Biopolymer-Stabilized Earth Materials for Resilient and Adaptable Infrastructures

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Project Title

Biopolymer-Stabilized Earth Materials for Resilient and Adaptable Infrastructures

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Final Report

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1. EXECUTIVE SUMMARY

Earth dams and levees are constructed and retrofitted nowadays using the same materials that were used in the past, clays and sands. Despite the current advances in engineering, designing and constructing these critical infrastructure, earthen dams and levees continue to suffer from the same challenges over the years. These challenges include internal and surface erosions, loss of stability due to moisture migration, and inability to self-heal potential failure points. This project focuses on the use of biopolymers as additives to strengthen earthen dams and levees targeting an overall increase in their resilience.

Explicitly, the report for Milestone 3 presented the results of an experimental program aiming to assess the impacts of biopolymers on the physical and mechanical properties of the typical materials used in the construction of earthen dams and levees: sands and clays. This program focused on determining the impact of biopolymers on (1) the index properties of cohesive soils as an easy way to assess the biopolymer impacts on the strength of these soils, (2) the compaction characteristics of sands and clays, and (3) the shear strength of sands and clays treated with biopolymers. Additionally, the report explains the observed behavior of the soils treated with biopolymers using known biopolymer responses and properties (i.e., viscosity).

The results of the experiments performed on the considered clayey soil showed that biopolymer treatment increases the plastic and liquid limits of the clay. Such increase in Atterberg limits is found to be independent of the used biopolymer type and percentage, which indicates that all biopolymer treatments for clays have the ability to increase their strength. In fact, the strength of the clay treated with biopolymers was found to increase significantly compared to that of the pure clay as evident by the unconfined strength of compacted clay samples.

Additionally, the report discusses a practical approach to overcome the reduction in the shear strength of sandy soils when treated with pure biopolymers. This technique relies on stabilizing the biopolymers with clay fillers prior to mixing them with or injecting to the sand. The results of the triaxial experiments performed here prove that the magnitude of the strength gain in sandy soils treated with biopolymer-filler composites depends on the filler type, percentage and interaction with the used biopolymer. For a given filler type, it is noticed that increasing the viscosity of the biopolymer-filler composite reduces the internal friction angle but increases the cohesion between the sand grains.

This current report presents the results of advanced molecular dynamics simulations and experimental program to assess the biodegradability of biopolymers used for soil stabilization. The focus of these models and experiments are on coarse-grained soils stabilized with biopolymers since the pore structure in fine-grained soils prevents the growth of any micro-organisms that may consume the biopolymers. The main conclusion of these numerical models and experimental program is that the biodegradability of biopolymers used to stabilized soils is not significant. The
advanced molecular dynamics models showed that even at 50% degradation in the biopolymers, the viscosity of the biopolymer was reduced by 23%. This reduction is not considered significant since the initial viscosity is significantly higher than that of the pore water in untreated specimens. The experimental program, then, confirmed the finding of the numerical modeling as the experiments showed no significant reduction in the unconfined compressive strength of sand specimens treated with various xanthan gum-clay composites even after aging for 9 months.
2. POTENTIAL BIOPOLYMER FAMILIES FOR SOIL STABILIZATION

Biopolymers are polymeric materials that are produced by living microorganisms. They are composed of a repeated structure of bonded monomer units forming the main backbone chain, with or without branching units. The current uses of biopolymers extend to several disciplines including medical materials, packing, food additives, clothing, chemicals for water treatment, biosensors, and data storage [1].

There are a large number of naturally existing biopolymers which can also be manufactured for various uses. For practical reasons, it is very critical to narrow down the selection to a few of these biopolymers to be used in the experimental and numerical work planned for this project and in field implementation in the future. The adopted approach to identify the most promising biopolymers for soil stabilization considers biopolymer properties, natural bioavailability, our ability to produce the selected biopolymer in large quantities, and production costs. While biopolymer toxicity is an essential factor in the selection process, it does not form a viable concern since biopolymers are produced by natural micro-organisms and are decomposed to natural chemical compounds eliminating any potential soil or groundwater toxicity concerns.

Biopolymers are classified based on their compositional backbone chain or their source (e.g., bacterial, plant, etc.). The former classification is adopted since this project focuses on the practical use of biopolymers to stabilize soils rather than the explicit source of biopolymers. The compositional classification of biopolymers includes three main families [2]:

1) **Natural polyesters**, such as polyhydroxyalkanoates (PHAs) and polylactic acid, are given significant attention nowadays since they are considered biodegradable plastics. These natural polyesters are currently being used to replace oil-based synthetic rubbers and plastics [3]. Moreover, natural polyesters are being used in several medical applications since they degrade to normal constituents in human blood [2]. However, the current production cost of these natural biopolymers is relatively higher than other biopolymer types, which would limit their use for geoengineering applications.

2) **Proteins** represent the second biopolymer family considered in this study. Amino acids form the main composition of all proteins, with the type and sequence of the amino acids differentiate one protein from the other. Examples of protein biopolymers include, among others, silks, soy, adhesin, collagen, gelatin, elastin, wheat gluten, and polyamino acids. These proteins can be extracted from animals (e.g., collagen) or plants (e.g., soy). Protein biopolymers are currently being used as coatings and adhesives, membrane separators, and medical and optical materials. [4]. Similar to natural polyesters, producing protein biopolymers is extremely costly limiting any potential use of this biopolymer family for enhancing earth materials.

3) **Polysaccharides** which are sugar-based biopolymers that are found in all living
organisms [5]. Since polysaccharides represent one of the most important fractions in soil organic matter [6, 7], they are considered the most suitable biopolymer family to stabilize soils. Moreover, the cost-effectiveness of producing large quantities of different types of polysaccharides biopolymers [8] makes this biopolymer family more attractive for practical use in geoengineering compared to the other two biopolymer families.
3. BACKGROUND

As stated in the previous section, the polysaccharides family is believed to be the most promising biopolymers family for geoengineering applications. Polysaccharides biopolymers are produced by different types of bacteria, fungal, plants and algal, and animals. Thus, polysaccharides biopolymers are typically distinguished by their producer as shown in Table 1.

Table 1. Examples of polysaccharides biopolymers categorized by their main producer [4]

<table>
<thead>
<tr>
<th>Bacterial Polysaccharides</th>
<th>Plants/Algal Polysaccharides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xanthan</td>
<td>Starch</td>
</tr>
<tr>
<td>Dextran</td>
<td>Cellulose</td>
</tr>
<tr>
<td>Gellan</td>
<td>Agar</td>
</tr>
<tr>
<td>Levan</td>
<td>Alginate</td>
</tr>
<tr>
<td>Curd ian</td>
<td>Guar</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Animal Polysaccharides</td>
</tr>
<tr>
<td></td>
<td>Chitin/Chitosan</td>
</tr>
<tr>
<td></td>
<td>Hyaluronic acid</td>
</tr>
<tr>
<td></td>
<td>Natural rubber</td>
</tr>
<tr>
<td></td>
<td>Polyphenols (e.g., Lignin, Tannin)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fungal Polysaccharides</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pullulan</td>
<td></td>
</tr>
<tr>
<td>Elsinan</td>
<td></td>
</tr>
<tr>
<td>Yeast glucans</td>
<td></td>
</tr>
</tbody>
</table>

Despite the producing microorganism, polysaccharides biopolymers may have no charge (i.e., non-ionic), negative net charge (i.e., anionic), or positive net charge (i.e., cationic). The net charge of biopolymers is a critical factor that must be considered for geoengineering applications; it is in fact more critical than the source of the biopolymer. The importance of the biopolymer net charge comes from the direct impact of this charge on the amount and strength of the biopolymer adsorption to the surfaces of soil particles. Uncharged biopolymers, for instance, are attracted to soil particles mainly through ion-dipole and van der Waals interactions [9]. On the other hand, the attraction of charged biopolymers (anionic and cationic) to soil particles occurs due to coulombic interactions [10]. Cationic biopolymers, for example, are attracted to the negatively charged clay particles via cation exchange mechanisms; while ionic biopolymers are repelled from these negatively charged clay particles and thus have less adsorption compared to the cationic biopolymers [9]. Therefore, this study considers the net charge of the soil particles when selecting the most appropriate biopolymer to enhance the mechanical properties of a given soil.

Previous uses of biopolymers in geotechnical engineering covers a wide range of applications including undisturbed soil sampling [11-13], forming impervious barriers [14-17], strengthening soils with more focus on the dry state [18-24], controlling soil erosion [25], stabilizing drilled holes and temporary excavations [26], resisting liquefaction [26, 27], reducing volume changes in problematic soils [28, 29], improving slope stability and reducing sediment losses in water runoff [30], preventing piping of earth dams [31], and mitigating the migration of heavy metals in
the ground [32]. Collectively, the results of these past studies can be summarized as below:

(1) The ability of biopolymers to enhance soil properties depends on many factors including the soil and biopolymer types, biopolymer-soil compatibility, biopolymer dose, moisture content, and mixing procedure. Previous studies adopted trial-and-error approaches to identifying biopolymers with promising abilities to improve different soils, rather than methods based on understandings of basic biopolymer-soil interactions.

(2) Wetting-drying cycles and associated volumetric changes impact soils mixed with biopolymers. Currently, there is no viable mean to predict and control these wetting-drying volumetric changes for soils treated with biopolymers.

(3) The ultimate lifetime of soils stabilized with different types of biopolymers is currently unknown. Furthermore, critical factors contributing to the degradability process of biopolymers are not known. Recognizing these factors and bounding their limits will facilitate robust design of biopolymer stabilized soil.
4. STRENGTH OF BIOPOLYMER STABILIZED SOILS

4.1. Overview

This chapter focuses on assessing the physical and mechanical properties of soils treated with biopolymers. These properties include index properties, compaction characteristics, and shear strength. Moreover, this chapter concludes with a discussion about the practical implications of the improved soil properties with a focus on earthen dams. First, the various materials used in the experimental program are presented. Then, the methods used for the preparation of the different samples and testing procedures are described. Finally, the experimental results, their underlying mechanisms, and practical implications are discussed.

4.2. Materials

This section presents the physical properties of the materials used in the experimental program for this study. These materials include the used biopolymer, one soil exemplifying the response of fine-grained soil treated with the considered biopolymer, another soil exemplifying the effect of the biopolymer on coarse-grained soils, and the clay fillers used to stabilize the biopolymer prior to treating the coarse-grained soil.

4.2.1. Eagle Plastic Kaolin (EPK) Clay

The Edgar Plastic Kaolin (EPK) from Edgar, FL was used in this study as an example of fine-grained soils. This kaolin clay has 100% of its particles finer than 25 μm as determined using sedimentation (hydrometer) analysis according to ASTM D7928-17 (Figure 1). Additionally, more than 96% of the minerals in this clay were identified as kaolinite minerals using x-ray diffraction on the clay powder (Figure 2). The plastic and liquid limits of the EPK clay are 32% and 67%, respectively. Thus, it classifies as high plasticity fat clay (CH) according to the unified soil classification system (USCS).

