Biopolymers in geotechnical engineering for soil improvement

Nourhen Fradj*, Ákos Török and István Kádár

Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, Hungary

Received: August 27, 2023 • Revised manuscript received: December 4, 2023 • Accepted: December 12, 2023
Published online: April 25, 2024

AKADÉMIAI KIADÓ

Pollack Periodica • An International Journal for Engineering and Information Sciences

19 (2024) 2, 82–86

DOI:
10.1556/606.2023.00937

ORIGINAL RESEARCH PAPER

ABSTRACT

Several biopolymer applications in geotechnical engineering have been adopted in recent years, notably dust control, soil strengthening, and erosion control. Although biopolymer soil treatment approaches can assure engineering efficiency while satisfying environmental protection standards, this technology requires more validation regarding site adaptability, durability, and economic feasibility. The influence of biopolymers on soil behavior is discussed within geotechnical engineering applications and practices, including soil consistency limits, strength and deformation parameters, hydraulic conductivity, soil-water properties, and erosion prevention.

Laboratory studies were performed to confirm the behavior of the treated soil, including Atterberg limits, proctor, and direct shear tests utilizing two types of biopolymers: guar gum and xanthan gum.

KEYWORDS

biopolymers, geotechnical engineering, soil strengthening, plasticity index, water content

1. INTRODUCTION

Soil is an essential natural resource sustaining life on Earth. However, soil deterioration and erosion are environmental severe challenges that can reduce soil production and nutrient loss. Biopolymers like guar and xanthan gum have been proposed as a solution to enhance soil's physical and mechanical characteristics while reducing erosion proneness [1].

The literature review has revealed that several studies have investigated the use of gum and xanthan gum as soil stabilizers in the case of different soil types and have reported promising results. For example, Chang et al. [2] found that adding guar gum improved soil aggregate stability and reduced soil erosion, while another study by Mendonça et al. [3] found that xanthan gum improved the rheological properties and erosion resistance of silty clay soil.

Both studies investigated the effects of biopolymers on the geotechnical properties of loess soil. Tong et al. [4] found that guar gum injection can significantly increase the unconfined compressive strength of loess soil, while also reducing soil permeability. Also, xanthan gum can improve the elastic modulus and shear strength of loess soil and its effectiveness is related to the concentration used.

In one laboratory experiment, the addition of 0.2% guar gum increased the unconfined compressive strength of loess soil by up to 50% compared to untreated soil [5]. Another study found that the addition of 0.2% xanthan gum increased the elastic modulus and shear strength of loess soil by up to 180% and 77%, respectively [4]. Note that the exact improvement in soil properties depends on many factors, namely soil type, biopolymer type and concentration, and curing time, and may vary for different soils and biopolymers. Further research is needed to establish a comprehensive understanding of the effects of biopolymer treatment on soil properties and to verify the improvement of Hungarian soil conditions.

*Corresponding author.
E-mail: nourhenmohcen.fradj@edu.bme.hu

AKJournals

Atterberg limits in the actual research were used to classify and describe fine-grained soils, and yet only two of these limit values are frequently used in current engineering applications, which are the plastic limit and the liquid limits (A 3rd limit, known as the shrinkage limit, is used on occasion). The liquid limit is the moisture percentage at which the soil transitions from a plastic to a viscous fluid state. The moisture content that indicates where the soil volume will not drop further if the moisture content is reduced is known as the shrinkage limit.

For instance, because of Atterberg limits tests done on the loess soil before applying the treatment with the guar gum, the liquid and plastic limits values have been determined as 26 and 19%, respectively, and a plasticity index of 8.5% according to ASTM D4318-17e1 [6].

The direct shear test is used to determine the shear strength parameters, Shear stress is the maximal resistance that a material can bear when sheared. It is among the most frequent and simple methods to determine the strength of soil, and it may be done both on undisturbed and remolded samples [7, 8].

This research intends to demonstrate the change in soil behavior following treatment with biopolymers, as determined by different geotechnical laboratory experiments. The investigations permitted the evaluation of the mechanical characteristics of raw soil and treated soil with biopolymer powder. These findings imply that the use of biopolymers in geotechnical engineering applications can successfully improve soil durability and strength.

2. MATERIALS AND METHODS

2.1. Natural soil

The soil used in the study was collected from a construction site, located near the city of Székesfehérvár in Hungary, the project's name is "South Connection Road".

