

STUDY OF THE IMPACT OF BIOPOLYMER AND GEOSYNTHETICS REINFORCEMENT ON SOIL STRENGTHENING

Assel Tulebekova

Department of Civil Engineering¹

Zhanar Kusbergenova✉

Department of Civil Engineering¹

kusbergenovazh@gmail.com

Balganym Dosmukhambetova

Department of Civil Engineering¹

Talgat Abilmazhenov

Department of Civil Engineering¹

Ilyas Zhumadilov

Department of Civil Engineering and Geodesy²

¹L. N. Gumilyov Eurasian National University

2 Satpayev str., Astana, Republic of Kazakhstan, 010008

²Shakarim University

20A Glinka str., Semey, Republic of Kazakhstan, 071412

✉ Corresponding author

Abstract

Under contemporary conditions, various soil reinforcement methods are employed, each possessing distinct characteristics and applications. These methods aim to improve the strength characteristics and stability of soil foundations. This study evaluates the effectiveness of combined soil reinforcement using a biopolymer (xanthan gum) and a geosynthetic (non-woven geotextile). The study included preparation of the modified soil, pH determination, and structural analysis using scanning electron microscopy to evaluate the physicochemical properties of soil, particle morphology, and interaction with the biopolymer. Unreinforced soil samples, as well as samples modified with biopolymer and combined reinforcement (biopolymer-geosynthetics), were shear tested to study their strength properties and resistance to deformation. The aim was to examine the effect of different reinforcement methods on the mechanical behavior of the soil. The test results showed that the combined reinforcement with biopolymer and nonwoven geosynthetics improved the shear strength. It was observed particularly at a low shear stress level. At the same time, soil cohesion increased significantly, while the impact on the friction angle was generally negligible. The friction angle of the soil after combined reinforcement increased by 14 %, and soil cohesion increased from 8 kPa to 23 kPa. Discussing the application of the combined reinforcement method, technological features, and advantages of the technique is important for understanding the overall effectiveness of soil stabilization. This method of soil modification has demonstrated effectiveness and represents a promising approach for enhancing soil properties.

Keywords: biopolymer, geosynthetics, soil strengthening, reinforcement, shear test, sample, modification, xanthan gum, microstructure, efficiency.

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1. Introduction

Today the urgent problem is to reduce the negative impact of engineering activities and search for new environmentally friendly solutions [1, 2]. Various methods are used to strengthen weak soils, significantly improving their properties. Many traditional methods, however, have harmful environmental impacts that may be irreversible [3]. For example, cement-based soil stabilization, which involves adding cement to the soil, is widely used for its reliability and effectiveness

but requires high material and energy costs [4]. Another example is gypsum stabilization, used for clayey and shallow soils [5]. These methods use products from the cement industry that contribute to carbon dioxide emissions, which contribute to global warming and have serious impacts on biodiversity.

In this regard, the development of modern methods of strengthening weak soils using biopolymer soil treatment holds significant potential [6]. The main idea of which is to use biopolymers produced from cultural complexes with both quantity and quality control. Biopolymers are naturally occurring polymers produced by living organisms and fall into three main groups: polynucleotides, polypeptides, and polysaccharides [7]. They are sustainable, low-carbon, and renewable resources because they come from nature. Today in the world practice among the biopolymers used are xanthan, gellan, guar gum, alginate, and agar gum [8].

The study [9] investigated the effect of guar gum treatment on consistency limits, compaction characteristics, permeability, compressive strength, and durability of soil at different percentages of guar gum content. The results showed an increase in yield strength, plasticity limit, and shrinkage by 44 %, 80 %, and 105 %, respectively.

A comparative study of the effectiveness of carrageenan with xanthan as the most used biopolymer in geotechnical construction is presented in the investigation [10], where kaolinite silt and sand in different proportions treated with different ratios of biopolymers to increase the strength of the material were used to analyze the effect of soil particle size. The addition of carrageenan and xanthan increased compressive strength regardless of the biopolymer content.

