soils could not withstand by themselves after 16 weathering cycles. The same soils treated with 1.5% (by dry weight) food-grade Xanthan gum maintained 140% and 88% initial shear strength of untreated soils after 16 weathering cycles for wet-dry cycles and wet-freeze-thaw-dry cycles, respectively. The same soils treated with 1.5% (by dry weight) Gellan gum maintained 82% and 60% initial shear strength of untreated ones after 16 weathering cycles, respectively. Similar results were obtained for crushed shales, manifesting that the biopolymerization method may be adopted as a new eco-friendly method to enhance the weathering durability of these problematic soils of glacial tills and shales.

Keywords: biopolymer; glacial till; Gellan gum; shale; weathering; Xanthan gum

1. Introduction

1.1 Geological history of soils in Nebraska and Mid-Western states

Bedrocks for Nebraska and Mid-Western states were formed during the Cretaceous period (approximately 145 to 66 million years ago). Many Mid-Western states were under the Western Interior Seaway during this period, as shown in Fig. 1.

Fine particles deposited in this sea formed shales. Then the current Rocky Mountains area was uplifted during the late Cretaceous period and early Tertiary era, draining out water from the sea and converting this sea area to a dry prairie. Westside of this prairie became high lands, and precipitation transported loose surface particles eastward. But the eastward slope was too gentle to transport the particles to major rivers such as the Missouri River.

These particles, therefore, are deposited on the lower land of the prairie. This freshwater deposit in the Mid-Western area is called the Ogallala formation. With permeable freshwater deposits at the top and the low-permeability shales at the bottom, this area created a gigantic underground water reservoir called the Ogallala aquifer. Far eastside of Nebraska was a part of Appalachia and used to be slightly higher than West and Mid-West area

when Western Interior Seaway once covered West and Central Nebraska, and it was dry land. And thus, the freshwater alluviums from the high lands (Rocky Mountains) did not reach the far eastside of the Nebraska area. Instead, the area was covered by a glacial ice sheet during the Last Glacial Maximum that covered this area 0.026 to 0.02 million years ago (Digitalatlas 2020), as shown in Fig. 2. Then the melting glaciers deposited thin to very thick (over 50 m) glacial tills (UNL Conservation and Survey Div. 2020) on East Nebraska on the top of Cretaceous shales and other bedrocks. The glacial tills contained intermittent layers or lenses of Loess - wind-blown and non-cohesive glacial tills (Mason 2001).



Fig. 1 Western Interior Seaway (King 2021)

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Fig. 2 Glacial Maximum and Laurentide Ice Sheet (Digitalatlas 2020)

The disappearance of glaciers during the Quaternary era removed the effective overburden of the ice sheet, and thus created highly overconsolidated shales, while glacial tills are mostly normally consolidated.

1.2 Geotechnical implication of soils in this area

In most highly populated areas of Nebraska - Lincoln, and Omaha areas, shales are bedrocks covered by glacial tills and intermittent Loess layers/pockets, as summarized in Pabian (1970). And these layers are targets for major structures such as cut/fill slopes, structural foundations, subgrade for highways, dams, and levees. The weathered shales contain close to 80% fine contents. The swelling pressure of these weathered shales is in the range of 10 kPa to 24 kPa, according to Song *et al.* (2019). 24 kPa swelling pressure is high enough to nullify the effect of overburden thickness up to 12 m and open up cracks in the soils. In addition, the temperature condition in this area is frequently below -20°C during winter, but it is frequently above 40°C during summer. Freeze-thaw cycles combined with dry-wet cycles may cause substantial strength reduction for these soils. Glacial tills typically contain 10% to 25% fines with the occasional inclusion of core stones, and their strength characteristic is significantly affected by the water content. The glacial tills at the surface during the rainy season show immeasurably low vane shear strength while it is in the range of 980 kPa during dry seasons (Song *et al.* 2019).

Back calculated strength of failed slopes in Nebraska by Song *et al.* (2019) showed that the field strength of these soils at failure could be in the range of 70% to 10% of the initial shear strength. Extensive laboratory test results by Stark and Eid (1994), Stark *et al.* (2005), and Wright *et al.* (2007) also showed the substantial strength loss for highly plastic soils through ring shear tests and drained triaxial compression tests. Findings of these previous studies indicated that weathering-induced strength degradation of surface soils in this area could be an underlying source of troubles in many different geotechnical structures.

This study attempted to quantify the weathering-induced strength loss of shales and glacial tills in this region. At the same time, the study attempted to devise a biopolymer-based method to mitigate the weathering effect of the problematic soils in the area.