This is the naturally occurring silty sand soil beneath the road; it is from 2 to 3 m depth. It is a loess soil forming around two-thirds of Hungary's total area, rendering it vulnerable to erosion and mass movement processes, particularly in mountainous areas. On hill slopes under agriculture, soil erosion is the largest environmental risk, but mass movement processes occur on all land cover types [9]. Loess is a geological deposit composed primarily of silt-sized grains held together loosely by calcium carbonate. It is usually homogeneous and exceedingly porous, with vertical capillaries that allow the silt to fracture and form vertical cliffs [10].

This type of soil has a low moisture content of 10–15%, which rises as porosity falls. It has a porosity of 50–55% and drops to a depth of around 10 m. Below this depth, porosity varies as a function of grain size distribution. When loess is combined with clay, the porosity can range between 34 and 45%. The porosity of sandy loess is around 60% [10, 11].

Furthermore, it is a kind of sediment that is weakly consolidated and has a low compressive strength [8]. It is, nevertheless, stable as long as it is kept dry.

2.2. Guar gum

Guar Gum (GG) is a neutrally charged polymer produced from the seeds of the leguminous plant *Cyamopsis tetragonoloba*. Guar gum is a member of the Galactomannan family. It has a 1.4-linked D-mannopyranose backbone and random branch points of D-galactose units. The tendency of guar gum to hydrate fast in cold water systems results in highly viscous solutions even at low concentrations. At the same biopolymer-to-water ratio, the guar gum solution has a greater viscosity than the xanthan gum solution. Concentration, dispersion, temperature, pH, and the presence of other substances all influence the rheology of guar gum solutions. Uncontrolled hydration can cause a decline in viscosity, limiting the use of guar gum [12].

Guar gum is renowned for its ability to reduce the potential of collapse and resist settlement after saturation. It was explained by the larger molecular weight of guar gum compared to xanthan gum, where higher molecular weights produced higher viscosities in solutions and quickly increased bonding between particles, which reduced permeability.

2.3. Xanthan gum

The bacterium Xanthomonas generates the anionic polymer Xanthan Gum (XG) campestris. Xanthan gum solution will be exceedingly viscous when combined with both cold and hot water due to its viscous hydrogel formation with water.

Because it absorbs water molecules via hydrogen bonding, xanthan gum is commonly employed as a viscosity thickener.

In geotechnical engineering, xanthan gum is used to reduce the permeability of sandy soils by filling their pores and to increase soil erosion resistance by improving water retention [13].

According to Chang et al. [2], a small amount of Korean red-yellow soil treated with xanthan gum increased soil erosion resistance and vegetation culture. Xanthan gum-treated soil exhibits high water adsorption during the rainy season and high soil moisture retention during the dry season [14].

The impact of saturation was decreased by the reduction in permeability, which also prevented seepage within the soil matrix. Guar gum combination has a better shear resistance than xanthan gum mixture because guar gum has a higher solution viscosity than xanthan gum [15].

2.4. Sample preparation

For at least 16 h, the soil sample was oven dried. After that, preparatory tests; the sieve test, Proctor test, and Casagrande test were carried out.

The main study findings will be obtained by the application of the Atterberg limit and the direct shear test. First, untreated sample soil is used in the studies; thereafter, biopolymer-based soil is used.

Guar gum and xanthan gum were put into the soil at a ratio of 1% of soil mass. The crucial point to note is that, unlike previous studies, there is no consideration of a curing period throughout this experiment. The mixing technique was in dry form, after determining the precise weight of the whole combination, the soil sample was mixed with the biopolymer powder in dry form using a thick plastic bag to make it more uniform before adding the specified amount of water estimated by percentage. Subsequently, the sample was mixed with the specified amount of water (in this study, the optimal water content was used), and the direct shear test was performed with different loads on different sample compositions (loess soil plus Guar gum or Xanthan gum). The same procedure is employed for the Atterberg limit test; however, the amount of water used in this test was determined by the workability of the soil paste with the biopolymer powder.

2.5. Test procedure

As a start, and to identify the soil type and describe it, the sieve analysis was performed to determine the grain size distribution for soils with diameters greater than 0.075 mm according to the ASTM D6913-04(2009)e1 standard [16]. The sieves are made of woven wires with square holes used in this procedure combined with soil hydrometer analysis according to ASTM D7928-21e1 standard [17]. The results of the test show the grain size distribution of soils smaller than the No. 200 (75 m) sieve.

When combined, it gives a complete gradation profile of soils, including coarser particles. Figure 1 shows the particle size distribution.

A Proctor test according to ASTM D698-12 (2021) standard [18] was also performed to evaluate the connection between soil moisture and dry density for a particular compaction effort. The amount of mechanical energy given to the soil mass is called the compaction test effort. Tables 1 and 2 illustrate the test conditions and the trials' measurements.