A microstructural study on the effectiveness of carrageenan and xanthan showed that the biopolymer films were located in the soil pores and formed polymer film binding soil particles through three main interactions for kaolinite soil: hydrogen bonding, electrostatic interaction, and hydrophobic bonding. Another practice presented [11] comparisons of a locally produced biopolymeric soil stabilizer (cassava peel powder) with an imported biopolymeric stabilizer. Geotechnical tests for compaction, strength, and hydraulic conductivity were carried out using clayey soil taken from Isan, Nigeria. The results showed that the shear strength of soil treated with each of the two biopolymer materials increased with increasing curing time of up to 28 days. Microstructural results showed that chemical reactions between the tested biopolymers and clay particles led to the formation of new cementitious products that bonded the soil particles and filled the pore space. The soil with cassava peel showed better results than the soil with carboxymethyl cellulose.

Extensive studies investigated [12] the effect of clay modification with six different biopolymers (xanthan gum, sodium alginate, carrageenan kappa gum, locust bean gum, agar gum, and gellan gum) considering different hydration conditions, biopolymer concentration, curing time, wetting-drying time. The results showed that of the six different biopolymers, the clay treated with sodium algalanum provided the highest compressive strength under the same conditions. Also, the clay treated with xanthan gum maintained compressive strength without limitation even after curing for 378 days and 3 wetting-drying cycles.

Other practices [13], along with standard biopolymers, demonstrate the effectiveness of soil modification using dextran, beta-glucan, curdlan, polyacan, chitosan, starch, and casein. Chemical combination methods such as combining xanthan gum with trivalent chlorine and combining xanthan gum with guar gum are also considered in soil modification studies [14, 15].

Studies note that each biopolymer requires a specific mixing method with the substrate. There are four main methods: dry mixing at room temperature, wet mixing at room temperature, dry mixing in hot water, and wet mixing in hot water. The choice of method significantly impacts the performance and properties of the modified soil [12]. Also, the soil type (clay, sandy, or sandy loam) influences how effectively the biopolymer penetrates and forms strong bonds with the soil particles [8]. Therefore, it is important to consider the physical and mechanical properties of the soil when selecting and applying biopolymers to achieve optimal results.

Despite extensive research, many aspects of the problems mentioned are far from being solved. In this context, the application of a combined soil consolidation method is of particular interest. This approach can provide a more effective solution to the existing problems by combining the advantages

of different methods and allowing to achievement of optimal results in soil modification and consolidation. Also, regional characteristics such as soil types, and their physical and mechanical characteristics play a key role in determining the effectiveness of biopolymers. The main objective of this study is to investigate a combined soil reinforcement method using biopolymer and geosynthetic material for developing effective and environmentally sustainable methods for soil stabilization and reinforcement.

2. Materials and methods

2. 1. Experimental setup and materials

The study used a combined soil reinforcement method using biopolymer and geosynthetic material. The effectiveness of the modified soil reinforced with geosynthetic material was investigated using the direct shear test (GOST 32804-2016, GOST 12248.1-2020).

The investigations were conducted in the "ENU-Lab" laboratory of L. N. Gumilyov Eurasian National University (Republic of Kazakhstan) with a constant external temperature of approximately 20 °C. The experiment's technical process consisted of the following main procedures:

1. Test setup and equipment calibration.
2. Determination of physical and mechanical properties of soil.
3. Preparing modified soil.
4. Measurement of the pH level of soil and the biopolymer soil.
5. Scanning electron microscopy analyses of soil and the biopolymer soil.
6. Specimen preparation for the direct shear test.
7. Conducting direct shear tests of soil, the biopolymer soil, and the biopolymer-nonwoven geotextile soil.
8. Estimation of the cohesive strength and friction strength of soil, the biopolymer soil, and the biopolymer-nonwoven geotextile soil.
9. Analysis of exploring the interrelationship between received results.

Sand with fine friction (Astana, Republic of Kazakhstan) was employed for the experiment. Sieve, hydrometer, liquid, and plastic limit analyses were conducted to classify the soil. The liquid limit and plastic limit analyses were performed to assess the soil's consistency and plasticity characteristics (ST RK 1285-2004). These tests allowed for a comprehensive understanding of the soil's texture and behavior, which is essential for evaluating its suitability for reinforcement. Physical characteristics of soil are presented in **Table 1**. Soil composition contains 60.794 % sand, 19.193 % silt and 15.609 % clay. The particle size distribution curve for soil is shown in **Fig. 1**.