![Figure 1. Particle size distribution of the EPK clay used in this study.](image-url)
4.2.2. Carver sand

The sand used in this study was acquired from a coring mine between Brentwood and Islip, NY. This sand is the Carver sand that belongs to the outwash plain of the Riverhead-Plymouth-Carver association of Long Island [33]. 100% of the Carver sand particles are smaller than 2 mm (i.e., sieve size 10); it contains less than 1% fines passing sieve #200, as shown in Figure 3. Additionally, Table 2 presents the particle gradation information for the Carver sand. Based on this information, the Carver sand classifies as poorly graded sand (SP) according to the Unified Soil Classification System (USCS).

Before using this sand in the strength experiments reported in this chapter, it was washed using de-ionized water on sieve #200 then it was oven-dried for 24 hours.
This cleaning process is critical to ensure that the sand is free of any fines other than those selectively added to enhance the biopolymer, if any. Moreover, the washing process ensures that the sand does not contain any micro-organisms that may degrade the used biopolymers (see Chapter 5). Thus, the impact of the type and quantity of the biopolymer and fines used in the experiments on the results can be accurately assessed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D10</td>
<td>0.28 mm</td>
</tr>
<tr>
<td>D60</td>
<td>0.40 mm</td>
</tr>
<tr>
<td>Average particle size (D50)</td>
<td>0.45 mm</td>
</tr>
<tr>
<td>D90</td>
<td>0.52 mm</td>
</tr>
<tr>
<td>Coefficient of uniformity (Cu)</td>
<td>1.86</td>
</tr>
<tr>
<td>Coefficient of gradation (Cc)</td>
<td>1.10</td>
</tr>
</tbody>
</table>

4.2.3. Biopolymer

The main biopolymer used in this project was xanthan gum, which is a polysaccharides biopolymer naturally produced by fermentation using the Xanthomonas campestris bacteria [34]. Xanthan gum was selected as the model biopolymer for this project because: (1) it is commercially available at a competitive cost for large scale implementation of biopolymer treated soils upon the success of this project. (2) it is approved to be used for food and agriculture uses in the US, which will facilitate its incorporation into earthen structures without imposing contamination or health related concerns. And (3) its behavior is well investigated, understood, and documented in the literature simplifying the interpretations of the experimental results. The xanthan gum used in this study is a food grade purchased from Judee’s. The rheological properties of this biopolymer are assessed following the method in Section 4.4.1 with the properties presented in Section 4.5.1.

Two other biopolymers were also considered in this study to determine the impact of the biopolymer type on the soil response. These two biopolymers were Locust Bean Gum (LBG) and Gellan Gum (GG). The two biopolymers were purchased from Judee’s. These two biopolymers were selected to identify the impact of a non-charged biopolymer (i.e., LBG) and a biopolymer with a relatively high negative charge (i.e., GG) compared to this of the xanthan gum.

4.2.4. Clay fillers

Two clays were used as fillers to stabilize xanthan gum in this study; these are a montmorillonite clay and a halloysite clay. These two clays were selected for this study to quantify the impact of the filler’s minerology, morphology, and surface area on the response of the sand stabilized with the resulting xanthan gum/clay composite. Additionally, montmorillonite and halloysite clays exemplify the most commonly
used fillers for producing biopolymer-clay composites for other applications [35].

The montmorillonite clay was acquired from Honeydew Products with a commercial name of “100% pure bentonite clay”. The origin of this clay is Crook Country, Wyoming, USA. It includes 43% Cesium (Cs)-based montmorillonite clay mineral, 27% Lithium (Li)-based montmorillonite clay mineral, and 30% Zeolite minerals as revealed by the x-ray powder diffraction in Figure 4.a. The particles of this montmorillonite have a plate-like shape (Figure 5.a) with a 1 μm maximum particle size. A typical surface area of this montmorillonite clay exceeds 650 m²/gm [36].

The halloysite clay used in this study was acquired from applied minerals under a commercial name of “Dragonite-HP”. The composition of this clay is the same as that of a kaolinite clay mineral (Figure 4.b) except that the particles of the halloysite clay have a hollow tubular shape (Figure 5.b) due to lattice mismatch between adjacent silica and aluminum layers. The diameter of the halloysite tubes is typically less than 100 nm, while the lengths of the tubes range from 200 nm to 2 μm [37]. The surface area of this halloysite clay ranges between 35-65 m²/gm.

![Figure 4. X-ray diffraction patterns for the used clay fillers (a) montmorillonite clay and (b) halloysite clay.](image)

![Figure 5. Scanning electron microscopy (SEM) images for the used clay fillers (a) montmorillonite clay and (b) halloysite clay.](image)
4.3. Sample Preparation Methods

Two techniques were typically used to mix soils with biopolymers: dry and wet mixing [38, 39]. The dry mixing relies on initially mixing the dry biopolymer powder, the dry clay filler (if used), and the dry soil; then, the desired amount of water is added. While the wet mixing starts with forming a biopolymer solution (with or without a clay filler) by mixing the biopolymer, and the clay filler (if used), with water. After that, the biopolymer solution is mixed with the soil. In this study, the wet mixing procedure was adopted because (1) it appears to be the most practical procedure to mixing, or injecting, in-situ soils. In fact, the injection of polymerized solutions in soils is currently adopted, for example, in microbially-induced calcite precipitation (MICP) [40]. (2) It ensures effective polymerization of the raw biopolymer powder and enhances biopolymer-filler interactions. On this front, it should be noticed that preliminary experiments performed using the dry mixing method showed no significant impact of the fillers on the soil response. And (3) it allows full control of the water content during mixing ensuring uniform moisture distribution in the samples or in-situ soil layers.

4.3.1. Polymerization process

For pure xanthan gum mixtures, the desired quantity of xanthan gum powder was mixed with de-ionized water using a commercial food mixer (Black and Decker PowerCrush, 900W). Mixtures of xanthan gum-clay composites started with mixing the selected amount of the clay filler with de-ionized water using the same food mixer, then the xanthan gum was slowly added. It should be noticed that advanced polymerization processes using magnetic stirrers, with or without temperature control, was not adopted in this study because, despite their better polymerization results, they are not practical for field applications. The addition of xanthan gum powder, to the de-ionized water in the former mix and to the clay-water colloid in the latter mix, was done at a slow steady rate (~0.2 x 10^3 kg/min.) to avoid aggregation and ensure an even dispersion of the gum in the clay mixture. Mixing was performed initially at the mixer’s minimum speed, which was increased as the xanthan gum percentage increases to overcome the increase in the mixtures’ viscosity. Additionally, the temperature of the mixtures was carefully monitored to ensure that mixing was always performed at room temperature except when a higher mixing temperature was desired.

4.3.2. Biopolymer-soil mixtures

The quantities of the different components were based on the total mass of the soil needed to fill a standard Proctor compaction mold (~2 kg), where the initial bulk samples were prepared as discussed later. Two xanthan gum percentages, with respect to the dry mass of the soil, were used in this study: 0.5% and 1% corresponding to about 10 gm and 20 gm xanthan gum per compaction mold, respectively. These percentages were selected based on previous studies in the literature that suggested an optimum biopolymer percentage ranging between 0.5 and 2% [41, 42].
a. **Mixtures with EPK clay.** The used kaolin specimens were compacted inside a 33 mm diameter and a 71 mm height compaction mold. The inner surface of the compaction mold was greased to easy the sample extraction process. The dry mass of the EPK clay powder was back-calculated from the volume of the compaction mold targeting a dry unit weight of 12.65 ± 0.3 kN/m³ corresponding to the maximum dry unit weight for the pure and treated clay (see Section 4.5.2.b). The water contents used during the compaction process correspond to the optimum moisture content of each mixture, with or without biopolymer, to mimic the expected field construction procedures. As discussed in Section 4.5.2.b, the pure EPK clay has an optimum moisture content of 27%, while the optimum moisture content for the same clay treated with xanthan gum is 35%. Thus, the water contents used for compacting the pure EPK clay samples and the treated clay samples were 27% and 35%, respectively.

The desired clay powder was mixed with distilled water or with the biopolymer-water solution prepared following the polymerization process in Section 4.3.1. The resulting wet clay was then placed gradually in the compaction mold in 10 layers. Each layer was compacted with a steel hammer until no kaolin-water clumps were seen, and until a smooth clay surface was obtained. The surface of each layer was scratched before placing the following layer to eliminate any wake planes within the samples. At the end of the compaction process, the samples were extracted out of the mold and trimmed to ensure 2:1 length-to-diameter ratio for unconfined testing. Initial moisture contents of the compacted clay samples were measured from the trimmings, which were used to quality control the dry unit weight. The final moisture contents of the samples were measured after finishing the unconfined tests, which were found to agree well with the initial measurements.

b. **Mixtures with Carver sand.**

A total of 280 gm of water was used during the polymerization of xanthan gum for all sand mixtures. This water quantity ensures that sand samples have an initial moisture content of 14%, which is the average optimum moisture content for the used sand when treated with various xanthan gum polymer mixtures in a standard Proctor test as discussed later. In addition to testing sand with pure xanthan gum, xanthan gum mixtures with the two considered clay fillers (i.e., montmorillonite and halloysite) at three masses (2, 5, and 10 gm) were used in this study. These masses correspond to filler percentages of 10%, 25%, and 50%, respectively, with respect to the used xanthan gum dry mass (20 gm). It should be mentioned that the impact of the clay filler type and percentage on the optimum moisture content and maximum dry unit weight of the treated carver sand was found to be insignificant as discussed later. Table 3 presents a summary of the xanthan gum treatments used for the sand in this chapter.

Xanthan gum and clay fillers, if used, were first polymerized following the polymerization process mentioned earlier. Then, the carver sand was thoroughly mixed with the various xanthan gum biopolymer mixtures using a stand mixer (Waring commercial, 7qt) operating at its slowest speed to prevent entrapping
excessive air voids. After mixing, bulk samples of the sand treated with the different biopolymer composites were compacted following the standard Proctor test Method A of ASTM D 698 [43]. The bulk samples were compacted to the optimum moisture content (± 14 ± 1.5%) of the carver sand treated with xanthan gum targeting a maximum dry unit weight of about 16.75 ± 0.25 kN/m³ as discussed later.