The previous laboratory tests were conducted at the Laboratory of Geotechnics and Engineering Geology of

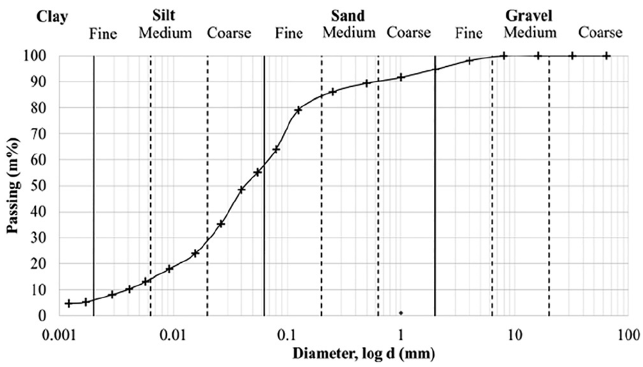

Fig. 1. Particle size distribution curve (*Source*: Authors')

Budapest University of Technology and Economics only on untreated soil (raw soil).

The main two laboratory tests considering the treatment of the soils with biopolymers are the Atterberg limits and the direct shear test.

The Atterberg test was conducted on the untreated soil in the preliminary phase after that it was performed on the soil samples treated with biopolymers GG and XG.

This test was originally developed to describe fine-grained soils, and yet only two of seven limit values are frequently used in current engineering applications which are the plastic limit and the liquid limit.

Finally, the direct shear test was performed on nine specimen samples of untreated loess soil, with three loading points each (50, 100, and 150 kPa) to compare a range of data. The same procedure was performed on biopolymer-treated specimens, with only a 1% ratio of both biopolymers, GG and XG, to treat the soil.

Because there was no preceding literature outlining the specific process of mixing, this experiment was carried out utilizing the optimal water content in the mixing samples in the direct shear test.

3. RESULTS AND DISCUSSION

3.1. Atterberg test

As a result of Atterberg limits tests performed on the soil before applying the treatment, the liquid and plastic limit values have been determined as 27% and 18%, respectively, and a plasticity index of 8.5% according to ASTM D4318-17e1 [6].

Furthermore, the particle-size distribution of the soil, as measured by hydrometer and sieve tests and following Eurocode, indicates that the soil is low plasticity sandy silt.

After treating the soil sample with 1% guar gum and 1% xanthan gum, it is observed in Table 3 a remarkable increase in the plasticity index (three times the untreated soil plasticity), from 8.5% (untreated soil) to 26% after applying 1% of GG and increased to 24.7% after applying 1% of XG.

Increasing the liquid limit value of soil after treatment from 26% for untreated soil to reach 53.3% with 1% of GG and 47.5% with 1% of XG.

Furthermore, prior studies [19] utilizing Scanning Electron Microscopy (SEM) revealed that the gum takes on a gel-like structure after being combined with water, and this gel-like structure forms some bonds between the soil particles. This process is assumed to be responsible for the change in consistency limit after adding the two gums to sandy silt soil.

Table 1. Proctor test conditions

Test conditions					
Machine compression		Number of layers	5	Mold diameter	10.2 cm
Ramming mass	4.5 kg	Number of strokes per layer	25	Mold height	11.6 cm
Drop height	46 cm	Mold type	Proctor	Mold volume	947.9 cm^3

Source: Based on Proctor Test Standards [18].

Table 2. Table of data

Trials		1	2	3	4	5
Compaction Result						
Mold & wet soil mass	(g)	4,470.0	4,650.0	4,840.0	4,820.0	4,730.0
Mass of wet soil	m_n (g)	1,745.0	1,925.0	2,115.0	2,095.0	2,005.0
Mass of dry soil	m_d (g)	1,704.6	1,815.7	1,933.1	1,857.5	1,730.0
Dry bulk density	ρ_d (g cm^{-3})	1.80	1.92	2.04	1.96	1.83
Determination of water content						
Wet weight	m_n (g)	128.2	124.7	136.9	112.2	110.8
Dry weight	m_d (g)	125.2	117.7	125.1	99.5	95.6
Water content	w (%)	2.4	6.0	9.4	12.8	15.9

Source: Authors'.