The biopolymer is xanthan gum composed of chains of sugars, the molecules have a complex structure including a main chain of β -D-glucopyranose and side chains of α -D-glucuronic acid and β -D-mannose. This structure allows the formation of viscous solutions. From geosynthetic material was chosen nonwoven geotextile which is a durable fabric made of polypropylene fibers bonded by needle-punching with subsequent heat treatment.

Table 1

Physical characteristics of the soil

Soil characteristic	Value
Specific gravity, g/cm ³	2.538
Maximum dry density, g/cm ³	2.031
Optimum water content, %	10.194
Sand sized fraction (75 μ m–2 mm), %	60.794
Silt sized fraction (5–75 μ m), %	19.193
Clay sized fraction (<5 μ m), %	15.607
Liquid limit, LL, %	23.251
Plastic limit, PL, %	1.190
Plasticity Index, PI, %	22.061

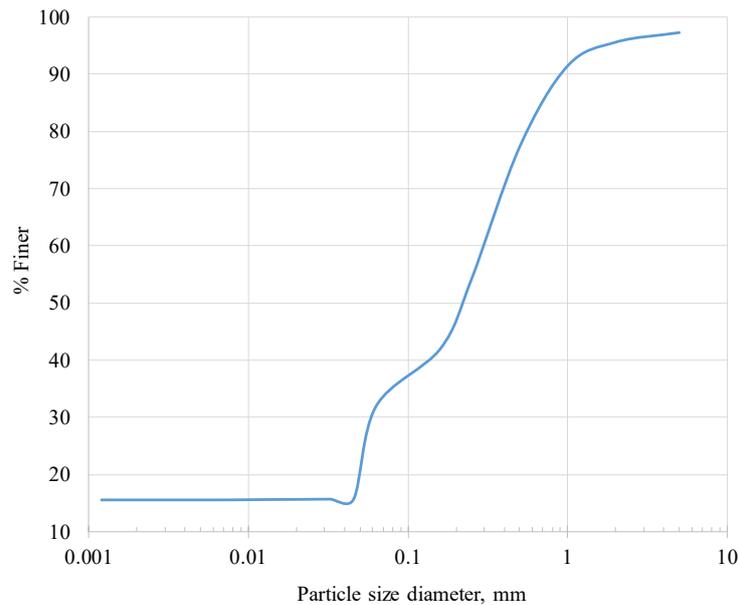


Fig. 1. Particle size distribution curve

This method of production ensures the durability of the material, which can withstand a variety of external conditions and mechanical loads. This geotextile is used to prevent the mixing of road surface layers, create drainage systems, strengthen bases, and stabilize slopes. The mechanical characteristics of nonwoven geotextiles are presented in **Table 2**. Some of the materials used in the study are presented in **Fig. 2**.

Table 2

Physical and mechanical characteristics of nonwoven geotextile

Name of indicators	Nonwoven geotextile
Surface density, g/m ²	400
Tensile strength, no less, kN/m	13.0
Relative elongation at break length/width, %	55–130



Fig. 2. The main materials used in the study:

a – sand with fine friction; *b* – biopolymer; *c* – nonwoven geotextile; *d* – mixing bowl

The modified soil was prepared with sand, xanthan gum, and water (wet mixing) which was carefully inspected and weighed on a scale before being mixed. The proportion was 231.48:5:8 grams respectively.

First, the biopolymer was mixed with water and mixed thoroughly until a homogeneous mass was obtained. The process involved carefully measuring the appropriate amount of biopolymer and water and then combining them in a mixing container. The mixture was stirred continuously to ensure that the biopolymer was fully dissolved or dispersed in the water, achieving a uniform consistency. After achieving a homogeneous mixture, the solution stabilized for 1 hour.

This stabilization period is essential for ensuring the even distribution of the biopolymer throughout the mixture. During this time, the biopolymer particles continue to interact with the water, allowing them to fully integrate and achieve the desired consistency.

The stabilization helps in reducing any potential clumping or settling of the biopolymer particles, which could otherwise lead to inconsistent application and ineffective soil treatment. Once the stabilization period was complete, the mixture was applied to the soil. The wet method allowed for easier control of the viscosity and flowability of the mixture, which simplified the mixing process. **Fig. 3** presents the process of soil modification.