2. Evaluation of biopolymer-based shallow soil mixing techniques compared to other techniques

Traditional approaches for ground stabilization techniques are mixing or injecting artificial materials such as cement, epoxy, acrylamide, phenoplasts, and polyurethane into the pore space of soils to bind soil particles together (Xanthakos *et al.* 1994, Karol 2003, DeJong *et al.* 2010). However, cement and lime-based stabilization techniques are also known for causing adverse effects on the environment. Leaching problems associated with cement, such as reported by van der Sloot (2000), and lime stabilization, such as reported by Ulugonul (1960), are known to be a long-standing environmental concern. Degradation of long-term strength for cement-based treatment was also frequently found (Pham *et al.* 2017, Kim *et al.* 1991). Another critical concern in using cement could be the emission of greenhouse gasses during their production (Schneider *et al.* 2011). Larson (2011) reported that the heat energy required during cement production could generate approximately one ton of carbon dioxide per every ton of cement production. The cement manufacturing process was reported to generate about 5 to 8% of the global carbon dioxide emissions (Karol and Berardinelli 2003, Chang and Cho 2012, Petroleum 2009, Worrell *et al.* 2001). In line with reducing the carbon footprint of the cement production process, Subramanian *et al.* (2018) reported the application of CSA (Calcium SulfoAluminate) for high water to cement cases, where CSA is known to have a much smaller carbon footprint than that for the ordinary portland cement.

Chemical solutions such as Acrylamide, Acrylate, Phenoplast, and Aminoplast were also widely used in the past. However, they were reported to show compromised performance to freeze-thaw or wet-dry cycles (Kutzner 1996, Karol 2003) – which is a critical performance deficiency to be applied in Mid-Western states in the USA, which often experience severe weather conditions. Notably, Aminoplast was reported to be set up only under acid conditions, a unique limitation to the utility of applying this chemical (Karol and Berardinelli 2003). Similar to cement-based ground stabilization techniques, the chemical solution-based stabilization techniques were also known for causing environmental issues. Acrylamide grout, for example, was associated with five cases of water poisoning in Japan, 1974, resulting in the ban of nearly all chemical grouts (Clifton 1986). With many confirmed cases of environmental issues related to chemical stabilization solutions (Mona *et al.* 2001), certain countries proposed to ban the application of synthetic grouting materials (DeJong *et al.* 2003).

As a result of technical and environmental concerns of traditional soil modifiers (Afolabi *et al.* 2012), the shift toward alternative sustainable solutions such as eco-friendly technique is crucial. Among new techniques for soil improvement, microbial or bacteria that induce biopolymers have become an attractive option due to their effectiveness in enhancing the properties of soils and their friendliness to the environment. Mortensen *et al.* (2011), Fauriel and Laloui (2012), and Martinez *et al.* (2014) successfully improved the strength of granular soils by applying Microbial-Induced Calcite Precipitation (MICP) technique.

On the other hand, Jiang *et al.* (2018) applied Bacterial-Enzyme-Induced-Calcite-Precipitation (BEICP, also called EICP) to enhance levee soils containing up to 10% fines (particles finer than #200 sieve). BEICP may be a subcategory of MICP, and it does not use microbial (bacteria) but use enzymes extracted from bacteria or other sources. The size of microbial that generate calcium carbonate in the MICP technique is in the 1 μm range, while the size of enzymes that generate calcium in the BEICP technique is 0.01 μm range. Therefore, the BEICP technique has higher mobility of the agents and could enhance the strength of finer soils. However, the applicability of both methods is not verified yet for clay-rich soils such as weathered shales which contain 10% to 30% clay contents. The typical size of clay particles is smaller than 2 μm . Still, particles are electrically charged, and the role of bacteria and microbes in the charged environment is not thoroughly studied yet.

An alternative to MICP and BEICP can be biopolymer-based techniques. Biopolymers are biodegradable polymers produced by living organisms such as algae, fungus, or bacteria. They are broadly distributed in nature and serve as skeletal structure-forming substances and water-binding substances (Chang *et al.* 2015a). Usually, biopolymers have been utilized mainly in the food production industry, agriculture, cosmetics, medicine, and pharmaceuticals (Chang *et al.* 2015a). For example, Xanthan gum (called Xanthan hereafter) is one of the polysaccharides commonly used as a food additive for rheology modifier for frozen foods (Ferrero *et al.* 1993, 1994, Lo and Ramsden, 2000). It is a soluble fiber produced by fermentation of glucose or sucrose by the *Xanthomonas campestris* bacterium (Chang *et al.* 2015b). Research by Kierulf (1988) showed that the molecular structure of Xanthan transitioned from “order” (=stable) to “disorder” (unstable) state at an approximate temperature higher than 30°C, that is also a desirable property to be applied to soils in Northern hemisphere where the ground temperature usually stays below 30°C. Gellan gum (called Gellan hereafter) is also one of the polysaccharides. Similar to Xanthan, it is a kind of soluble fiber produced by the fermentation of lactose or glucose by the *Spingomonas elodea* microbe. The “order” to “disorder” transition temperature is similar to that for Xanthan, approximately 30°C (Nitta 2005), indicating desirable to be applied to soils in the Northern hemisphere.