Table 3. Atterberg limits for different soil compositions

	Untreated soil	1% GG	1% XG
Liquid limit: w_L (%)	26.8	53.3	47.5
Plastic limit: w_p (%)	18.4	27.3	22.8
Plasticity index: I_p (%)	8.5	26	24.7
Natural water content: w_n (%)	9.8	9.8	9.8
Relative consistency index: I_c (%)	2.01	1.67	1.53

Source: Authors'.

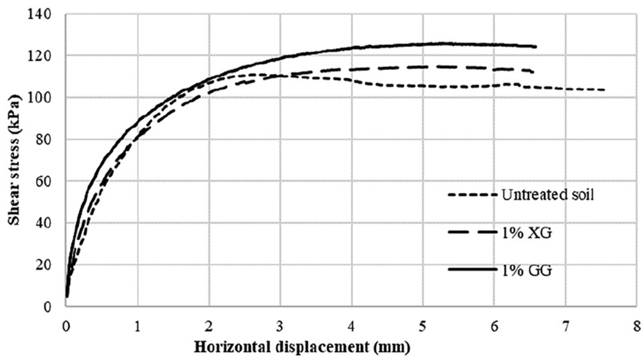

Fig. 2. Variation of the shear stress with the strain for different soil mixtures (*Source*: Authors')

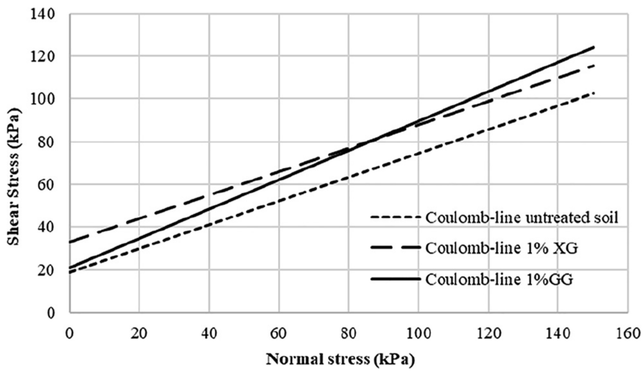

Fig. 3. Variation of the shear strength interface accordingly with the normal stress for different soil mixtures (*Source*: Authors')

3.2. Direct shear test

Biopolymer treatment has slightly improved the cohesion compared to the untreated condition for the xanthan gum (c' = 33 kPa), and a slight decrease after treatment with guar gum (c' = 16.6 kPa) after being initially at (c' = 18.7 kPa) before treatment.

Meanwhile, it has a small effect on the inter-particle friction angle of the soils (φ), so it increased from the untreated condition angle of 29°–35.5° with GG and it kept the same value with the XG.

In the wet state, which is the case in the actual research, the friction angle value of the treated soils is slightly more than the value of the friction angle in the untreated soils, showing that the wet biopolymers hydrogels filling the pores have a negligible influence on inter-granular friction according to some research for instance, the Chang et al. [12] study.

The same study [12] has indicated that the change in cohesion and friction angle is affected by biopolymer and soil type. For instance, the same study has proved with results that the xanthan gum gives better results for sandy soils (granular soils) and the guar gum is more suitable or gives better results for clay soils (fine soils).

As it is shown in Figs 2 and 3, the shear strength increases with the use of the biopolymers and as a result, the behavior of the curves tends to be more plastic.

Based on the test results in Fig. 3 it is observed that the Coulomb line of the soil mixed with 1% of XG is parallel with the original soil's line, which means that the cohesion has increased compared to the original, but the friction angle remained the same.

In the case of GG, different behavior can be seen as a slight increase in the cohesion and friction angle, summarized results are shown in Table 4.

Table 4. Shear parameters change from untreated to treated condition

	Untreated soil	1% GG	1% XG
Peak value f' (°)	29	35.5	29
Peak value c' (kPa)	18.7	16.6	33
Residual f' (°)	29	36	29.5
Residual c' (kPa)	12.9	14.4	28.1

Source: Authors'.

4. CONCLUSION

The purpose of the study is to look into the effect of biopolymers on the strength of soil in confined environments. A variety of laboratory tests were conducted in the Laboratory of Geotechnics and Engineering Geology of Budapest University of Technology and Economics to attain this goal. This testing included particle size distribution, Proctor tests, Atterberg limit testing, and direct shear tests. These experiments were performed on soil samples both in their original state and after treatment with guar and xanthan gum biopolymers.