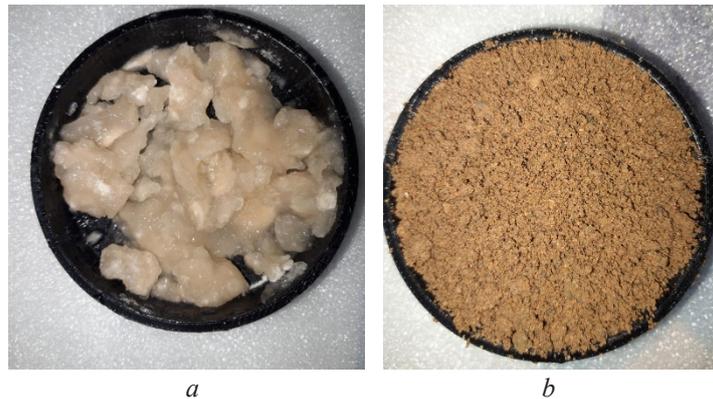


Fig. 3. Process of soil modification: *a* – biopolymer with water; *b* – biopolymer soil

Since xanthan gum is not an acidic or alkaline substance and does not contain ions that could change the pH of the soil, long-term monitoring of pH changes was not required. The pH was measured at three positions for the soil and the biopolymer soil using an ITAN pH meter. Micrographic features of the soil before and after treatment were observed by scanning electron microscope (SEM) TM4000Plus, HITACHI, Japan.

2. 2. Direct shear test

Direct shear soil tests were performed using the Wykeham Farrance 27CWF2060, Digishear (UK) device. The device has a cylindrical box made of aluminum that can withstand the stresses during the test. The shear system consists of a moving part that moves horizontally, creating shear stress in the specimen. Force and strain sensors allow the shear and strain parameters to be recorded. The tests were carried out in loading stages of 25, 50, and 100 kPa, with a 0.1 mm/min cutting speed. For one determination of the values of the angle of internal friction, and adhesion, three tests were conducted at different values of normal stress (**Fig. 4**).



Fig. 4. General view of Digishear device

During the test, attention was paid to the compaction of the soil sample to obtain reliable results, as compaction provides the necessary density and structure of the soil, which affects its strength characteristics [16]. Before placing the sample in the box, it was verified that the inner walls of the cylinder were clean. The specimen was positioned so that its contact with the box's inner walls was uniform [17]. In the tests (**Fig. 5**), the geosynthetic material was positioned along the shear surface, making it possible to evaluate its influence on the soil's sliding resistance and strength characteristics [18, 19].



Fig. 5. The geosynthetic material position

A total of 27 samples were tested. During the test, data on the applied shear load and specimen deformation were recorded to analyze the strength characteristics of the soil. Estimation of the angle of internal friction and cohesion of the soil was carried out using the Mora-Coulomb formula:

$$\tau = c + \sigma \cdot \tan \varphi, \quad (1)$$

where τ – shear stress, kPa; σ – normal stress, kPa; φ – friction angle of soil; c – soil cohesion, kPa.

Since for each normal stress level, three specimens were tested (three specimens each at 50 kPa, 75 kPa, and 100 kPa) for unreinforced soil, biopolymer-reinforced soil, and soil reinforced by the combined method, the calculation of confidence intervals was applied to evaluate the convergence of the results. This allows to objectively assess the degree of variability of the results, as well as to determine the range of values in which the true parameters characterizing the soil behavior under different reinforcement conditions are located with high probability.

3. Results and Discussions

3. 1. pH analysis

The pH of sand with fine friction before and after treatment was 7, which shows a neutral environment. Xanthan gum did not change the acid-alkaline balance. The neutral pH of sand represents the optimum condition for application in construction. This value provides stability and minimizes the need for additional adjustments.

3. 2. Scanning electron microscope analysis

SEM image analysis shows (**Fig. 6**) that the structure of the polymer soil is modified, and the gum interacts with the soil particles to form a kind of film. The soil without polymer has a more homogeneous texture.