**Table 3. Xanthan gum treatments used in this study to stabilize carver sand.**

<table>
<thead>
<tr>
<th>Treatment reference ¹</th>
<th>Filler type</th>
<th>Filler percentage ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Sand</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>XG</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>XG + 10% Montmorillonite</td>
<td>Montmorillonite</td>
<td>10%</td>
</tr>
<tr>
<td>XG + 25% Montmorillonite</td>
<td>Montmorillonite</td>
<td>25%</td>
</tr>
<tr>
<td>XG + 50% Montmorillonite</td>
<td>Montmorillonite</td>
<td>50%</td>
</tr>
<tr>
<td>XG + 10% Halloysite</td>
<td>Halloysite</td>
<td>10%</td>
</tr>
<tr>
<td>XG + 25% Halloysite</td>
<td>Halloysite</td>
<td>25%</td>
</tr>
<tr>
<td>XG + 50% Halloysite</td>
<td>Halloysite</td>
<td>50%</td>
</tr>
</tbody>
</table>

¹ All XG treatments were based on 1% XG with respect to the dry mass of the carver sand.
² All filler percentages refer to the dry mass of the XG used in the experiments.
³ No clay filler.

### 4.4. Testing Methods

#### 4.4.1. Biopolymer characterization

De-ionized water-based dilute solutions with a total concentration of 0.005 gm solid particles per 1 gm of water were produced. The solids in these solutions were either the pure xanthan gum for mixtures without clay fillers, or xanthan gum and clay filler particles at the desired weight-based ratios shown in Table 3. For a uniform and homogeneous mix, the solutions were placed in a VWR incubating waver at 50 °C with a wave rate of 15 rpm. After two hours of incubation, gel-like solutions were formed which were used for the rheological measurements. All viscosity measurements were performed using a cone-plate geometry in a Bohlin Gemini HR Nano rheometer from Malvern instruments. The viscosity was measured as a function of the shearing rate. For shear rate dependence, the viscosities of the solutions were measured using a frequency sweep from 10⁻³ to 0.5 Hz at room temperature.

#### 4.4.2. Soil characterization

- **Atterberg limits for EPK clay.** A simple and quick assessment of the behavior of cohesive soils is typically performed using Atterberg limits, with especial focus on the plastic and liquid limits. These limits highly depend on the chemistry of pore fluid [44], which is altered when biopolymers are used. Thus, Atterberg limits were first determined, according to ASTM D4318 [45], for the pure clay with no biopolymers which was used as a base reference. Then, Atterberg limits were determined for each
clay-biopolymer mixture. In addition to xanthan gum biopolymer, which is the focus of this study, Atterberg limits for the EPK clay treated with other biopolymers were measured as shown in Table 4. These additional measurements aim to better understand the interaction between different biopolymers and the clay and justify the focus of xanthan gum as a representative biopolymer as discussed later.

Table 4. Different biopolymer mixtures used for Atterberg limits measurements.

<table>
<thead>
<tr>
<th>Mixture #</th>
<th>Primary biopolymer Type (%)</th>
<th>Secondary filler Type (%)</th>
<th>Mixing conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--³</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>XG⁴ 0.5</td>
<td>--</td>
<td>20 °C</td>
</tr>
<tr>
<td>3</td>
<td>XG 1</td>
<td>--</td>
<td>20 °C</td>
</tr>
<tr>
<td>4</td>
<td>XG 1</td>
<td>--</td>
<td>80 °C</td>
</tr>
<tr>
<td>5</td>
<td>LBG⁴ 1</td>
<td>--</td>
<td>20 °C</td>
</tr>
<tr>
<td>6</td>
<td>XG 1 Montmorillonite 10</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>XG 1 Montmorillonite 25</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>XG 1 Montmorillonite 50</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>XG 1 Halloysite 10</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>XG 1 Halloysite 25</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>XG 1 Halloysite 50</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>XG 1 LBG 50</td>
<td>45 °C</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>XG 1 Starch 50</td>
<td>20 °C</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>XG 1 GG⁴ 40</td>
<td>20 °C</td>
<td></td>
</tr>
</tbody>
</table>

¹ Primary biopolymer percentages refer to the dry mass of the clay used in the experiments.
² Secondary filler percentages refer to the dry mass of the primary biopolymer.
³ None.
⁴ XG: Xanthan gum; LBG: Locust bean gum, GG: Gellan gum

b. Compaction tests. Adopting the proposed biopolymer-stabilized soils for the construction of earth dams and levees requires identifying the impact of biopolymers on the compaction characteristics of various soils. Thus, a series of standard Proctor compaction tests, following Method A of ASTM D 698 [43], were performed on the two considered soils treated with pure xanthan gum at different percentages as well as the sand stabilized with xanthan gum-clay composites in Table 3.

4.4.3. Shear strength

The main focus of this project is on the use of biopolymer-stabilized soils to increase the resiliency and sustainability of the materials for earth dams and levees. Thus, assessing the shear strength of these soils is an essential part of the project. Therefore, a series of triaxial tests were performed on the two considered soils. These triaxial
experiments included all sand mixtures in Table 3, the pure EPK clay, and the clay treated with 0.5% and 1% xanthan gum. Sand samples were tested after isotropic consolidation under undrained shearing with pore pressure measurements allowing the determination of effective and total strength parameters. While unconfined triaxial tests were used to assess biopolymer effects on the used clay.

The sand samples used for the triaxial tests were compacted to the desired dry unit weight in the standard Proctor compaction mold following the same mixing procedure discussed in Section 4.3.2.b. After compaction, the bulk soil blocks were extracted from the compaction mold. Then, two triaxial samples were trimmed from the center of each bulk block; each sample was 35-mm in diameter and 70-mm in height. Trimming the two samples for each mixture out of the same bulk block was adopted to eliminate potential differences between various bulk sand-biopolymer batches. Each of the samples for a given biopolymer treatment was tested under a different confining stress.

Each of the triaxial sand samples was mounted in a triaxial cell (Trautwein, GeoTace); for this, the samples were enclosed in 0.3-mm Latex membranes and sandwiched between filter papers and porous stones. The ASTM D 4767-11 [46] procedure for consolidated undrained triaxial tests was adopted in this study. In this procedure, a 35 kPa seating pressure was initially applied to the samples followed by an automatic backpressure saturation stage in which water was pushed into the sample from the top and the bottom boundaries under constant effective stress of 35 kPa. The backpressure saturation stage was completed when Skempton’s pore water pressure B-value reached at least 0.97. After that, one sample of each mixture was consolidated under 250 kPa while the other was consolidated under 500 kPa total confining stress. These stresses were selected as they correspond to soil elements at depths of about 15 m (50 ft) and 30 m (100 ft), which represent typical earth dams’ heights. Upon reaching to the end of primary consolidation, undrained shearing at a constant rate of 1.46%/hr. was performed. This shearing rate was determined from the consolidation curve as per the ASTM D 4767-11. Additionally, this selected shearing rate ensures that the viscosity of the various xanthan gum mixtures remain approximately constant. During shearing, the deviatoric stress, axial deformation, and induced pore pressures at the bottom of the same were recorded.

The clay samples used in the unconfined triaxial tests were prepared following the approach in Section 4.3.2.a. After compaction, the samples were tested under unconfined conditions following ASTM [47]. All samples were sheared at a 1%/min. rate. The axial deformation and corresponding axial load were recorded and used to develop the stress-strain curve for each sample. The peak axial stress was used as a failure criterion to estimate the unconfined strength of the soil.

4.5. Results and Discussions

4.5.1. Biopolymer rheological characteristics

The change in the viscosity of the pure xanthan gum solution, corresponding to 1%
xanthan gum in the soil, is presented in Figure 6. As shown in this figure, the viscosity of the xanthan gum solution depends on the shear rate significantly; it reduces exponentially as the shear rate increases. Other than dynamic effects, the expected shearing rate at the particulate level in typical geotechnical applications is very small (≤ 0.1 Hz). Thus, the comparisons between the viscosities of the pure xanthan gum and the gum-filler composites were performed using a semi-logarithmic scale for a reduce shear rate range up to 1 Hz as shown in Figures 7 and 8 for the montmorillonite and halloysite fillers, respectively.

It can be seen in Figures 7 and 8 that the two clay fillers used in this study altered the viscosity of the xanthan gum solution for shear rates less than 0.1 Hz. Since this is the range for typical geotechnical applications, the use of different fillers and filler percentage is expected to impact the soil behavior significantly, as shown in the following sections. At the biopolymer solution level, it is observed in Figure 7 that 10% montmorillonite clay filler caused a slight reduction in the viscosity of the solution at shearing rates less than 0.015 Hz. Beyond this rate, the viscosity of the montmorillonite treated gum was slightly higher than that of the pure gum. On the other hand, xanthan gum solution with 25% montmorillonite filler appears to have about the same viscosity at the pure gum solution at 0.01 Hz, but slightly higher viscosity at higher shear rates. Finally, 50% montmorillonite filler increased the viscosity of xanthan gum solution significantly (Figure 7).

Figure 6. Viscosity evolution versus shear rate for pure xanthan gum solution.

All xanthan gum solutions treated with halloysite clay filler at all percentages have viscosities much higher than that of the pure xanthan gum for shear rates less than 0.1 Hz as shown in Figure 8. At higher shear rates, all solutions merge to the viscosity of the pure xanthan gum curve. Unlike the response with montmorillonite filler, the viscosity of xanthan gum with the halloysite filler increased as the filler
percentage decreased. This filler type-dependent response suggests that the selection of the filler type is a critical aspect to stabilize soils with biopolymers as discussed later.

Figure 7. Comparison between the viscosity-shear rate relations for pure xanthan gum and xanthan gum-montmorillonite solutions.

Figure 8. Comparison between the viscosity-shear rate relations for pure xanthan gum and xanthan gum-halloysite solutions.

A common approach in polymer sciences used to infer the impact of fillers on the viscosity of polymers is to report the viscosity at zero shear by extrapolating the viscosity-shear rate curve to zero shear. For simplicity and since the viscosity of the
used biopolymers at very small shearing rates is believed to control the soil behavior, we adopted this technique. Table 5 presents the viscosity at zero shear rate for all considered xanthan gum solutions, with and without fillers. These viscosities will be used to justify the observed soil behavior in the following sections.

<table>
<thead>
<tr>
<th>Mixture #</th>
<th>Filler Type</th>
<th>Viscosity (kPa·sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--</td>
<td>8.35</td>
</tr>
<tr>
<td>2</td>
<td>Montmorillonite</td>
<td>7.14</td>
</tr>
<tr>
<td>3</td>
<td>Montmorillonite</td>
<td>7.83</td>
</tr>
<tr>
<td>4</td>
<td>Montmorillonite</td>
<td>8.94</td>
</tr>
<tr>
<td>5</td>
<td>Halloysite</td>
<td>14.10</td>
</tr>
<tr>
<td>6</td>
<td>Halloysite</td>
<td>10.96</td>
</tr>
<tr>
<td>7</td>
<td>Halloysite</td>
<td>9.90</td>
</tr>
</tbody>
</table>

4.5.2. Biopolymer effects on soil characteristics

a. Atterberg limits for EPK clay.