The major difference between the biopolymer and previous MICP/BECIP techniques is that the biopolymer technique utilizes pre-produced biopolymers and applies them to the field soil directly, while the MICP/BECIP techniques precipitate microbes, bacteria, or enzymes into the ground and let the precipitated substance form bonding agent with time. In addition, the biopolymers are fully cured in the manufacturing facility, and additional nutrient precipitating is not needed.

Recent studies found the promising applicability of biopolymers in geotechnical engineering (e.g., Canacki *et al.* 2015, Chang *et al.* 2017a, Chen *et al.* 2013, Ceylan *et al.* 2010, Ham *et al.* 2018, Zhang *et al.* 2014, Ayeldeen *et al.* 2016). Notably, the experimental study of Chang *et al.* (2015c) showed that the Xanthan interacted directly with

the charged surfaces of clayey particles; and it showed a substantial strength increase. In another study by Chang *et al.* (2015b), the uniaxial compression tests indicated that both 1% Gellan and Agar gum improved the soil strength by 120% and 80%, respectively. Chang *et al.* (2015c) also reported that mixing 0.5% biopolymers (Xanthan and Beta Glucan) improved the erodibility of Korean red-yellow soils. In addition, Chang *et al.* (2021) reported that the pore fluid chemistry could affect Xanthan gum's effectiveness in enhancing the strength of soils. On the other hand, Im *et al.* (2021) reported improving the performance of starch-based polymers (e.g., Xanthan) by crosslinking two or more polymers.

However, most of these studies are for sandy and silty soils; studies for clay-rich soils are not abundant. This current study focused on enhancing the weathering durability of Xanthan and Gellan treated clay-rich soils - crushed shales and glacial tills in Nebraska, USA

3. Experimental scheme

3.1 Materials and sample preparation

This study collected glacial till from Peoria, Iowa (41.462987, -92.803937) and shale from Spencer, Nebraska (42.849730, -98.652353) for testing. The glacial till was in light brown color with a unified soil classification symbol (USC) SC. The crushed shale was in light gray color with a USC symbol CH.

For sample preparation, target soils were crushed and kept in an oven with a temperature of 105°C for 48 hours to be completely dry. For crushed shales, larger particles than #200 sieve were sieved out. Then, the crushed and dried soils were mixed with the designated amount of biopolymers in an electric bucket mixer (Dayton, Model No. 3K772). Next, the prescribed amount of water was gradually added to the mixer so that the field moisture content, 19.5% for the glacial tills and 20.1% for the crushed shales, was achieved. The mixing process continued until all the particles were mixed thoroughly with water, and a visually homogenous material was acquired. This mixing process typically took about 20 minutes. However, it was expected that there may be some crumbs that might have lower moisture contents than the surrounding soil-water mixture. The effect of these crumbs was not included in the scope of this study. It was also noted that the method of mixing technique may affect the strength characteristics (Seo *et al.* 2021) of biopolymer mixes. The method used in this study was close to the one typically used by the contractor.

For compacting test specimens, a compaction method developed by Sullivan *et al.* (2015) was adopted. This method was called “Preparation of test specimens using the plastic mold compaction device” and was intended to produce test specimens with similar specimen density obtained from AASHTO T 99. This method used a plastic mold compaction device, called PM device hereafter, to prepare cylindrical specimens with an approximate 2:1 height to diameter ratio (Howard *et al.* 2013). The PM



Fig. 3 Plastic mold (PM) for compaction

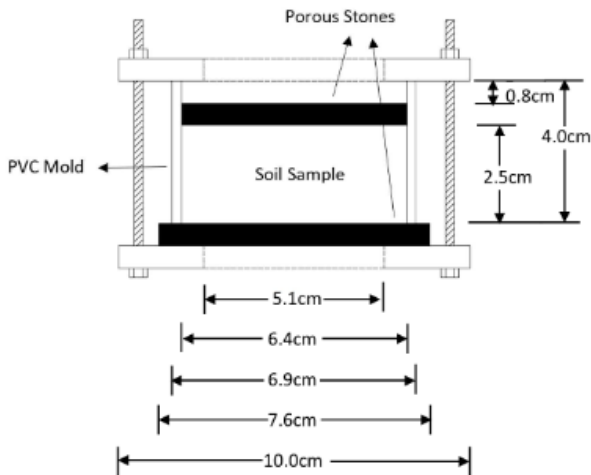


Fig. 4 Mold used for weathering soil samples (after Khan 2016)

device manufactured in-house for the current study was shown in Fig. 3.