The biopolymer films filled the pores and coated the soil grains, which facilitated the joining of neighboring particles through several mechanisms. These mechanisms include:

- adhesion: the biopolymer films adhered to the soil particles due to the attraction forces between the polymer and the soil surface;
- cohesion: within the biopolymer film itself, cohesive forces (forces of attraction between similar molecules) hold the polymer chains together and contribute to the integrity of the film and its ability to bridge gaps between soil particles;
- mechanical binding: as the biopolymer film dried and set, a rigid network was formed that mechanically bonded to soil particles, increasing the soil's resistance to breakdown.

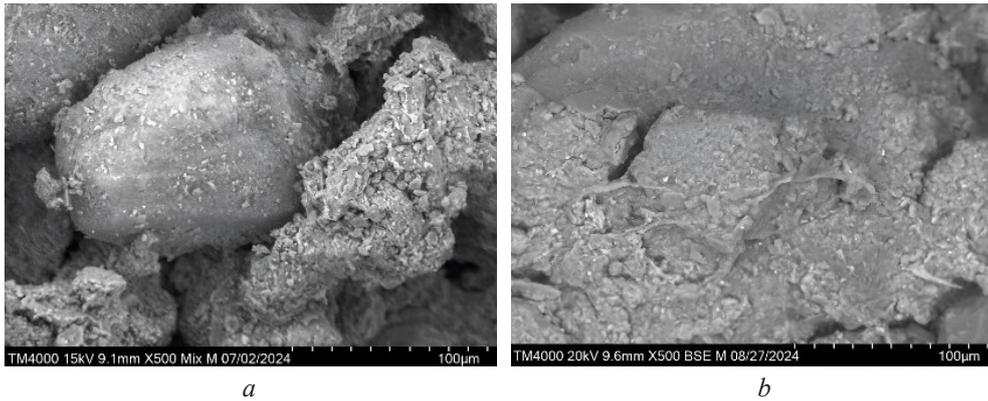


Fig. 6. Scanning electron microscope image: *a* – soil before treatment; *b* – soil after treatment

3.3. Definition of the cohesive strength and friction angle

Shear stress versus horizontal displacement curves were plotted for all tested specimens (**Fig. 7**). **Fig. 7** shows the curves for unreinforced specimens and specimens with biopolymer and biopolymer-nonwoven soil (σ , 50 kPa). In graphs, horizontal displacement represents how much the specimen has deformed horizontally relative to its initial thickness.

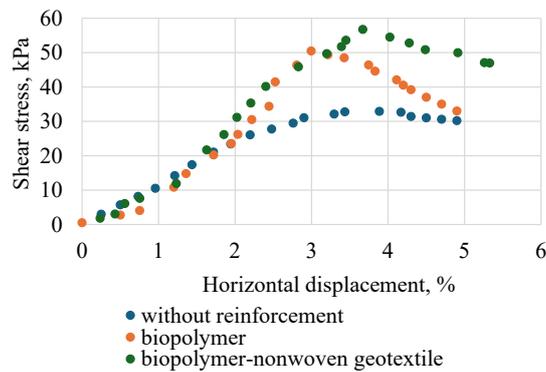


Fig. 7. Results of the direct shear test: shear behavior for normal stress 50 kPa

The calculation of confidence intervals and deviations from the test results of the 27 soil samples are presented in **Table 3**.

Table 3
Statistical analysis

Normal stress, kPa	The average value of shear stress, kPa	Standard deviation, kPa	Accepted value, kPa	Standard error, kPa	Lower bound, kPa	Upper bound, kPa
Without reinforcement (WR)						
50	36.03	0.11	35.92	0.07	35.78	36.31
75	49.93	0.28	49.71	0.28	49.21	50.28
100	63.9	0.06	63.93	0.06	63.73	64.06
Biopolymer (B)						
50	49	0.13	48.8	0.13	48.6	49.3
75	64.9	0.15	64.7	0.15	64.54	65.25
100	79.9	0.11	79.8	0.11	79.68	80.21
Biopolymer-nonwoven geotextile (BG)						
50	55.9	0.06	55.8	0.06	55.73	55.96
75	71.96	0.04	71.92	0.04	71.85	72.04
100	88.86	0.11	88.75	0.11	88.58	89.01

The convergence of the data presented in **Table 3** shows that the test results for the different specimens (three specimens for each value of normal stress) have a low deviation from each other. The measurements for each of the stresses are within a small spread. This indicates a satisfactory convergence of the results. Confidence intervals ensured that the results are not random, for 50 kPa the confidence interval ranges from 35.78 to 36.31, indicating that the measurements are stable and accurate within these limits. Similar values are observed for other stress levels (**Fig. 8, a–c**).