The plastic and liquid limits for the considered clay-biopolymer mixtures (Table 4) are presented in Table 6. It can be observed in this table that, regardless of the biopolymer type and percentage, the plastic and liquid limits for the clay treated with biopolymers are higher than the limits for the pure EPK clay. These higher limits indicate that, for a comparable shear strength, the biopolymer-stabilized clays will contain more water compared to the pure clay. For example, the higher plastic limits for the former clays indicate that the water quantity needed to have the biopolymer-treated clays behave plastically, with an approximate undrained shear strength \( (S_u) \) of 170 kN/m\(^2\) [48], is more than that needed to trigger the plastic response in the pure clay. Similarly, the water quantity needed to reduce the strength of biopolymer-stabilized clays to behave as a liquid (i.e., \( S_u = 1.7 \) kN/m\(^2\) [48]) is much higher than that needed to have the same strength in the pure clay. These high-water contents required to change the consistency of the biopolymer-treated clays are attributed to the hydrophilicity of the xanthan gum biopolymer, i.e., the ability of the biopolymer to adsorb water.

Moreover, it appears from Table 6 that the percentage of the biopolymer impacts Atterberg limits of the treated clay. The clay treated with 0.5% mass-based xanthan gum, for example, had a higher plastic limit yet a lower liquid limit compared to the clay treated with 1% xanthan gum (Table 6). The higher plastic limit for the former clay-gum mixture is a result of having a small quantity of the gum in the clay and the competing attractions of the gum to the water and to the clay [35]. The anionic xanthan gum polymer chains get attached to the positive charges on the EPK clay surface. Since these positive charges are localized on the clay surface, the polymer chains form train-loop-tail configurations (Figure 9). For the 0.5% xanthan gum treatment, more loops cross-link between different clay particles exposing a
significant length of xanthan gum chains to the pore water. This exposure allows the gum to adsorb large amount of water before a clear impact occurs on the clay consistency. On the other hand, the large number of polymer chains in the 1% xanthan gum mixture is enough to saturate clay particles with individual xanthan gum chains. This, in turn, results in a smaller number of exposed chain loops and more clay-attached trains compared to the 0.5% xanthan gum mixture. The limited exposed chain loops reduce the amount of water that the xanthan gum can adsorb resulting in a lower plastic limit for the 1% treated clay compared to the 0.5% treated clay. However, the impact of the limited quantity of the polymer chains in the 0.5% xanthan gum mixture also constrains the maximum amount of water it can adsorb. This constrained water adsorption capacity explains the lower liquid limit for the 0.5% xanthan gum mixture compared to the 1% mixture, which has more water adsorption capacity.

Table 6. Atterberg limits for different EPK clay-biopolymer mixtures.

<table>
<thead>
<tr>
<th>Mixture #</th>
<th>Mixture1, 2, 3</th>
<th>Plastic Limit (%)</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure EPK clay</td>
<td>32.0</td>
<td>67.0</td>
<td>35.0</td>
</tr>
<tr>
<td>2</td>
<td>0.5% XG</td>
<td>51.3</td>
<td>106.5</td>
<td>55.2</td>
</tr>
<tr>
<td>3</td>
<td>1% XG</td>
<td>44.0</td>
<td>126.5</td>
<td>82.5</td>
</tr>
<tr>
<td>4</td>
<td>1% XG @ 80 °C</td>
<td>41.9</td>
<td>114.9</td>
<td>73.0</td>
</tr>
<tr>
<td>5</td>
<td>1% LBG</td>
<td>44.3</td>
<td>104.5</td>
<td>60.2</td>
</tr>
<tr>
<td>6</td>
<td>1% XG + 10% Montmorillonite</td>
<td>47.5</td>
<td>105.0</td>
<td>57.5</td>
</tr>
<tr>
<td>7</td>
<td>1% XG + 25% Montmorillonite</td>
<td>55.6</td>
<td>108.0</td>
<td>52.4</td>
</tr>
<tr>
<td>8</td>
<td>1% XG + 50% Montmorillonite</td>
<td>44.0</td>
<td>122.3</td>
<td>78.3</td>
</tr>
<tr>
<td>9</td>
<td>1% XG + 10% Halloysite</td>
<td>53.7</td>
<td>105.2</td>
<td>51.5</td>
</tr>
<tr>
<td>10</td>
<td>1% XG + 25% Halloysite</td>
<td>49.1</td>
<td>104.0</td>
<td>54.9</td>
</tr>
<tr>
<td>11</td>
<td>1% XG + 50% Halloysite</td>
<td>49.6</td>
<td>105.4</td>
<td>55.8</td>
</tr>
<tr>
<td>12</td>
<td>1% XG + 50% LBG</td>
<td>40.3</td>
<td>123.7</td>
<td>83.4</td>
</tr>
<tr>
<td>13</td>
<td>1% XG + 50% Starch</td>
<td>40.0</td>
<td>114.6</td>
<td>74.6</td>
</tr>
<tr>
<td>14</td>
<td>1% XG + 40% GG</td>
<td>46.5</td>
<td>119.7</td>
<td>73.2</td>
</tr>
</tbody>
</table>

1 Primary biopolymer percentages refer to the dry mass of the clay used in the experiments.
2 Secondary filler percentages refer to the dry mass of the primary biopolymer.
3 XG: Xanthan gum; LBG: Locust bean gum, GG: Gellan gum

Moreover, the impact of the degree of polymerization of the biopolymer on the clay’s liquid limit appears to be significant. The degree of polymerization of any polymer indicates the length of the polymer chains upon mixing as well as the capacity of the polymer to adsorb water after the initial polymerization. Higher degrees of polymerization correspond to longer polymer chains and less post-polymerization water adsorption capacity compared to lower degrees of polymerization. Variations in the degree of polymerization may be triggered by
having different mixing conditions or using fillers to stabilize the biopolymer. The effect of the mixing conditions is presented in Table 6 by mixtures 3 and 4, both of which consisted of 1% xanthan gum; however, mixture 3 was mixed at room temperature (i.e., 20 °C) while mixture 4 was mixed at 80 °C. Mixing at elevated temperatures increases the degree of polymerization significantly [35], thus the latter mixture has a much higher degree of polymerization than the former. The higher degree of polymerization for mixture 4 reduced the post-polymerization water adsorption capacity compared to that for mixture 3. This limited water adsorption capacity for mixture 4 explains the lower plastic and liquid limits for this mixture compared to those for mixture 3. Despite the inconsistencies in the plastic limits, a similar effect of the different fillers was also observed in the liquid limit of the biopolymer-stabilized clays. As shown in Table 6, all mixtures consisting of xanthan gum and a filler, either clay (mixtures 6 through 11) or other biopolymers (mixtures 12, 13, and 14), had less liquid limit compared to the pure xanthan gum in mixture 3. This is because fillers promote the initial polymerization process which reduces the post-polymerization water adsorption capacity.

Figure 9. Sketch of the train-loop-tail configurations of biopolymer and clay particles [3].

Despite the previously discussed effects of filler-induced changes on the clay Atterberg limits, it appears in Table 6 that these changes are not significant for the considered clay type and for a given xanthan gum percentage. For all 1% xanthan gum treatments, the average and standard deviation of the plastic limit were 46.5% and 5.1%, respectively; while the average and standard deviation of the liquid limit were 113.6% and 8.5%. Accordingly, all 1% xanthan gum treatments have plastic and liquid limits that are within one standard deviation of the respective average values proving that the observed variation due to filler type is not significant.

Finally, the practical implications of the high Atterberg limits of the
biopolymer-stabilized clays are twofold. The first is an expected higher shear strength compared to the pure clay at the same water content. For instance, the pure clay will behave plasticly at a water content of 34%, while biopolymer-treated clays will continue to have a semi-solid consistency as this water content is less than the plastic limits for these treated clays. Similarly, the pure clay will become liquid at water contents of 67% or more, while all other biopolymer-treated clays will still have plastic consistency due to their high liquid limits. The second practical implication of the high Atterberg limits of biopolymer-stabilized clays is an expected lower permeability of the biopolymer-stabilized clay at all degrees of saturations. This expected lower permeability will enhance the hydraulic performance of the clay cores in earth dams and levees.

b. Compaction tests.

The results of the standard Proctor compaction tests for the carver sand and the EPK clay treated with various xanthan gum mixtures are shown in Figures 10 and 11, respectively. For the treated carver sand (Figure 10), it appears that the various xanthan gum treatments do not have significant impacts on the optimum moisture content and the maximum dry density. All data follow the same overall trend showing a slight increase in the dry unit weight up to a moisture content of 14 ± 1.5% corresponding to a maximum dry unit weight of 16.75 ± 0.25 kN/m³. After this moisture content, the dry unit weight experiences a dramatic reduction as the moisture content increases. Therefore, all samples used to assess the impact of biopolymer on the shear strength of the used sand were compacted at a moisture content of ~14% targeting a dry unit weight of 16.75 kN/m³.

Moreover, the maximum dry unit weight of the biopolymer-treated clay matches this of the pure EPK clay as shown in Figure 11. However, treating the clay with xanthan gum increased the optimum moisture content (35%) significantly compared to this of the pure clay (27%). This difference in the optimum moisture content is attributed to the unique clay-biopolymer-water interactions discussed in the previous section. However, the effect of the xanthan gum percentage on the optimum moisture content and the maximum dry unit weight of the EPK clay was insignificant as shown in Figure 11 for the 0.5% and 1% xanthan gum treatments. For these two mixtures, the optimum moisture content and maximum dry unit weight are 35% and 12.65 kN/m³, respectively. These results agree with the minor impact of the various biopolymer treatments on Atterberg limits of the EPK clay as discussed in the previous section. Therefore, compacted clay samples used to assess the impact of the biopolymer treatment of the shear strength of the clay were compacted using the respective optimum moisture content for each mix, 27% for the pure EPK clay and 35% for the clay with xanthan gum, targeting a dry unit weight of ~12.65 ± 0.3 kN/m³.
4.5.3. Biopolymer effects on shear strength

a. EPK clay.

The stress-strain curves from the unconfined tests of the pure EPK clay and the clay treated with 0.5% and 1% weight-based xanthan gum are shown in Figure 12. These unconfined tests were performed on samples compacted at the optimum moisture content for each mixture (27% for pure clay and 35% for clay with xanthan gum as...
shown in Figure 11) to a dry unit weight of $12.65 \pm 0.3 \text{ kN/m}^3$. These compaction conditions were selected to mimic those expected to be followed on actual construction sites, i.e. each soil layer is compacted to its maximum dry unit weight.

