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Enhancement of soil mechanical properties with biopolymers

Amélioration des propriétés mécaniques des sols avec des biopolymères

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ABSTRACT: The utilization of biopolymers in geotechnical engineering to enhance soil properties has garnered significant interest owing to their environmentally friendly, biodegradable, and sustainable characteristics. Various biopolymers, including chitosan, alginate, pectin, cellulose, and starch, have been explored for soil improvement purposes. Notably, guar and xanthan gums have emerged as prominent biopolymers for soil stabilization applications. The primary objective of employing biopolymers is to augment mechanical properties such as shear strength, stability, and permeability of soils. Evaluations of treated soils have consistently demonstrated the effectiveness of guar gum and xanthan gum in enhancing soil behavior, rendering them suitable for diverse geotechnical applications. Moreover, they represent a sustainable and eco-friendly alternative to conventional chemical and mechanical soil improvement techniques, which may entail adverse environmental consequences. In the research, several laboratory tests, including Atterberg limits, Proctor, and direct shear tests, were conducted on Hungarian soils treated with guar and xanthan gums to observe their mechanical behavior after treatment. Specifically focusing on uniformly graded sandy soil, the research delves into shear test parameters discussion and microscopic visualizations depicting the bonds between guar and xanthan gums and the sand particles.

RÉSUMÉ: L'utilisation de biopolymères dans l'ingénierie géotechnique pour améliorer les propriétés des sols a suscité un grand intérêt en raison de leurs caractéristiques écologiques, biodégradables et durables. Divers biopolymères, dont le chitosane, l'alginate, la pectine, la cellulose et l'amidon, ont été étudiés à des fins d'amélioration des sols. Les gommes de guar et de xanthane se sont notamment imposées comme des biopolymères de premier plan pour les applications de stabilisation des sols. L'objectif premier de l'utilisation des biopolymères est d'augmenter les propriétés mécaniques telles que la résistance au cisaillement, la stabilité et la perméabilité des sols. Les évaluations des sols traités ont constamment démontré l'efficacité de la gomme guar et de la gomme xanthane dans l'amélioration du comportement des sols, ce qui les rend appropriés pour diverses applications géotechniques. En outre, elles représentent une alternative durable et écologique aux techniques conventionnelles d'amélioration chimique et mécanique des sols, qui peuvent entraîner des conséquences néfastes sur l'environnement. Dans la recherche actuelle, plusieurs tests de laboratoire, y compris les limites d'Atterberg, les tests Proctor et les tests de cisaillement direct, ont été effectués sur des sols hongrois traités avec des gommes de guar et de xanthane afin d'élucider leur comportement mécanique. En se concentrant spécifiquement sur les sols sableux à granulométrie uniforme, la recherche examine les résultats des tests de cisaillement et les visualisations microscopiques décrivant les liens formés entre les gommes de guar et de xanthane et les particules de sable.

Keywords: Biopolymers; soil stabilization; shear strength; stability; permeability.

1 INTRODUCTION

Over time, several approaches have been developed to enhance the geotechnical characteristics of soil. These include chemical stabilization, dewatering, natural and synthetic soil reinforcement, and the provision of drains.

The type of soil, the project's requirements, the budget, the available expertise, and other considerations all play a role in the technique selection. One of the most often used methods for improving the quality of the ground is the use of different admixtures and additives to change the properties of the soil. But there's also reason for considerable concern over how this stabilizing method affects the soil ecosystem.

When it comes to improving the strength of soil, chemical techniques that include adding cementitious additives, such as cement, lime, etc., work incredibly well, but they also permanently change the soil's environment. Furthermore, throughout the cement product's production process, significant greenhouse gasses such as carbon dioxide are released (Chang et al., 2016)

The use of cement and lime is often seen as less ecologically benign than the use of industrial by-products. Industrial by-products are fundamentally more sustainable because they constitute a beneficial reuse application that is an alternative to landfilling or another comparable by-product disposal. Because of the high Ca $(OH)_2$ concentration of the stabilizer, traditional additive stabilization typically elevates soil pH following treatment, which may have negative environmental impacts such as affecting groundwater quality or limiting vegetation growth. Traditionally treated soils are also overly brittle, which can have an impact on the performance and stability of structures (Chang et al., 2015).