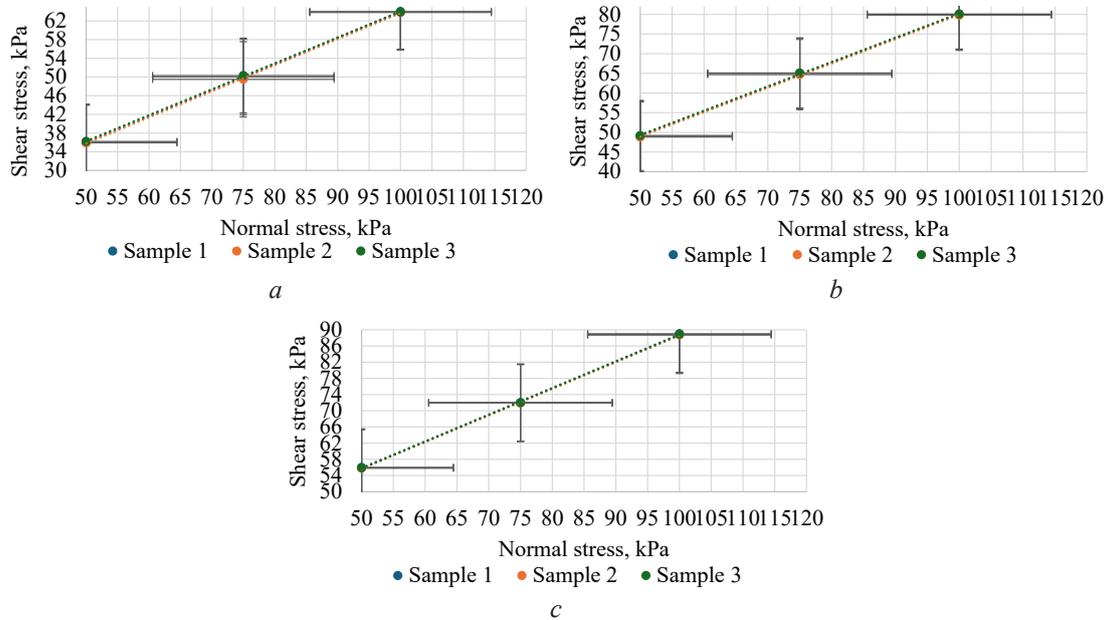


Fig. 8. Soil shear strength characteristics: *a* – WR; *b* – B; *c* – BG

The lack of significant variation between samples at each stress level indicates that the results are convergent and that the observed data have good statistical characteristics and can be applied for further analysis. The values of the shear angle are presented in **Table 4**.

The values of the cohesion, analyzed using the graphs in **Fig. 8** are presented in **Table 5**. Cohesion measures the internal molecular attraction between soil particles, contributing to the soil’s overall shear strength.

Table 4

Soil friction angle

Type of sample	ϕ , friction angle, °
Without reinforcement	29
Biopolymer	31
Biopolymer-nonwoven geotextile	33

Table 5

Cohesion

Type of sample	<i>c</i> , kPa
Without reinforcement	8
Biopolymer	20
Biopolymer-nonwoven geotextile	23

To evaluate the effectiveness of the reinforcement, the shear strength coefficient of the reinforced soil (*K*) was used which shows how much the shear strength of the soil changes due to

reinforcement with biopolymer and biopolymer with nonwoven geotextile. The coefficient of the reinforced soil was estimated by the equation:

$$K = \frac{\tau_{reinf} - \tau_0}{\tau_0}, \quad (2)$$

where τ_{reinf} – shear stress of reinforcement soil, kPa; τ_0 – shear stress of soil without reinforcement, kPa.

The variations in the K of the different specimens at the three shear stresses are shown in **Fig. 9**.