As shown in Figure 12, the pure clay had a maximum deviatoric axial stress (i.e., unconfined strength) of 136 kPa, while the clay samples treated with 0.5% and 1% xanthan gum had peak deviatoric stresses of 220 kPa and 200 kPa, respectively. These unconfined strengths for the clay treated with 0.5% and 1% xanthan gum correspond to 62% and 47% strength increase over the pure clay, respectively. Additionally, it was noted that the stiffness of the clay treated with xanthan gum is slightly less than that of the pure clay. While these reduced stiffness for the biopolymer treated clays imply that these treated clays will experience higher strains at a given axial stress level, it is worth noting that all clay samples experienced the same strain level at the peak deviatoric stress of the pure clay (i.e., 136 kPa). However, the samples treated with xanthan gum did not fail like the pure clay sample. Accordingly, the reduced stiffness of the treated clay is not believed to be a critical factor in the design of earth dams and levees using biopolymer treated clays.

![Figure 12. Deviatoric axial stress versus axial strain for the pure clay and the clay treated with different xanthan gum percentages from the unconfined shearing tests.](image)

**b. Carver sand.**

Figure 13 presents the impact of 1% pure xanthan gum on the stress-strain curve and the shearing-induced pore water pressures of the carver sand at 250 and 500 kPa. As shown in this figure, xanthan gum reduced the stiffness of the sand and its strength significantly at the two considered stresses (Figures 13.a and 13.b). The maximum deviatoric stress of the sand treated with pure xanthan gum was about 68.5% of that of the clean sand for the two considered confining stresses. Moreover, the magnitude
of the pore water pressure developed during shearing of the sand treated with pure xanthan gum was less than that developed when the clean sand was sheared. This decrease in the shearing-induced pore water pressure is about 61% and 66% for the samples tested at 250 and 500 kPa, respectively. These results agree with other studies in the literature [49].

Figure 13. Results of isotropic consolidated undrained triaxial shear tests on the clean carver sand and sand treated with 1% pure xanthan gum at 250 kPa (a and c) and 500 kPa (b and d) confining stresses. (a and b) deviatoric stress-strain curves and (c and d) pore water pressures.

In order to overcome the reduced strength and stiffness associated with the use of pure xanthan gum biopolymer, this study focused on stabilizing xanthan gum biopolymer with clay fillers. Figures 14, 15, and 16 present the stress-strain curves and pore pressures induced during undrained shearing of sands treated with 10%, 25%, and 50% fillers, respectively. It can be observed in these figures that all percentages of the montmorillonite clay filler resulted in a maximum deviatoric stress more than that for the sand treated with pure xanthan gum and the clean sand. At 250 kPa confining stress, the maximum deviatoric stress for the samples treated with 10%, 25%, and 50% montmorillonite filler were about 108%, 128%, and 123% of those of the clean sand, respectively. These percentages increase to 120% and 143% for the 10% and 25% montmorillonite fillers, respectively, at 500 kPa confinement. Contrarily, the increase in the maximum deviatoric stress for the sand with 50% montmorillonite-stabilized xanthan gum over the clean sand at 500 kPa was 111%, i.e. less than that at 250 kPa.
stress (123%). While these shear strength enhancements appear to be relatively small in percentages, the increased shear strength is attributed mainly to an increase in the cohesion which has signification practical implications for the earth dams as discussed later.

Moreover, these strength improvements prove that the use of montmorillonite fillers to stabilize xanthan gum biopolymer prior to treating sand allows overcoming the negative impact of the pure xanthan gum on the strength of the sand. This success is demonstrated by the increase of the maximum deviatoric stress of the sand with xanthan gum-montmorillonite filler compared to that of the sand treated with pure xanthan gum. At 250 kPa confining stress, 10%, 25%, and 50% montmorillonite fillers increased the maximum deviatoric stress by 158%, 190%, and 188%, respectively, over the sand with pure xanthan gum. Similarly, enhancements of about 174%, 207%, and 161% were observed when using xanthan gum with montmorillonite fillers over the samples with only pure xanthan gum at 500 kPa. Thus, the use of montmorillonite filler to stabilize biopolymers offers a practical technique to eliminate the negative impacts of biopolymers on the strength of biopolymer-stabilized soils and other bio-mediated soil treatments that rely on biopolymers to trigger desired bioactivities such

Figure 14. Results of isotropic consolidated undrained triaxial shear tests on clean carver sand, sand treated with 1% pure xanthan gum, and sand treated with 1% xanthan gum pre-stabilized with 10% clay fillers at 250 kPa (a and c) and 500 kPa (b and d) confining stresses. (a and b) deviatoric stress-strain curves and (c and d) pore water pressures.
Moreover, the absolute value of the shearing-induced pore water pressures for the sand treated with montmorillonite-stabilized xanthan gum were higher than the pore pressures developed upon shearing clean sand and sand treated with pure xanthan gum for all montmorillonite percentages and confining stresses. These results indicate that sand samples treated with montmorillonite-stabilized xanthan gum experienced more suction (i.e., negative pore water pressures) upon shearing compared to the latter samples. Such large suctions contribute to the enhanced deviatoric stress for the former samples over the latter ones. Higher negative pore water pressures increased the effective stress applied between the soil grains, which increased the shearing resistance and therefore the shear strength of the soil.

Unlike the montmorillonite-filler, the impact of stabilizing xanthan gum with halloysite clay fillers on the maximum deviatoric stress depends on the base reference for the comparison. Compared to the sand treated with pure xanthan gum, halloysite clay filler resulted in slight improvements in the maximum deviatoric stress ranging between 109% and 147% at 250 kPa confining stress and between 116% and 154% at 500 kPa. However, comparing the maximum deviatoric stress of the sand with halloysite-stabilized xanthan gum to that of the clean sand reveals that a large quantity

![Diagram](image_url)

**Figure 15.** Results of isotropic consolidated undrained triaxial shear tests on clean carver sand, sand treated with 1% pure xanthan gum, and sand treated with 1% xanthan gum pre-stabilized with 25% clay fillers at 250 kPa (a and c) and 500 kPa (b and d) confining stresses. (a and b) deviatoric stress-strain curves and (c and d) pore water pressures.
of the halloysite filler is needed to ensure comparable strengths. For example, using xanthan gum stabilized with only 10% halloysite decreased the maximum deviatoric stress to 75% and 80% of the strength of the clean sand at 250 and 500 kPa confinements, respectively. While, 50% halloysite filler achieved 100% and 104% of the maximum deviatoric stress of the clean sand at 250 and 500 kPa confinements, respectively. These differences between the ability of montmorillonite filler to stabilize xanthan gum versus this of the halloysite filler is attributed to differences in the particle shapes, surface area, accessible surface charges as will be discussed in Section 4.6.

![Graph](image)

**Figure 16.** Results of isotropic consolidated undrained triaxial shear tests on clean carver sand, sand treated with 1% pure xanthan gum, and sand treated with 1% xanthan gum pre-stabilized with 50% clay fillers at 250 kPa (a and c) and 500 kPa (b and d) confining stresses. (a and b) deviatoric stress-strain curves and (c and d) pore water pressures.

**4.6. Discussions**

This section discusses the mechanisms underlying the strength changes of soils treated with xanthan gum biopolymer stabilized with the different fillers. These mechanisms are presented considering the rheological responses (i.e., viscosity) of various xanthan gum stabilizations to shearing.

**a. Mechanisms for biopolymer strengthening of sands.**

The carver sand used in this study is a silica-based sand that has minimal surface
interactions with its surrounding pore fluid. Therefore, the observed changes in the sand behavior when treated with xanthan gum, either pure or with clay fillers, are attributed mainly to the biopolymer behavior. The biopolymer first coats sand particles then, as the biopolymer percentage increases, it replaces pore water [42]. Accordingly, the presence of xanthan gum biopolymer in the sand altered its shear strength parameters (i.e., friction angle and cohesion). To demonstrate this impact, the results of the triaxial tests reported in Figures 14, 15, and 16 were used to determine the effect of xanthan gum on Mohr-Coulomb strength parameters of carver sand: the effective internal friction angle ($\phi'$) and cohesion ($c'$). Table 7 presents the strength parameters defining Mohr-Coulomb failure envelop for each of the considered treatments.

**Table 7. Effective friction angle and cohesion of clean carver sand and sand treated with xanthan gum composites.**

<table>
<thead>
<tr>
<th>Treatment reference</th>
<th>Effective internal friction angle ($\phi'$), degrees</th>
<th>Effective cohesion ($c'$), kPa</th>
<th>Viscosity of XG treatment at shear rate $= 0$ Hz, kPa·sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Sand</td>
<td>33</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>XG only (1%)</td>
<td>23</td>
<td>201</td>
<td>8.35</td>
</tr>
<tr>
<td>XG + 10% Montmorillonite</td>
<td>33</td>
<td>0</td>
<td>7.14</td>
</tr>
<tr>
<td>XG + 25% Montmorillonite</td>
<td>30</td>
<td>131</td>
<td>7.83</td>
</tr>
<tr>
<td>XG + 50% Montmorillonite</td>
<td>17</td>
<td>657</td>
<td>8.94</td>
</tr>
<tr>
<td>XG + 10% Halloysite</td>
<td>25</td>
<td>201</td>
<td>14.10</td>
</tr>
<tr>
<td>XG + 25% Halloysite</td>
<td>31</td>
<td>74</td>
<td>10.96</td>
</tr>
<tr>
<td>XG + 50% Halloysite</td>
<td>33</td>
<td>0</td>
<td>9.90</td>
</tr>
</tbody>
</table>

As shown in Table 7, biopolymer treatments alter the internal friction angle and the effective cohesion between sand particles. Sand treated with only 1% pure xanthan gum experiences $10^\circ$ reduction in the internal friction angle with a significant increase in the cohesion. These changes are attributed to differences in the viscosity of the pure xanthan gum compared to the pore water in the clean sand. The highly viscous pure xanthan gum (1) cross-links sand particles together which increases the cohesion and (2) lubricates the interface between sand particles reducing the internal friction angle. These changes result in lower shear strengths for the sand treated with 1% pure xanthan gum compared to the clean sand at the considered confining stress levels as shown in Figure 13.

When clay fillers were used to stabilize xanthan gum, it is noted that the viscosity of the biopolymer-clay composite plays a significant role on the strength parameters of the sand. For a given filler type, the treated sand experienced higher cohesion (Figure 17.a) but less internal friction angle (Figure 17.b) as the viscosity of the used biopolymer-filler composite increased. As the viscosity of xanthan gum with a specific filler type increased, the strength of the biopolymer cross-linking bridges between sand particles increased raising the cohesion of the treated sand. Meanwhile,
higher viscosities decreased the ability of the biopolymer-filler composite to flow under shearing. In turn, this limited flow ability reduced direct interparticle sand contacts by sandwiching a biopolymer lubricating layer in between particles, which reduced the internal friction angle of the treated sand.