The mold includes a metal split mold, collar, and base plate. The cylindrical plastic mold meets ASTM C470 requirement, and the size was 76.2 mm in diameter and 152.4 mm in height. To prepare specimens for weathering and further testing, the compacted samples were cut and trimmed as follows. In the first step, each compacted sample was cut into three pieces. Each piece was then trimmed using a consolidation ring to obtain the final dimension with 6.4 cm diameter and 2.5 cm height to fit into a weathering mold shown in Fig. 4.

Then, soil samples placed in the weathering molds were wrapped with saran wrap to prevent moisture loss, and kept in curing/homogenizing condition for a week. After curing, pre-determined two different weathering cycles (wet-dry or wet-freeze-thaw-dry) were applied. The wet-dry weathering cycles simulated the weathering condition in non-freezing areas, while the wet-freeze-thaw-dry weathering cycles simulated that in occasionally freezing areas.

The weathering mold included a PVC section having an inner diameter of the same size as the soil specimens (6.4 cm), an outer diameter of 6.9 cm, and a height of 4 cm. The specimens were placed inside the PVC mold, and two porous stones with diameters of 7.6 cm (bottom one) and 6.4 cm (top one) were placed at the bottom and top of the mold, respectively, to provide water infiltration and drainage. While the bottom stone completely covered both



(a) Soil sample in the weathering ring (Left: Glacial Till, Right: Crushed Shale)



(b) Soil samples with filter paper placed (c) Soil samples with porous stone placed

Fig. 5 Soil samples prepared for weathering tests



Fig. 6 Samples locked in the mold for weathering

mold and specimen, preventing the sample from dropping, the top stone set inside the PVC mold, preventing particle migration but allowing shrinkage and swell during drying and wet cycles. The gap between the top of the mold to the top of the porous stone was about 0.8 cm allowing enough volume expansion and shrinkage of samples. Additionally, filter papers were placed between the specimen and porous stones to prevent stones from clogging and the migration of fine particles from the soil sample.

Fig. 5 shows scenes after placement of specimen (a), filter papers (b), and porous stones (c). The whole mold was then placed between two hollowed polycarbonate plates and secured using four bolts. Two hollowed polycarbonate plates are designed to allow air/water infiltration into and out of the soil sample. Fig. 6 shows the samples in the weathering mold ready for experiencing wet-dry and wet-freeze-thaw-dry weathering cycles.

For the wet-dry condition, a cycle of weathering was initiated by first placing the samples in the water bath at room temperature for 24 hours and then keeping them in the oven for 24 hours with a temperature of 75°C. Then the process was repeated according to the required number of weathering cycles. For the wet-freeze-thaw-dry condition,

the samples were placed in the water bath for 24 hours, placed in the freezer at -18°C for 24 hours, then followed by a thaw and drying cycles in the oven 75°C for 24 hours. Four different weathering cycles, including 2, 4, 8, and 16, were chosen to study the effect of weathering cycles on the strength of soil samples. It was also noted that one set of samples called the “unweathered” group was tested for dedicated samples without applying any weathering cycles.

3.2 Testing

A total of 108 specimens were tested, considering two replicates for each group of samples. These included the specimens treated with Xanthan, Gellan, and untreated samples. After applying the designated weathering cycles to each set of samples, the strength of soil samples was determined based on the conventional direct shear test (ASTM D3080). Then, six hours wetting period was allowed before conducting the direct shear tests to create wet and low strength conditions. The samples with no weathering cycles were also placed in the water bath for six hours before testing to reach a similar moisture content level to weathered samples.

Extra samples just for measuring moisture content were also prepared in addition to the samples for strength measurement and subjected to the same weathering cycles as the other samples. Then, the moisture content was measured according to ASTM D2216-19. Instead of taking the weight of a small amount of soil, this study took the weight of the whole sample for moisture content measurement to enhance the accuracy. A summary of the measurement results of samples was shown in Table 1.

Columns 4 and 5 of Table 1 show that the water content of samples before testing did not vary much among samples treated with different biopolymers. It implicitly means that the moisture absorbing and evaporating characteristics of samples were little affected by the biopolymer contents, consistency of soils, and the number of weathering cycles.