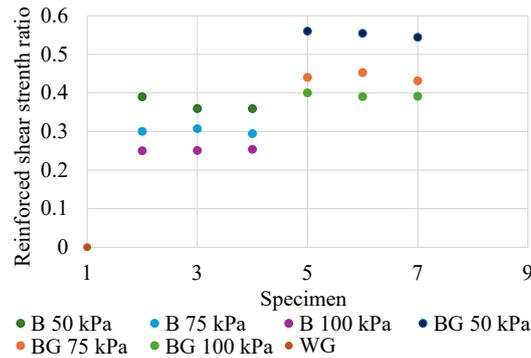


Fig. 9. Reinforced soil shear strength ratio for specimens

Compared to the shear strength of the soil without reinforcement, the ultimate shear stresses of the reinforcement soil by biopolymer and combined biopolymer and geotextile are higher under the different vertical stresses.

The K value of the biopolymer soil is approximately 39 %, 30 %, and 25 % under normal stress of 50, 75, and 100 kPa, respectively. The reinforcement provided by xanthan gum showed a sufficient effect. The K value of the combined soil reinforcement is approximately 56 %, 44 %, and 40 % under normal stress of 50, 75, and 100 kPa, respectively. The reinforcement of soil provided by nonwoven geotextiles is fundamentally driven by their tensile strengths, which are a key determinant in enhancing the stability of soil.

Table 5 shows that cohesion increased by 15 kPa for each sample reinforced with biopolymer and in the biopolymer-geosynthetic work. The non-tan geotextile induced additional soil quasi-cohesion. The angle of internal friction for fractional sand samples increased by 2–4 degrees when reinforcing materials were applied.

The increase in soil cohesion induced by biopolymer and nonwoven geotextile can be attributed to the effectiveness of geotextile in reducing surface erosion, and the interaction of xanthan gum with soil, which was presented in the SEM analysis, of the grains of the studied soil was characterized by closer proximity to the soil samples before modification. The images show that the gaps between grains are small.

The limitation of the present study is that laboratory tests do not fully reproduce the conditions encountered at the construction site, as the proportions between the size of the reinforcing elements and the soil particles, as well as the degree of their interaction, differ. However, such a study provides valuable data on the basic behavior of the soil-reinforcement system and provides a cost-effective and operational approach. The development of this study can be achieved by conducting experiments on different types of soils, which will help determine the scalability of the applied soil reinforcement method.

4. Conclusions

1. Regularity of reinforcing material distribution: the uniform distribution of the polymer agent in the soil mixture has been found to provide more stable and effective reinforcement. Inconsistencies in material distribution can result in concentrations of the reinforcing agent in certain areas, creating weaknesses in the structure and reducing its overall strength and stability.

2. Gum-soil interaction pattern: the study found that gum interacts effectively with soil particles to improve soil consolidation and structure. The better the interaction between the polymer and the soil, the more homogeneous and stable the soil structure becomes at the micro level, which positively affects its strength characteristics.

3. Regularity of compaction effect on strength characteristics: the results showed that the density and degree of compaction of soil directly affect its behavior under shear loads. Improper compaction leads to distorted test results and consequently incorrect conclusions about the strength of the soil. Thus, significant control of compaction parameters is required to obtain reliable data.

4. Regularity of geotextile reinforcement performance: placing nonwoven geotextiles along the shear plane improves the adhesion between soil particles and promotes better reinforcement, especially at the material-soil contact points. This indicates the importance of accurate positioning of reinforcing materials to optimize their impact on the soil.

5. Regularity of effect of normal stresses on reinforcement effectiveness: the study found that soil reinforcement with biopolymers and geotextiles is more effective at low normal stresses (50 kPa). However, with increasing normal stresses (100 kPa), the role of biopolymer decreases and the friction between soil particles and their interaction becomes the main importance, making reinforcement less noticeable at high stresses.

6. Regularity of friction angle change: the study observed that reinforcement of soil with biopolymers increased the friction angle. This increase was more pronounced with the combined reinforcement of biopolymer and geosynthetics, which confirms the synergistic effect of these materials in improving soil adhesion and friction resistance. The friction angle of the soil increased by 7 % with reinforcement using biopolymer alone, and by 14 % with the combination of biopolymer and geosynthetics.

7. Regularity of cohesion enhancement: incorporation of biopolymer into soil increases its cohesion, and this enhancement is more prominent when biopolymer and geosynthetics are combined. This indicates that the combination of materials gives a better result in strengthening the soil by increasing its cohesion and strength characteristics.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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