The biopolymer powder ratio used was 1%. This percentage was chosen based on previous research in the field. These include 1%, 2%, and 3% mixing ratios, which showed noticeable improvement in the mechanical behavior of the treated soil. As a result, in this article, a ratio of 1% was utilized to show the following findings:

- The plasticity indexes witnessed a threefold increase compared to their original value after GG and XG treatment;
- The liquid limit saw a significant rise, whereas the plastic limit demonstrated a comparatively modest increase;
- Treated soils showed higher shear strength. Alterations were observed in internal friction angle and cohesion;
- Biopolymer soil treatment can enhance geotechnical attributes and foster environmentally sustainable development;
- A small proportion of biopolymers (1%) can lead to substantial differences, highlighting the field's promising prospects for further research;
- Future studies should explore various ratios and confinement conditions to gain a comprehensive understanding of result variations.

ACKNOWLEDGMENT

The Laboratory of Geotechnics and Engineering Geology of the Budapest University of Technology and Economics and the technicians are acknowledged.

REFERENCES

[1] G. Nagy and Z. Illés, "Verification and modeling of seepage control walls," in *6th International Conference on Geotechnical and Geophysical Site Characterization*, Budapest, Hungary, September 26–29, 2021, pp. 1–8.
[2] I. Chang, A. K. Prasidhi, J. Im, H. D. Shin, and G. C. Cho, "Soil treatment using microbial biopolymers for anti-desertification purposes," *Geoderma*, vols 253–254, pp. 39–47, 2015.
[3] A. Mendonça, P. V. Morais, A. C. Pires, A. P. Chung, and P. V. Oliveira, "A review on the importance of microbial biopolymers such as xanthan gum to improve soil properties," *Appl. Sci.*, vol. 11, no. 1. 2021, Art no. 170.
[4] T. Jiand, J. D. Zhao, and J. R. Zhang "Splitting tensile strength and microstructure of xanthan gum-treated loess," *Sci. Rep.*, vol. 12, 2022, Art no. 9921.
[5] P. Bagheri, I. Gratchev, and M. Rybachuk, "Effects of xanthan gum biopolymer on soil mechanical properties," *Appl. Sci.*, vol. 13, no. 2, 2023, Art no. 887.
[6] *ASTM D4318-17e1:2018*, Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, 2018.
[7] *ASTM D3080-04:2022*, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, ASTM International, 2022.
[8] D. Bozsaky and R. Ábrahám-Horváth, "Laboratory tests on properties of innovative natural thermal insulation material," *Pollack Period.*, vol. 18, no. 2, pp. 125–130, 2023.
[9] P. Kassai and I. Sisák, "The role of geology in the spatial prediction of soil properties in the watershed of Lake Balaton, Hungary," *Geologia Croatica*, vol. 71, no. 1, pp. 29–39, 2018.
[10] J. W. Moggan, C. F. Forster, and L. Evlsont, "A comparative study of the nature of biopolymers extracted from anaerobic and activated sludges," *Water Research*, vol. 24, no. 6, pp. 743–750, 1990.
[11] A. Šoltész, D. Baroková, Z. D. Shenga, and M. Cervenanská, "Hydraulic assessment of the impacts of gate realization on groundwater regime," *Pollack Period.*, vol. 15, no. 3, pp. 162–171, 2020.
[12] I. Chang, M. Lee, A. T. P. Tran, S. Lee, Y. M. Kwon, J. Im, G. C. Cho, "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices," *Transportation Geotechnics*, vol. 24, 2020, Art no. 100385.
[13] I. Chang, Y. M. Kwon, J. Im, and G. C. Cho, "Soil consistency and interparticle characteristics of xanthan gum biopolymer–containing soils with pore-fluid variation," *Can. Geotechnical J.,* vol. 56, no. 8, pp. 1206–1213, 2019.
[14] J. Im, A. T. P. Tran, I. Chang, and G. C. Cho, "Dynamic properties of gel-type biopolymer-treated sands evaluated by resonant column (RC) tests," *Geomechanics Eng.*, vol. 12, no. 5, p. 815–830, 2017.
[15] M. A. Khodabandeh, G. Nagy, and Á. Török, "Stabilization of collapsible soils with nanomaterials, fibers, polymers, industrial waste, and microbes: Current trends," *Constr. Build. Mater.*, vol. 368, 2023, Art no. 130463.
[16] *ASTM D6913-04(2009)e1*, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, 2017.
[17] *ASTM D7928-21e1*, Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, ASTM International, 2021.
[18] *ASTM D698-12(2021)*, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN·m/m^3)), ASTM International, 2021.
[19] B. Bagriacik, B. Ok, and M. T. M. A. Kahiyah, "An experimental study on improvement of cohesive soil with eco-friendly guar gum," *Solid and Rocks*, vol. 44, no. 2, pp. 1–9, 2021.