For direct shear tests, porous stones were removed from the weathering mold, and then soil specimens were removed from the weathering molds and placed into the shear box. A 20 kPa normal stress was selected and kept constant during the test. This much stress was intended to simulate the behavior of soils in shallow depth (≈ 1.1 to 1.4 m). A constant shear displacement rate of 0.25 mm/min was applied until the failure of samples.

4. Direct shear test results

4.1 Glacial tills

Fig. 7(a) compared the weathering resistance of glacial till samples for wet-dry cycles and wet-freeze-thaw-dry cycles. The figure shows that the shear strength for untreated samples was gradually but substantially reduced as the number of weathering cycles increased. The direct shear test results at 16 weathering cycles were not obtained due to the fragility of samples – samples failed by themselves during the handling process after 16 weathering cycles.

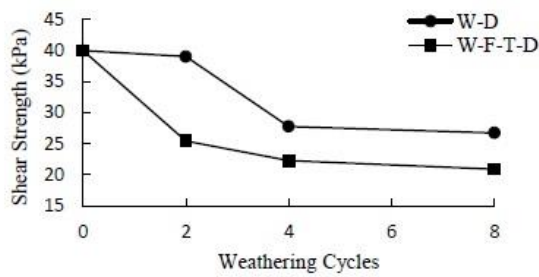
Table 1 Summary of test samples

| Biopolymer | Weathering condition | No of weathering cycles | Avg. moisture content % at test* | |
|------------|----------------------|-------------------------|----------------------------------|---------------|
| | | | Glacial tills | Crushed shale |
| None | wet-dry | 0 | 51.8 | 47.2 |
| None | wet-dry | 2 | 49.1 | 50.9 |
| None | wet-dry | 4 | 50.5 | 52.9 |
| None | wet-dry | 8 | 53.0 | 53.7 |
| None | wet-freeze-thaw-dry | 0 | 48.2 | 49.9 |
| None | wet-freeze-thaw-dry | 2 | 51.5 | 51.5 |
| None | wet-freeze-thaw-dry | 4 | 49.3 | 53.4 |
| None | wet-freeze-thaw-dry | 8 | 52.7 | 52.9 |
| Xanthan | wet-dry | 0 | 47.9 | 50.6 |
| Xanthan | wet-dry | 2 | 50.9 | 49.8 |
| Xanthan | wet-dry | 4 | 48.8 | 52.3 |
| Xanthan | wet-dry | 8 | 51.4 | 52.1 |
| Xanthan | wet-dry | 16 | 53.2 | 54.0 |
| Xanthan | wet-freeze-thaw-dry | 0 | 50.9 | 51.2 |
| Xanthan | wet-freeze-thaw-dry | 2 | 49.9 | 53.6 |
| Xanthan | wet-freeze-thaw-dry | 4 | 52.7 | 53.1 |
| Xanthan | wet-freeze-thaw-dry | 8 | 53.9 | 52.9 |
| Xanthan | wet-freeze-thaw-dry | 16 | 52.8 | 52.4 |
| Gellan | wet-dry | 0 | 48.6 | 51.0 |
| Gellan | wet-dry | 2 | 48.9 | 53.8 |
| Gellan | wet-dry | 4 | 50.4 | 52.1 |
| Gellan | wet-dry | 8 | 52.3 | 49.2 |
| Gellan | wet-dry | 16 | 51.9 | 50.1 |
| Gellan | wet-freeze-thaw-dry | 0 | 50.5 | 51.1 |
| Gellan | wet-freeze-thaw-dry | 2 | 52.1 | 53.7 |
| Gellan | wet-freeze-thaw-dry | 4 | 53.8 | 49.6 |
| Gellan | wet-freeze-thaw-dry | 8 | 50.9 | 49.9 |
| Gellan | wet-freeze-thaw-dry | 16 | 52.1 | 51.5 |

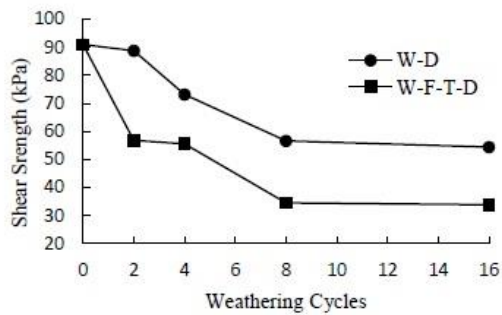
* Initial moisture content was 19.5% and 20.1% for glacial tills and crushed shales, respectively

The shear strength degradation after wet-freeze-thaw-dry cycles was much severer than that after wet-dry cycles. Shear strength of glacial tills after 8 weathering cycles was 26 kPa for wet-dry cycles, while it was 20 kPa for samples of wet-freeze-thaw-dry cycles. Compared to the initial shear strength, 40 kPa, these weathered shear strengths were only 62% and 50% of the initial one.