![Figure 17. Relation between viscosity at no shear of xanthan gum solution and (1) the internal friction angle, and (b) the cohesion of the treated sand](image)

Moreover, the other factors that appear to have a significant impact on the behavior of the treated sand are filler type, percentage and biopolymer-filler interactions. For all filler percentages, xanthan gum-halloysite composites have higher viscosities than those with montmorillonite fillers (Figure 18). Despite of their higher viscosity, the former composites resulted in lower cohesions between sand particles than the latter ones (Figure 17.b). Moreover, the cohesion of the sand treated with the highly viscous xanthan gum-halloysite composites was upper bounded by the cohesion of the sand treated with the less viscous pure xanthan gum. Similarly, the highly viscous xanthan gum-halloysite composites did not reduce the internal friction angle between sand particles as much as the less viscous pure xanthan gum or xanthan gum-montmorillonite composites (Figure 17.a). These responses suggest that the biopolymer-filler viscosity is not the only parameter controlling the treated soil behavior; it rather appears that the interactions between the used biopolymer and filler have critical effects.

The significance of the filler type, percentage, and respective interactions with xanthan gum biopolymer is demonstrated in Figure 18. As shown in this figure, the viscosities of the halloysite-based composites decrease as the percentage of the halloysite filler increases. Contrarily, an increase in the percentage of the montmorillonite filler increases the viscosity of the resulting composite. These different responses are attributed to the unique particle shape and surface chemistry
of each of these two fillers. The montmorillonite clay particles are plate-like with very high width-to-thickness aspect ratio, while the halloysite clay particles have a tube-like shape (Figure 5). Additionally, the surface area of the montmorillonite clay particles is much higher than that of the halloysite clay as discussed in Section 4.2.4. The former clay is also characterized by its high net negative charge, localized positive surface charges and cation exchange capacity, all of which significantly exceed those of the halloysite clay. Moreover, xanthan gum polymer chains are able to intercalate and partially exfoliate the montmorillonite particles [35], while these chains interact with only the exposed surfaces of the halloysite particles [35]. These unique montmorillonite clay characteristics (i.e., high surface area, localized positive charges, and easy of intercalation) produce stronger xanthan gum-montmorillonite composites compared to xanthan gum-halloysite composites [35, 50-53]. Thus, halloysite-based xanthan gum composites are much easier to lose their strength and break up on shearing than the montmorillonite-based composites. This weaker response explains the lower cohesion of the halloysite-based composites compared to the higher cohesion of the montmorillonite-based composites. Furthermore, a higher number of direct contacts between sand particles occurs as the halloysite-based composites fail at interparticle interfaces compared to the direct sand contacts for the stronger montmorillonite-based composites. These direct sand contacts allow preserving the internal friction angle for the halloysite-based composites.

![Figure 18. Impact of the filler type and percentage on the viscosity at zero shear for the resulting xanthan gum-filler composite.](image)

**b. Practical implications for biopolymer stabilized soils.**

In this section, we briefly discuss the various practical implications of the findings of this experimental program. The discussion presented here relies on current design and construction practices for earth dams and levees; it is, therefore, considered to be a qualitative discussion. The quantification of the expected factor of safety against slope
stability is presented in Chapter 6.

The practical implications for clays treated with biopolymers include:

1) Higher Atterberg limits indicate that biopolymer treated clays can preserve their consistency at higher water contents compared to the pure clays. The practical implication of this point is that the cores of earth dam made of compacted biopolymer treated clays will remain intact at water contents exceeding the plastic limit of the pure untreated clay.

2) The higher unconfined strength of biopolymer treated clays allows the construction of steeper and higher earth dams and levees using the same earth materials. This advantage will reduce the need to export and use non-native materials, such as cement and fly ash, to strengthen the national earthen infrastructure to sustain todays’ pressing design needs.

3) The ability of the biopolymers in the clay to adsorb water and fill any pores will allow the biopolymer treated clay cores to self-heal. While this self-healing ability was not examined in this project and should be studied in detail in future research, such ability will reduce the risks associated with internal erosions of earth dams and levees.

The practical implications for sands treated with biopolymers include the ability of biopolymer-treated sands to resist surface and internal erosions in earth dams and levees. To demonstrate this ability, various Mohr-Coulomb failure envelopes from all considered mixtures are plotted and compared to one another in Figures 19.a and 19.b for montmorillonite and halloysite fillers, respectively. As shown in Figure 19.b, the use of halloysite clay fillers does not increase the shear strength significantly, if any, over the plotted stress range. As discussed earlier, the maximum strength of the mixture with halloysite clay is achieved at 50% halloysite percentage and it is comparable to the strength of the clean sand.

On the other hand, Figure 19.a shows that 50% montmorillonite filler offers a significant increase in the shear strength, over the clean sand and sand treated with xanthan gum with other percentages of montmorillonite filler, up to about 1.8 MPa effective normal stress on the failure plane. This effective normal stress on the failure plane corresponds to an effective vertical stress of about 3.4 MPa, which represents about 200 m in the ground. Since most of the geotechnical engineering applications consider depths much shallower than this 200 m, the use of 50% montmorillonite fillers appears to be the most promising for xanthan gum stabilization for soil improvement. At 1 MPa (~20 ksf) normal stress on the failure plane expected at about 50 m in the ground, for example, the increase in the shear strength of the sand when treated with xanthan gum stabilized with 50% montmorillonite is about 60% (from 620 kPa to 970 kPa). Moreover, higher percent of shear strength enhancement is expected at shallower depths as shown in Figure 19.a. This high strength at shallow depths is attributed to the significant increase in cohesion between the sand particles.
Since soil cohesion is a major factor resisting the soil erosion \cite{54, 55}, it is expected that the observed increase in the cohesion of the biopolymer treated sand to increase the sand resistance to erosion.

![Figure 19. Overlapped Mohr-Coulomb failure envelopes for the different sand and xanthan gum mixtures. (a) montmorillonite clay fillers, and (b) halloysite clay fillers.](image)

### 4.7. Conclusions

The results of the experimental program used in this study show that:

1) For clayey soils:
   
   a. Atterberg limits of clayey soils increase when the clay is treated with biopolymers. However, the impact of the biopolymer type and percentage appears to be insignificant.
   
   b. The maximum dry unit weight of the biopolymer-treated clay matches this of the pure clay. However, the optimum moisture content needed to achieve this dry unit weight is much higher for the biopolymer-treated clay compared to the pure clay.
   
   c. The unconfined strength of compacted biopolymer-treated clays increases compared to this of pure clay at the same dry unit weight.
   
   d. A slight decrease in the stiffness of the biopolymer-treated clay is observed compared to the pure clay. However, this stiffness reduction is insignificant for the construction of earth dams and levees since the two clays experience the same deformation at stress levels corresponding to the undrained strength.

2) For sandy soils:
   
   a. Mixing sandy soils with hydrated biopolymers decreases their shear strength
mainly due to significant reductions in the internal friction angle between the soil particles, despite the increase in cohesion.

b. Stabilizing biopolymers using clay fillers offer a practical technique to overcome the strength reduction due to the lubrication effect of the pure biopolymers.

c. The magnitude of the strength gain in sandy soils treated with biopolymer-filler composites depends on the filler type, percentage and interaction with the used biopolymer.

d. For a given filler type, it is noticed that increasing the viscosity of the biopolymer-filler composite reduces the internal friction angle but increases the cohesion between the sand grains.
5. BIODEGRADABILITY OF BIOPOLYMER SOIL TREATMENTS

One of the most concerning issues about the use of biopolymers to stabilize soils is the biodegradability of the used biopolymers. Biopolymers may degrade due to many factors that are classified into either mechanical or chemical factors [56, 57]. The mechanical factors include forces applied to the chains of the biopolymer that may break its backbones. For biopolymers used to treat soils, the applied forces are not expected to be enough to break the covalent bonds forming the backbone of the biopolymer. Thus, the latter chemical scission is believed to dominate any potential degradability of the biopolymers soil treatments. This chemical scission may occur due to radiative effects due to ultra-violet (UV), temperature changes, or due to digestion as a result of microbes that are naturally present in the soil. For biopolymer used to stabilize soils, the former factor (i.e., UV light) is not believed to be a critical factor since these materials will be buried in the ground with limited exposure to any UV lights. Moreover, the second factor is not considered as well because the selection of the biopolymer for any given project will consider all environmental factors for that explicit project including expected temperature variations. Thus, the sole factor that may contribute to the degradability of biopolymers in soil treatments is the biological degradation as the native micro-organisms consume the biopolymer as a food and energy source.

Therefore, this chapter focuses first on the expected response of biopolymers due to various degrees of biodegradability, regardless of the triggering mechanism. This task is presented in Section 5.1 using advanced molecular dynamics simulations. Then, the degradability of xanthan gum biopolymer used to stabilize a sandy soil is assessed experimentally over a period of 9 months as presented in Section 5.2.

5.1. Advanced Numerical Models

Since the time scales for biopolymer degradation are unknown experimentally and require field tests, we can simulate the effect that degradation will have on the measured viscosity of the pore aquatic biopolymer solution. As discussed in the previous report, this viscosity affects the shear strength of the soil significantly. Thus, this report presents a specially designed Molecular Dynamics simulation to predict the changes in the pore fluid viscosity.

Molecular dynamics (MD) simulation of the biopolymer-clay composites was performed using the Large-Scale Atomic/Molecular Massively Parallel Simulator (LAMMPS), which is an open-source molecular dynamics environment distributed by the Sandia National Laboratory. In this study, we investigated the effects of volume fraction of the clay filler, the interaction strength between the biopolymer and clay filler, the presence of a water solvent and shearing speeds.
5.1.1. Modelling details

This section presents the details of the modelling approach adopted in this study including the approach used to model the biopolymer chains, clay fillers, and the mechanism followed to model shearing between soil particles.

a. Modeling biopolymer chains.

The biopolymers were modeled using the Kremer-Grest (KG) model [58, 59]. The KG model is one of the most popular CG representations of polymers in general. The model is very simple, yet computationally efficient. Here, the biopolymer is modeled as a sequence of beads connected by springs where the springs are defined by the Finite Extensible Nonlinear Elastic (FENE) potential given by Eq. (1).

\[
\nu_{\text{FENE}}(r) = \begin{cases} 
0.5 R_0^2 k \ln \left[ 1 - \left( \frac{r}{R_0} \right)^2 \right] & r \leq R_0 \\
\infty & r > R_0 
\end{cases}
\]  

(1)

where \( R_0 \) is the maximum extensible distance, \( r \) is the distance between beads and \( k \) is the elastic constant.

In our model, we also used the Nose-Hoover thermostat for temperature control [58]. Each polymer was modeled as a sequence of 64 beads. This is larger than the entanglement length of the biopolymer and will enable us to recover the correct dynamics of the considered biopolymer. The KG model, along with all other pairwise interactions in the simulation, uses the simple Lennard-Jones (LJ) potential \((V)\) defied in Eq. (2).

\[
\nu_{\text{LJ}}(r) = \begin{cases} 
4\varepsilon \left[ \left( \frac{\sigma}{r} \right)^{12} - \left( \frac{\sigma}{r} \right)^{6} \right] & \text{for } r \leq r_c \\
0 & \text{for } r \geq r_c 
\end{cases}
\]  

(2)

where \( r_c \) is the cutoff distance beyond which the LJ potentials were neglected, \( \sigma \) is the length scale of the simulation, and \( \varepsilon \) is the energy interaction parameter.

b. Modeling clay filler.