The review of existing literature has shown that numerous studies have explored the use of gum and xanthan gum to stabilize soil across various soil types, yielding promising outcomes. For instance, Chang et al. (2015) observed that the inclusion of guar gum enhanced soil aggregate stability and mitigated soil erosion, while Mendonça et al. (2021) noted that xanthan gum improved the rheological properties and resistance to erosion in silty clay soil. Both studies focused on assessing the impact of biopolymers on the geotechnical characteristics of loess soil. Jiang (2022) discovered that injecting guar gum significantly elevated the unconfined compressive strength of loess soil while decreasing its permeability. Similarly, xanthan gum was found to enhance the elastic modulus and shear strength of loess soil, with its effectiveness being linked to the concentration used.

In a laboratory trial, the addition of 0.2% guar gum led to a notable increase of up to 50% in the unconfined compressive strength of loess soil compared to untreated soil (Bagheri, 2023). Another study revealed that incorporating 0.2% xanthan gum resulted in substantial enhancements of up to 180% in elastic modulus and 77% in shear strength of loess soil (Jiang, 2022). It's important to note that the precise improvements in soil properties depend on various factors such as soil type and concentration of biopolymer, and curing duration, thus these effects may differ across different soils and biopolymers. Further research is necessary to fully grasp the impacts of biopolymer treatment on soil properties and to validate its efficacy in improving soil mechanical properties.

Biopolymers are naturally occurring polymers with remarkable tensile strength that are non-toxic and biodegradable. Because of potential cost savings, low environmental impact, non-toxicity, and non-secondary pollution, biopolymers are acknowledged as a viable alternative to traditional chemical polymers (Aminpour and O'Kelly, 2015).

2 MATERIALS

2.1 Soil

The soil was obtained from a construction site in Göd, Hungary originated from a mine of Dűne Szektor Kft. (October 2022).

It is greyish-black in color and does not contain any organic content.

The grain size distribution curve of the soil as measured by hydrometer and sieve tests and following the ASTM D, 2487-06 ASTM International (2021), indicates that the soil is a uniformly graded sand, as shown in Figure 1. The percentages of different soil components are presented in Table 1 and the grading characteristics of the soil are shown in Table 2.

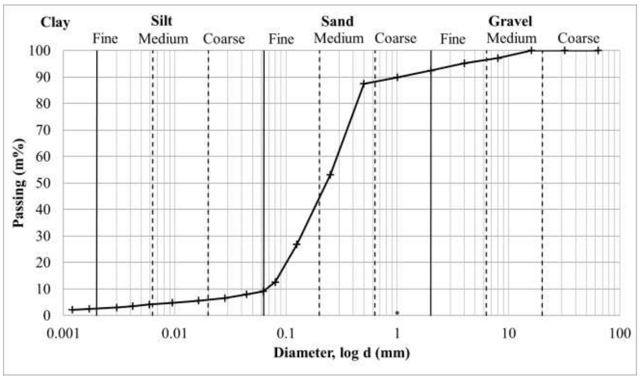

Figure 1. Grain size distribution curve of sand.

Table 1. Soil composition.

Soil Fractions m (%)	
Gravel K(Gr)	7.57%
Sand H(Sa)	83.17%
Silt I(Si)	6.63%
Clay A(Cl)	2.63%

Table 2. Grading characteristics of the soil.

Soil characteristics			
D90	1.059 mm	Cu	4.50
D60	0.300 mm	Cc	0.98
D30	0.140 mm	w	1.3%
D10	0.067 mm	γ_s	2.65 kN/m^3

2.2 Guar Gum (GG)

Guar gum, scientifically identified as Cyamopsis tetragonolobus, is a natural biopolymer obtained from the endosperm polysaccharide of guar seeds, classified within the Leguminosae family, and categorized as a seed gum. Its composition comprises D-galactose and D-mannose polymers in a 1:2 ratio (Sujatha and Saisree, 2019).

Upon complete hydration, guar gum transforms a thixotropic, viscous, colloidal dispersion. The borate ions inherent in guar gum serve as cross-linking agents, facilitating the formation of cohesive and thick gels.