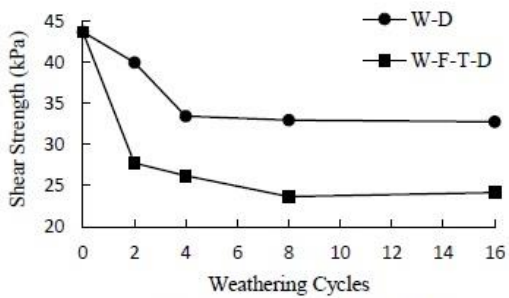
In addition, it was also noted that the shear strength was significantly reduced just after two weathering cycles for wet-freeze-thaw-dry cycles. In comparison, it was negligible for two wet-dry cycles, manifesting the destructive nature of freeze-thaw cycles.



(a) Untreated Glacial Tills



(b) Xanthan Treated Glacial Tills



(c) Gellan Treated Glacial Tills

Fig. 7 Direct shear test results for (a): Untreated Glacial Tills (b) Xanthan Treated Glacial Tills (c) Gellan Treated Glacial Tills

Xanthan treated glacial tills, on the other hand, showed much-improved shear strength, as shown in Fig. 7(b). The unweathered shear strength turned out to be 90 kPa while it was 40 kPa for untreated samples. Overall strength reduction with the number of weathering cycles was similar to the untreated samples by showing the lower wet-freeze-thaw-dry strength than the wet-dry strength. However, it showed that the shear strength after 16 cycles of wet-dry was 56 KPa, which was still close to 140% of the unweathered strength of the untreated specimen. After 16 cycles of wet-freeze- thaw-dry, the shear strength was 35 kPa, which was close to 88% of the unweathered strength of the untreated specimen. In addition, it seemed that this much shear strength (35 kPa) was stabilized and maintained from 8 cycles of wet-freeze-thaw-dry to 16 cycles. Gellan treated glacial tills showed slightly improved shear strength compared to the untreated soils, as shown in Fig.7(c). But

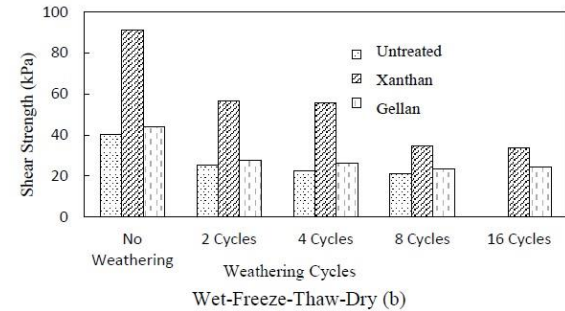
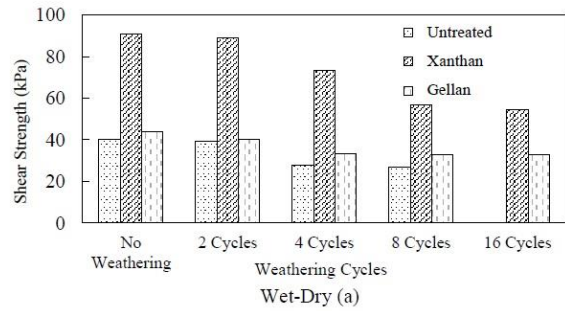


Fig. 8 Direct shear test results for glacial till (a) wet-dry condition (b) wet-freeze-thaw-dry condition

they lasted 16 weathering cycles while untreated soils could not survive these high weathering cycles.

Fig. 8 graphically compared the relative effectiveness of Xanthan and Gellan based on the same data as in Fig. 7. Fig. 8(a) was for the wet-dry weathering condition, and it showed that Xanthan provided much higher shear strength than the unweathered and untreated sample. Fig. 8(b) was for the wet-freeze-thaw-dry weathering condition, and it showed that the strength degradation was higher than that in the case of wet-dry weathering conditions. However, the weathered strength after 16 wet-freeze-thaw-dry cycles were still approximately 82 percent of the unweathered strength of the untreated sample. In the meantime, Gellan showed only marginal strength increase.

4.2 Crushed shales

Fig. 9 compared the weathering resistance of crushed shales for wet-dry and wet-freeze-thaw-dry cycles. Fig. 9(a) showed an apparent reduction in shear strength as the number of weathering cycles increased. Test results after 16 weathering cycles were not obtained due to the fragileness of samples – samples failed by themselves during handling after 16 weathering cycles, similar to cases in glacial tills.