The clay filler was created by combining 19 LJ spheres in a hexagonal lattice to form a plate-like particle. The LJ potential from Eq. (2) was used for interactions between clay particles and biopolymer chains. However, the interaction between clay particles was set to be repulsive to prevent clumping. The physical attraction between biopolymer and clay was simulated via short-range attractions according to the simple Lennard-Jones potential. The structure and strength of such materials were studied using
viscosity measurements and particle orientation from the simulation.

c. *Shearing between soil particles.*
In addition to equilibrium simulations, where there was no shear applied to the system, the dynamics of the biopolymer-clay composite under an applied shear were modeled to mimic the condition when a soil is subjected to shearing. In order to account for shear, and to mimic the pore fluid being sheared between soil particles, we modeled the soil surfaces as planar walls. Two walls were created perpendicular to the z-axis of the simulated domain (Figure 20), which bounded the biopolymer and clay filler. The wall was made up of similar LJ spheres in a structured face-centered cubic (FCC) lattice. Pairwise interactions between biopolymer and the wall, and clay and wall were included using the LJ potentials from Eq. (2). The walls were pivotal in creating a constant pressure for the system and in the stress tests. Shearing was applied by moving the walls with similar velocities but in opposite directions. By changing the velocity of the walls, we effectively change the shearing rate (Figure 20). The velocity profile was then used to calculate the viscosity of the composite as discussed in the following section. For all the shearing calculations, we ensured that there were no-slip boundary conditions at the wall, where fluid velocity at the boundary is equal to the wall velocity.

![Figure 20. Schematic of velocity under constant shearing. Dotted lines represent the top and bottom walls while the solid arrows show the change in velocity through the layers.](image)

All simulations were performed in reduced units, called LJ units in LAMMPS terminology. All the computations were normalized by setting the various terms in the Lennard-Jones equation (Eq. (2)) to unity. Once the force and pressure calculations were performed, the normalized quantities ($f^*$ and $P^*$) were converted back to real values using Eq. (3) and Eq. (4), respectively.
Force: \[ f^* = f \cdot \frac{\sigma}{\varepsilon_f} \]  

Pressure: \[ P^* = P \cdot \frac{\sigma^3}{\varepsilon_f} \]

where \( \sigma \) is the length scale and \( \varepsilon \) is the energy scale of the simulation.

For all simulations, the velocity and trajectory of each particle were determined using the Verlet-velocity algorithm with a time step \( \Delta t = 0.005 \cdot \tau \), where \( \tau \) is the unit of time. The system was kept at a constant temperature of \( 1.1 \cdot \varepsilon \) by Nose-Hoover thermostat to ensure the biopolymer stays in the melt phase. A simulation domain in the shape of a cubic box of length of \( 40 \cdot \sigma \) was created with 800 biopolymer chains introduced at random positions. The clay filler volume fraction and the energy parameter between clay particles and biopolymer chains (\( \varepsilon_{fp} \)) were the main variables studied in this setup. Figure 21 shows the initial morphology of the system. Note that in this case, the solvent particles were not included in the simulation; rather, we modeled the solvent as an implicit solvent to determine the equilibrium structure of the biopolymer-clay system. For an implicit solvent, the solvent was modeled using an effective averaged potential, rather than including them explicitly. The volume fraction of the biopolymer used in these simulations is 12.2%.

![Image](image_url)

**Figure 21.** The initial configuration of the biopolymer-clay composite. The system was bounded by two walls, top and bottom (green color). The biopolymer chains (blue color) and the clay nanoplatelets (red color) were randomly distributed.

All equilibration was done under constant load conditions, where the system was allowed to reach an equilibrium state in a zero-stress state. While we equilibrated the system under constant volume (NVT) constraints when shearing was considered. For the constant volume equilibration, the z-dimension of the system was fixed. In all cases, periodic boundary conditions were applied in the x- and y-directions.
5.1.2. Results

In order to model the degradation of the biopolymer chains, we considered the following cases: a) a pure biopolymer (no degradation) b) 20% degradation c) 30% degradation and d) 50% degradation. Since the locations of the scission on the biopolymer chains are randomly located, we assumed that on average a bond will be broken in the center of the biopolymer backbone, which is a conservative assumption. Thus, 20% of degradation assumes that on average 20% of the biopolymer chains will have a bond broken at the center of their backbone, effectively reducing their chain lengths to half of its original length. The process of the simulation was as follows: first, we ran the simulation using the original chain lengths to ensure that equilibrium was reached. Once we reached equilibrium, we performed the degradation step where the bond in the center of the backbone of a number of the modeled biopolymer chains, corresponding to the desired degradation percentage, were randomly selected and removed. We then re-equilibrated the system and then performed our shear test by using the procedure described earlier.

The results of our simulation are shown in Table 8. In this table, all units are in terms of the viscosity of the pure polymer systems (set to 1). As can be seen from Table 8, the biopolymer reserved a significant part of its viscosity even at 50% degradation. This is in large part due to the fact that the viscosity of biopolymers is dominated by chain interlockings and entanglements, which remain present even after the chain length reduce due to the degradation process. These results suggest that stabilizing soils with biopolymers will not experience a significant reduction in the soil strength due to biopolymer degradation.

<table>
<thead>
<tr>
<th>Degradation (%)</th>
<th>Ratio of scaled viscosity ($\eta/\eta_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.93</td>
</tr>
<tr>
<td>30</td>
<td>0.83</td>
</tr>
<tr>
<td>50</td>
<td>0.77</td>
</tr>
</tbody>
</table>

5.2. Experimental Assessment of Biodegradability Effects

This section aims to experimentally validate the main finding of the advanced molecular dynamics simulations about the biodegradability effects on biopolymer treated soils. As discussed in the previous section, the viscosity of the biopolymers treatments for soils is not expected to suffer significant reductions upon 50% degradation. If this finding is valid, no significant strength losses are expected to occur in biopolymer treated soils. Therefore, we use the change in the unconfined shear strength of sand treated with different biopolymer-clay composites as an indirect
measure inferring the degradability of the biopolymer in the sand over time.

5.2.1. Materials and sample preparation techniques

In the experiments for the biodegradability assessment, the carver sand described in Chapter 4 was used. However, unlike for the strength experimental program in Chapter 4, the sand used for the biodegradability experiments was not washed to ensure that any native micro-organisms that naturally exist in the sand deposit were present in the final specimens. Additionally, the biopolymer and clay fillers used in the biodegradability experiments reported in this chapter were the same as those described in Chapter 4. Moreover, all xanthan gum biopolymers (with and without clay fillers) were prepared following the procedure described in Chapter 4.

The preparation of the samples differs from that mentioned in Chapter 4. For the samples used in the biodegradability experiments, the quantities of the different components were based on the total mass of the soil needed to fill a small compaction mold of 33-mm in diameter and 70-mm in height (~ 115 ± 3 gm), where the initial bulk samples were prepared. The used mass ensures that the dry unit weights of all tested specimens are within 2% of the optimum unit weight for the used sand with 1% xanthan gum (i.e., 1675 kN/m³). One xanthan gum percentage (1%), with respect to the dry mass of the soil, was used in this study. This percentage was selected since it was the most promising percentage for this biopolymer based on the results of the shear strength experiments reported in Chapter 4.

A total of 15 gm of water was used during the polymerization of xanthan gum. This water quantity ensures that the sand samples have an initial moisture content of 14%, which is the average optimum moisture content for the used sand when treated with various xanthan gum polymer mixtures in a standard Proctor test as discussed in Chapter 4. In addition to assessing the degradability of the sand with pure xanthan gum, xanthan gum mixtures with two clay fillers (i.e., montmorillonite and halloysite) at two masses percentages of 10% and 50% were considered. Table 10 presents a summary of the xanthan gum treatments used for the sand in this degradability study.

The xanthan gum and clay fillers, if used, were first polymerized following the polymerization process mentioned earlier. Then, the carver sand was thoroughly mixed with the various xanthan gum biopolymer mixtures using a stand mixer (Waring commercial, 7qt) operating at its slowest speed to prevent entrapping excessive air voids. After mixing, bulk specimens of the sand treated with the different biopolymer composites were compacted in the used mold. Then, the specimens were extracted out of the mold and either tested fresh or stored for testing later. Specimens that needed storage were first wrapped in two layers of plastic wrap to minimize moisture losses, and avoid any strength gain due to dehydration. After that, the specimens were enclosed inside a water path tank with temperature control; all specimens were placed above the water level in the water path. The temperature of the water path was set to 20 °C to avoid any degradation due to thermal effects.
Table 9. Xanthan gum treatments used to stabilize carver sand for the biodegradability study.

<table>
<thead>
<tr>
<th>Treatment reference</th>
<th>Filler type</th>
<th>Filler percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Sand</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>XG</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>XG + 10% Montmorillonite</td>
<td>Montmorillonite</td>
<td>10%</td>
</tr>
<tr>
<td>XG + 50% Montmorillonite</td>
<td>Montmorillonite</td>
<td>50%</td>
</tr>
<tr>
<td>XG + 10% Halloysite</td>
<td>Halloysite</td>
<td>10%</td>
</tr>
<tr>
<td>XG + 50% Halloysite</td>
<td>Halloysite</td>
<td>50%</td>
</tr>
</tbody>
</table>

1 All XG treatments were based on 1% XG with respect to the dry mass of the carver sand.
2 All filler percentages refer to the dry mass of the XG used in the experiments.
3 No clay filler.

5.2.2. Unconfined compressive tests

The indirect assessment of the degradability of the xanthan gum biopolymer in the treated sand was performed using the unconfined compressive strength of comparable specimens tested at different times. The considered testing times are 0 (i.e., fresh mixtures), 1, 7, 28, 60, 90, 180, and 270 days.

All unconfined tests were performed using an automated loading frame provided by Trautwein GeoTAC group. The two surfaces of the specimens were first levelled then placed under the loading piston of the loading frame. All specimens were sheared at 1% strain per minute to failure. A load cell connected to the loading piston was used to measure the applied vertical load during shearing. Meanwhile, an LVDT connected to the top of the loading piston was used to measure the axial strain the specimens experience under the applied loads. In the end, samples were collected out of the failed specimens to measure the moisture content and confirm the dry unit weight of each specimen.

After shearing, the dimensions of the failed specimens were measured to allow correcting the cross-sectional area of each specimen for the respective failure mode (i.e., barrelling or slip surface). The corrected cross-sectional area and applied axial loads were then used to estimate the applied axial (i.e., vertical stress). The stress-strain curve for each of the tested specimens were then plotted and the peak axial stress (i.e., unconfined compressive strength) and the corresponding strain at failure were determined.