2.3 Xanthan Gum (XG)

Xanthan gum is a polysaccharide that is extensively used as a food additive and rheology adjuster; it is generated by the Xanthomonas campestris bacteria by fermentation of glucose or sucrose. Xanthan gum's ($C_{35}H_{49}O_{29}$) fundamental chemical structure is a linear linked b-D glucose backbone with a trisaccharide side chain on every other glucose. Using hydrogen bonds, the trisaccharide side chain is aligned with the backbone, providing stability and overall shape.

3 METHODS

3.1 Sample preparation

The soil samples are oven-dried at 100 °C to 110 °C for 24 h. The guar gum and xanthan gum-treated soil samples are prepared by adopting the dry mixing procedure. Initially, the biopolymer in powder form is mixed with the required amount of soil at percentages of 0.5% and 1% by weight of the soil.

The biopolymer powder is mixed thoroughly with the soil sample in a plastic bag to be sure that the fine particles of powder won't be wasted in the air, and then the required water amount is added. In this experiment, the optimum water content was added for the mixing, which is 9.5% of the total mass of the dry mixture. With the first contact of the biopolymer with water, the galactose, and the mannose present in the biopolymer hydrate at a faster rate by absorbing the water rapidly, and the soil becomes coated with the biopolymer.

3.2 Experimental investigation

3.2.1 Microscopic observations

The interaction of sand with the biopolymer was investigated microscopically using a transmitted illumination optical microscope (Olympus BH2 PLM Asbestos Polarizing Microscope) see Figure 2.

This Olympus BH2 microscope is equipped with a binocular head featuring a pair of CWHK 10x eyepieces, with one eyepiece incorporating a crossline reticle. The Bertrand lens module includes a rotating analyzer and is furnished with a 530 nm wave plate.

The nosepiece, offering four positions, is fitted with D Plan PO objectives of 10x, 20x, 40x, and a Central Stop Dispersion 10x A PO objective. The stage is capable of 360-degree rotation and is accompanied by a set of stage clips. Additionally, the flip-out condenser is complemented by an attached rotating polarizer (Microscope central, 2023).

For this research, samples were prepared in small portions immediately and observed by the microscope. The two types of biopolymers were observed independently to analyze their microscopic structure, then mixed dry with sand particles, Finally, some water drops were added to the mix to visualize the created bonds between the powders and the sand grains.

Figure 2. Olympus BH2 PLM Asbestos Polarizing Digital Microscope.

3.2.2 Shear box test

After finishing the preparation of the sample and where homogeneity was achieved, the direct shear test was conducted using the machine in Figure 3.

Figure 3. Direct shear test (The Laboratory of Geotechnics and Engineering Geology at BME University, Hungary).

This test is among the most frequent and simple methods to determine the shear strength of soils. It was performed on five specimens with 5 different mixtures: an untreated sandy sample and four treated samples with the ratios, respectively: 0.5%GG, 1%GG, 0.5%XG, and 1%XG. The amount of water was specified to be the optimum water content, which is 9.5%. The shear tests were done with three loading points each (50, 100, and 150 kPa) to get enough outputs to compare.

The setting inputs of the shear box test are resumed in Table 3.

Table 3. Direct shear box parameters used in geotechnical engineering laboratory (BME university).

DEVICE DATA		
Frame length (L):	60	mm
Frame width (B):	60	mm
Frame area (A):	3600	mm^2
LOADING PARAMETERS		
Shear velocity	0.5	mm/min
Max. displacement	6.5	mm
Loading type	Constant rate	
Consolidated	yes	

4 DISCUSSION

The preference for guar gum and xanthan gum as stabilizing agents was driven by their natural abundance and sustainable characteristics, leading to enduring positive impacts. Extensive experimental tests were carried out to investigate the feasibility of utilizing these biopolymers for enhancing the geotechnical characteristics of soil, and the findings from these tests are detailed in the study.

4.1 Microscope

According to the results obtained using the Olympus microscope at different magnifications, the granules displayed an interesting diversity of morphologies ranging from oval, spherical, and polygonal to irregular forms depending on the type of the utilized biopolymer. In this phase of research, the Olympus microscope provided a simple visualization of the GG and XG powders on a bigger scale which also allowed us to compare the shapes and forms of these biopolymers, see Figures 4 and 5.