The shear strength of crushed shales after 8 weathering cycles was 24 kPa for samples of wet-freeze-thaw-dry cycles, while it was 32 kPa for wet-dry cycles. These numbers are about 60% and 74% of the shear strength of untreated and unweathered conditions. In addition, the shear strength was significantly reduced from the second weathering cycle for wet-freeze-thaw-dry, while the reduction was not very severe after two wet-dry cycles. This behavior was consistent with the cases for glacial tills.

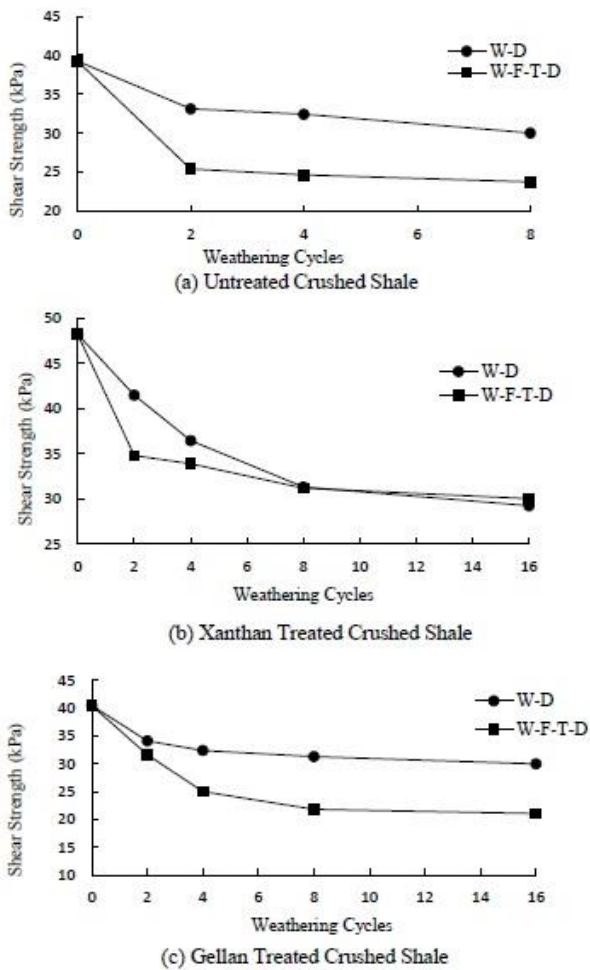


Fig. 9 Direct shear test results for crushed shale

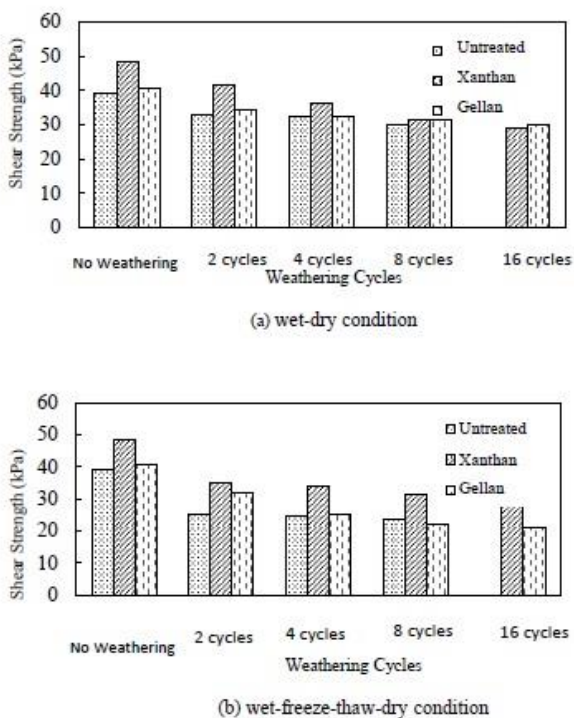


Fig. 10 Direct shear test results for crushed shale

Xanthan treated crushed shales, on the other hand, showed improved shear strength, as shown in Fig. 9(b). The unweathered shear strength was slightly increased to 47 kPa while it was 40 kPa for untreated samples. This time, the difference of weathered strength of Xanthan treated samples between wet-dry and wet-freeze-thaw-dry cycles was not substantial, particularly at high weathering cycles. The strength after 16 cycles of wet-freeze-thaw-dry or wet-dry was 30 KPa, which was still close to 75% of the unweathered strength of the untreated specimen. And it seemed like this much shear strength (30 kPa) was stabilized and maintained from 8 cycles of wet-freeze-thaw-dry to 16 cycles, similar to the trend shown in the glacial tills.