5.2.3. Results and Discussions

Figures 23 and 24 presents the unconfined compressive strength versus time for the specimens treated with xanthan gum with montmorillonite and halloysite fillers, respectively. As shown in these figures, the unconfined compressive strength for each of the considered specimens appears to fluctuate over time. However, no significant reduction in the unconfined compressive strength of the treated sand is observed for any of the mixtures even after 9 months (i.e., 270 days in Figures 23 and 24). Thus, it
appears that xanthan gum biopolymer in the sand specimens was able to provide the strength increase over time suggesting that minimal degradation occurred on these specimens. These results agree well with the main conclusion of the advanced molecular dynamics simulation discussed in the previous section. These results also agree with the findings of Chang et al. [39], who concluded that the biopolymers used to stabilize soils do not undergo major degradation based on the unconfined compressive strength of 2 years aged specimens with different biopolymers.

![Unconfined compressive strength of Carver sand treated with pure xanthan gum (XG) and XG-montmorillonite clay filler (at 10% and 50%) versus age of the specimens in days.](image)

It should be noticed here that the unconfined compressive strengths of the sand treated with pure xanthan gum or xanthan gum-clay composites appear much lower than the effective cohesion predicted from the triaxial tested in the previous section. This discrepancy is justified since the unconfined compressive strength used in this report is double the undrained shear strength ($S_u$), while the previous section considered the drained effective cohesion ($c'$). Thus, the two experiments consider different strength parameters: one for undrained (this report) while the other considers the drained parameters (Section 5). The lack of direct relations between the two strength parameters limited our ability to relate the results of the two experimental programs.
Figure 23. Unconfined compressive strength of Carver sand treated with pure xanthan gum (XG) and XG-halloysite clay filler (at 10% and 50%) versus age of the specimens in days.

5.3. Conclusions

The main conclusion of the numerical models and experimental program performed as part of this milestone is that the biodegradability of biopolymers used to stabilized soils is not significant. The advanced molecular dynamics models showed that even at 50% degradation in the biopolymers, the viscosity of the biopolymer was reduced by 23%. This reduction is not considered significant since the initial viscosity is significantly higher than that of the pore water in untreated specimens. The experimental program, then, confirmed the finding of the numerical modeling as the experiments showed no significant reduction in the unconfined compressive strength of sand specimens treated with various xanthan gum-clay composites even after aging for 9 months.
6. FIELD TEST DESIGN

The main aim of this report is to design a full-scale field test in which the performance of biopolymer stabilized soils will be assessed in a full-scale earth dam. The design of the proposed earth dam will utilize the knowledge acquired from all previous milestones and will target data collection from a field experiment over an extended period of time. Potentially, the field experiment is to be constructed at one of the U.S. Army Corps of Engineers facilities that allow accelerated weathering of earth structures to facilitate assessing the biodegradability on site. The field experiment described in this report is to be constructed in collaboration with other federal and state agencies that have interest in the proposed technique. On going efforts of the project team in this front target securing the required funding for this field experiment. This report present the main design of the field experiment including the overall geometry of the proposed earth dam (Section 6.1), the selection of the various materials to be used (Section 6.2), the results of the preliminary slope stability numerical models for the proposed earth dam (Section 6.3), techniques to be followed to transition the proposed technology into field scale (Section 6.4), and the long-term performance predictions that will be measured during the field experiment (Section 6.5).

6.1. Overall geometry of the proposed earth dam.

Figure 25 presents the geometry of the proposed earth dams and a plan view of the different segment of the dam. This earth dam mimics the geometry of the Prompton dam in Lackawaxen River, PA. This earth dam was designed and constructed by the U.S. Army Corps of Engineers and provided in the USACE engineering manual for General Design and Construction Considerations for Earth and Rock-Fill Dams (EM 1110-2-2300) as an example of an unzoned embankment dam with interior inclined and horizontal drainage layers to control through seepage. The proposed earth dam is to be constructed in three segments:

1. Segment 1 will be used as a basis for the comparison. It will extend for the first 50 ft of the dam length and will be constructed using pure EPK clay for the compacted fill zone. The side slopes for this segment will be 1V : 2.75H, matching the slopes used for the Prompton dam.

2. Segment 2 will extend between 50 and 100 ft along the dam alignment. EPK clay treated with xanthan gum biopolymer that was pre-stabilized with 50% montmorillonite clay will be used for the construction of the compacted fill zone for this segment. The side slope of this segment will be i.e. 1V : 2.75H, similar to Segment 1.

3. Segment 3 will extend from 150 ft to 200 ft along the dam alignment and will use the same materials as this used for Segment 2. The only difference between Segment 2 and 3 is the slope of the dam sides; the latter segment will have steeper side slopes of 1V : 1.75H (~ 30° from horizontal).
It is proposed to install a vertical wall in between each two segments to insulate the failures. The sides of these vertical walls are to be painted with tar to minimize the impact of wall-soil friction on any detected failure.

![Plan View](image)

**Plan View**

![Cross-section](image)

**Cross-section**

Figure 24. Plan and elevation views of the proposed field experiment.

6.2. **Product Selections**

The materials selected for the proposed field experiment were described in the previous section for each of the proposed segments. These materials are:

1. The EPK clay as the main cohesive soil for the compacted fill. This clay was selected for the proposed demo because it meets the requirements for the compacted fill zone of earth dams and is radially available in the market in large quantities.

2. Xanthan gum biopolymer as the main biopolymer type to be used to stabilize the EPK clay. This biopolymer was selected because it is one of the cheapest biopolymers currently available in the market with sufficient quantities to be used in earth dams. Moreover, the response of Xanthan gum biopolymer is very well
characterized in the literature. Additionally, the performance of the EPK clay stabilized with xanthan gum was analyzed in this project and is currently fully understood.

(3) Montmorillonite clay as a filler to stabilize xanthan gum biopolymer before using the stabilized biopolymer to treat the EPK clay. This filler type was selected based on the experimental results performed in this project that showed a significantly better performance of the xanthan gum stabilized with montmorillonite clay filler compared to the other considered fillers.

6.3. Experimental and numerical modeling results

The factor of safety against slope stability for the proposed field demo was estimated using SLIDE limit equilibrium package. The geometry of the proposed earth dam was constructed in SLIDE for each of the segments as shown in Figure 26.

![Figure 25. SLIDE slope stability models. (a) right-to-left failure, and (b) left-to-right failure surface.](image)

As shown in Figure 26, the geometry and zones of the Promton dam were adopted
in the SLIDE models since these zones are recommended for the proposed field demo. The results of the laboratory experiments on the considered materials were incorporated in these slope stability models. Explicitly, the unconfined compressive strength of the compacted EPK clay with and without xanthan gum treatment determined in the experimental program was assigned to the compacted fill zone of the dam for each respective analysis. The foundation soil was assigned an infinite strength to eliminate any failure surface from penetrating into the foundation soil. For the site condition, the earth dam will be constructed on a concrete slab to ensure that the foundation soil does not influence any slope failure.

For each of the considered conditions, the factor of safety was determined following Bishop simplified, Janbu simplified, Spencer, and Crops of Engineers #1 methods. The lowest factor of safety of all these method (mostly Janbu simplified) was considered in the assessment of the performance performed here. While the proposed experiment considers only two slopes, these slopes were selected based on the factor of safeties obtained (Figure 27).

As shown in Figure 27, the factors of safety for the EPK clay stabilized with xanthan gum (with 50% montmorillonite clay filler) are significantly higher than those for the pure EPK clay for all side slopes. For the right-to-left failures (Figure 3.a), xanthan gum stabilization results in an increase of about 50% in the safety factor. While an increase of about 25% in the factor of safety is noticed for the biopolymer stabilized EPK clay over the pure clay considering left-to-right failures. It should be noticed also that the proposed slope for Segments 1 and 2 corresponds to 20° from the horizontal, while the proposed slope for Segment 3 corresponds to 32° from the horizontal.

It should be noticed here that the limit equilibrium method, the underlying basic method for all techniques used to determine these factors of safety, does not provide good estimates of the expected deformations. However, this analysis is considered sufficient since the main goal of this field experiment is to demonstrate the ability of biopolymer treated soils to support steeper slopes and resist biodegradability over the years. Thus, the proposed biopolymer soil treatment is considered successful is the field demo remains standing for the monitoring period and beyond. Clear deformations for all segments will be periodically measured on site using aerial and other techniques.

6.4. Techniques to transition to field scale

In the lab, the biopolymers were mixed with the EPK clay using a lab-scale mixer. To be able to apply this in the field, concrete mixing trucks are proposed to be used to ensure adequate mixing of the biopolymers with the clay powder. Additional, techniques that may be considered in-situ depending on the funding availability would be injection into an additional dam segment (not shown in Figure 25) consisting of silty sand material.
Figure 26. Minimum factor of safety for (a) right-to-left failure, and (b) left-to-right failure.

6.5. Long-term performance measures

The long-term performance measures that will be recorded in the proposed field demonstration will include:

(1) Surface contours of the dam, which will be measured using aerial images and conventional surveying techniques.

(2) Pore water pressures within the earth dam, to be measured using pore pressure gauges and tensiometers to determine any suction within the earth dam. These
gauges and tensiometers are to be installed symmetrically around the top of the dam every 25 ft (horizontally measured distance) of the side slopes. A pore pressure gauge and a tensiometer are to be installed every 10 ft into the dam at every one of the selected locations. Finally, three different sections of each Segment (Figure 25) are to be instrumented: 10 ft, 25 ft, and 40 ft from the beginning of the segment.

These contours will be used to determine the stability of the slopes of the earth dam. Furthermore, these results will be used to validate advanced finite element numerical models that will allow generalizing the results of this field experiments to other cases in the future.
7. TRANSITION TO USE PLAN

The end users will gain a free access to the project outcomes (e.g., reports and data) via the Stony Brook University Repository Academic Commons. Academic Commons is both a repository and a service to collect, organize, store, and share the scholarly output of Stony Brook University. Academic Commons furthers the engagement mission of the University by providing a platform from which the global community can benefit from the scholarly output of Stony Brook University. For more information about this system, please visit https://library.stonybrook.edu/scholarly-communication/academic-commons/

In addition to depositing all the project outcomes in the Academic Commons Repository, the contacts for the PI and all co-PIs will be provided in the final report of the project. All interested agencies will be encouraged to contact the project team to gain access to the information.

7.1. Partnerships

The project team has identified the following partners that will make use of the project outcomes in the near future:

1) The U.S. Army Corps of Engineers
2) The U.S. Bureau of Reclamation
3) Federal Emergency Management Agency (FEMA)
4) Wayne County Water and Soil Authority (Local Agency in Upstate NY)

7.2. FUNDING

There is no funding needed for the maintenance or support of the project outcomes for this project. However, any funding to address application-specific design will be provided by the agency managing such application if needed.
REFERENCES


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