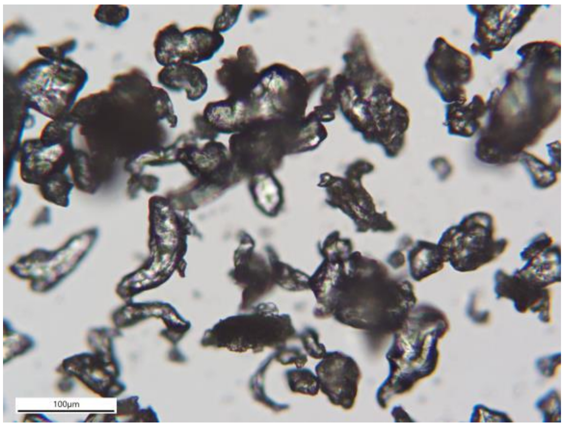

Figure 4. Guar gum at 200X magnification.

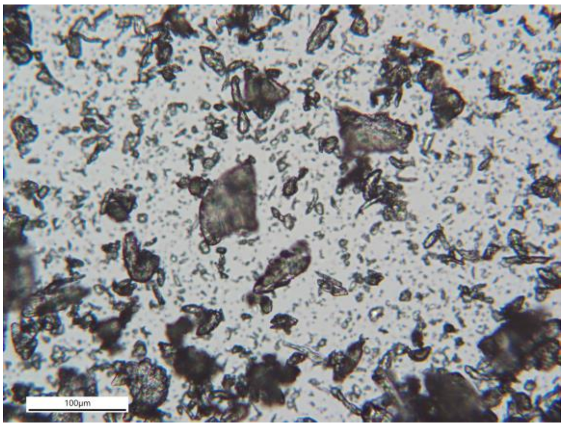

Figure 5. Xanthan gum at 200X magnification.

For instance, at the same 200X magnification, it is clear that GG has bigger particles than the XG particles, they are more fine and dense, it is also shown that the particle quantity of XG is more than the one of GG, as a result, it was mostly the reason why it works more with granular soils proving the results found by previous literature (Bagheri, 2023; Chang et al., 2015). However, GG was proved more efficient with cohesive soils (Bagriacik et al., 2021). Under the microscope, the raw soil in this study—which is sand—also revealed an intriguing shape with shades of brown and yellow colors. Refer to Figure 6.

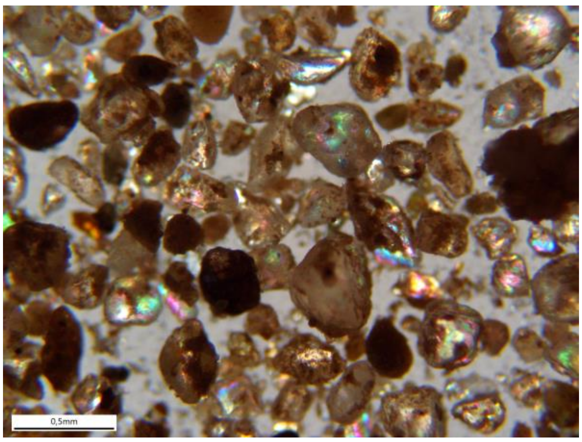

Figure 6. Sand sample with 40X magnification.

Observing the behavior of the soil in dry form with the two different powders and the entire mixture after adding water was the most fascinating aspect. It was shown by the microscopic magnification that the hydrogen linkages formed the instantaneous bonds between the biopolymer grains and soil crystals.

The water filled the voids, and the powder created a coating on the sand particles, the white-colored shapes are the gel-like structure created by water plus powder.

Figures 7 and 8 show both dry and wet mixtures of soil with GG and XG biopolymers at 40X magnification.

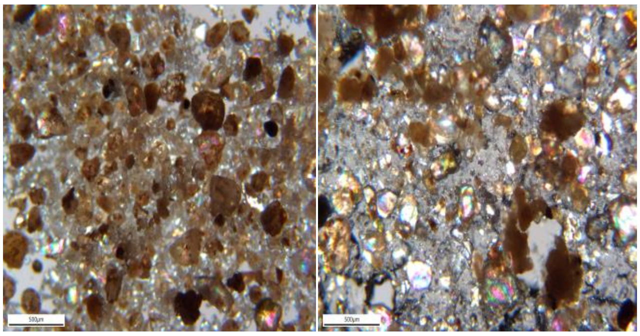

Figure 7. Dry (left) and wet(right) mixtures of soil with GG at 40X magnification.