Gellan treated unweathered crushed shales showed improved shear strength, as shown in Fig. 9(c). However, the improvement effect after wet-freeze-thaw-dry cycles was slightly lower than Xanthan's effect, similar to the case for glacial tills.

4.3 Cross comparison of Xanthan and Gellan

Fig. 10(a) showed that Xanthan provided higher than or similar to the shear strength of the Gellan treated crushed shales for wet-dry weathering cycles. Fig. 10(b), however, showed that Xanthan provided consistently higher shear strength for the wet-freeze-thaw-dry weathering condition. Notably, the weathered strength after 16 cycles was still approximately 75 percent of the unweathered strength of untreated samples. Particularly, Gellan treated samples showed lower shear strength even than untreated samples at 8 wet-freeze-thaw-dry weathering cycles. The exact reason why Xanthan provided better performance than Gellan was beyond the scope of this study. It needs clarification in future studies.

4.4 Discussion

These strength test results showed that eco-friendly biopolymerized soils, particularly with Xanthan, could increase the strength of soils, compensating weathering effect even after 16 severe wet-freeze-thaw-dry cycles. To check the particle level adhesion of biopolymers and soil grains, gradation and Atterberg limit tests were conducted. Gradation in Fig. 11 showed that there was no substantial change in gradation curves for biopolymer treated glacial tills and untreated glacial tills, implying that biopolymer bonding might be almost completely broken down and washed away during crushing and water bathing period for sieve analysis and hydrometer analysis. Similar test results were obtained for crushed shales.

Contrary to the gradation test results that required the washing out process, the Atterberg limit test results in Table 2 showed that all three parameters - liquid limit, plastic limit, and plasticity index, were substantially increased. The results indicated that the biopolymer treated soils could maintain the high consistency even at much higher moisture content. From a different aspect, it may mean that biopolymerized soils could maintain tighter bonding than untreated soils at the same moisture content, resulting in

higher strength which supports the strength enhancement effect in test results

Another notable result in Table 2 was 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 ($\approx 70\%$) than glacial tills ($\approx 26\%$). A secondary test for 1.5% Gellan content samples resulted in practically identical results. Recalling that the strength increased for 1.5% Gellan content glacial tills was strangely low in Fig. 7(c), the behavior of glacial tills with 1.5% Gellan was an outlier with reasons needing further research.

Combining Fig. 11 and Table 2, it showed that a small amount of biopolymer mixed in soils would greatly enhance the consistency of soils and increase the shear strength. At the same time, the bonds between soil grains and biopolymers were not irreversible bonds but reversible ones. Supplying enough water might wash out biopolymer bonds. The latter result was desirable because it represented that the biopolymers could improve soil strength when they stayed in the pore space and interacted with pore water. Still, they could be removed by water-flushing, nullifying the hydrophilic potential when needed.

This research showed promising results for using biopolymers to improve fine grained soils found in Mid-Western states in US. However, it also showed that one biopolymer worked better than the other for soils in this study, though different studies (Ayeldeen *et al.* 2016) showed different results. The background science for this complicated behavior was researched (Chang *et al.* 2015a, b, c), but the extremely complicated nature of biopolymers still prohibited the emergency of a widely accepted field construction specification. Some examples include the research on the application method (dry application and wet application as reported by Seo *et al.*, 2021), compaction equipment (smooth roller, sheep foot roller, vibration roller or pneumatic tires), and compaction moisture content (optimum moisture content of field soils, or that of field soil and biopolymer mixture).

5. Conclusions

This study evaluated the behavior of glacial tills and crushed shales mixed with two types of biopolymers; Xanthan and Gellan, at 1.5% by weight concentration. The samples were subjected to two types of weathering cycles, “wet-dry” and “wet-freeze-thaw-dry” up to 16 cycles to investigate the effects of weathering cycles on the durability of samples, and the following conclusions were obtained:

- Results for glacial tills showed that Xanthan might become a good candidate for soil modification agent to compensate for strength loss due to weathering. The glacial tills treated with 1.5% (by dry weight) Xanthan maintained 88% initial shear strength of untreated soils after 16 weathering cycles. The same soil treated with 1.5% (by dry weight) Gellan showed similar results, but the improvement effect was not as significant as that for Xanthan.

- Similar results were obtained for crushed shales. Xanthan maintained approximately 75% initial shear strength of untreated soils after 16 weathering cycles. Overall improvement effect of glacial tills was not as good as that of Xanthan for soils in this study.
- In overall, Xanthan provided a good weathering durability both for glacial tills and crushed shales.
- The application of biopolymers altered the consistency of soils substantially. Still, it did not alter the gradation of soils in a measurable amount, indicating that biopolymers could also be washed out when needed by flushing it with water, an eco-friendly feature.

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