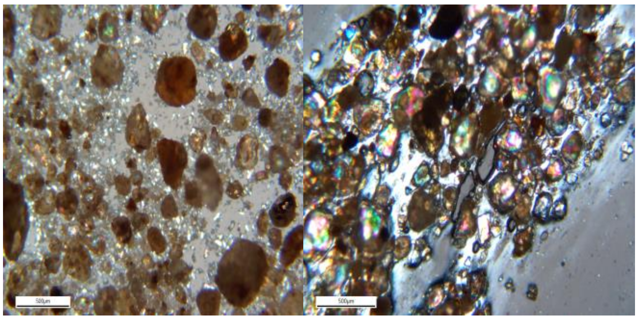

Figure 8. Dry (left) and wet(right) mixtures of soil with XG at 40X magnification.

4.2 Shear test

The initial soil exhibits a friction angle with a peak value of 33° and 0 kPa cohesion, characteristic of sandy soil. Subsequent treatment with Guar Gum (GG) and Xanthan Gum (XG) at varying ratios results in notable changes in soil properties. Simultaneously, cohesion experiences substantial improvement, with the peak value reaching 18.4 kPa, after being initially cohesionless, this result was achieved with just a 0.5% addition of GG. A parallel evolution is observed with a 1% addition of the same powder.

On the other hand, XG-treated sand demonstrates significant improvements in cohesion, exceeding the GG, results are shown in Table 4. This observation is consistent with current literature findings (Chang et al., 2020), indicating that XG is more commonly employed for granular soils, such as the soil under investigation in the present research.

Biopolymers like guar gum and xanthan gum can act as lubricants between soil particles, reducing inter-particle friction. This lubricating effect can lead to a slight decrease in friction angle as the soil particles experience less resistance to sliding past each other. However, this decrease is typically minimal compared to the increase in cohesion. The addition of biopolymers may also influence the arrangement of soil particles. The formation of a cohesive matrix can promote closer packing of particles, leading to improved interlocking and a slight reduction in friction angle.

Table 4. Shear Test results.

	Friction angle (°)		Cohesion (kPa)	
(%)	**Peak**	**Residual**	**Peak**	**Residual**
0.5% GG	23.5	26.5	18.4	6.9
1% GG	26	27	9.8	6.4
0.5% XG	27.5	25	18.4	16.6
1% XG	28.5	27	11.9	11.4

5 CONCLUSIONS

The research delves into an examination of guar gum and xanthan gum biopolymers concerning the stabilization of sand soil, aiming to enhance geotechnical properties while preserving mineral compositions. The findings reveal observable modifications in geotechnical properties with the addition of 0.5% and 1% concentrations of both guar gum and xanthan gum. This study provides valuable insights into the underlying mechanisms of stabilization between biopolymers and soil, as uncovered through various laboratory tests, including meticulous microscopic investigations.

Key conclusions drawn from the study highlight a change in the behavior of the granular soil;

- In Xanthan-treated granular soil, the enhanced strength primarily arises from the formation of the Xanthan matrix on the soil's surface and within voids. This matrix notably contributes to the increased shear strength of the soil.
- When water, guar gum, or xanthan gum is added to improve sandy soil, cohesion increases due to enhanced particle bonding facilitated by these substances. This results in higher overall shear strength. However, the friction angle may remain steady or increase slightly due to changes in particle arrangement and interlocking.
- Determining the optimal dosage of biopolymers is crucial and contingent on specific purposes,

such as stabilization, enhancing dam permeability, or improving the plasticity of a given soil.

Future studies aimed at precisely quantifying the use of xanthan and guar gum in soil stabilization would significantly enhance our understanding of stabilization mechanisms and improve overall process efficacy. Embracing these microbial enhancers opens avenues for altering biopolymer stabilization and modifying soil characteristics in ways not achievable with conventional stabilizers like cement.

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