Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-15

Biopolymers for sustainable cut slope stabilisation: a green engineering approach

J. Josifovski[1], A.N. Atanasovska[1], B. Susinov[1], S. Abazi[1]

[1]*Faculty of Civil Engineering Skopje, University Ss. Cyril and Methodius, Skopje, RNM*

ABSTRACT: Biopolymers offer an environmentally friendly and sustainable solution for soil stabilisation, especially on cut slopes prone to instability from erosion and weathering. In this study, biopolymers are used to enhance soil properties, reduce erosion, and promote vegetation growth. A unified methodology of physical and numerical modelling, as well as laboratory and experimental testing, was employed. The research methodology was organised into two stages: laboratory testing followed by experimental testing on a large-scale physical model. First, strength-deformation properties and the coefficient of permeability of the natural (untreated) and improved (treated) soil were defined. Hence, through comparison, the improvement effects and degree of improvement were defined. Second, experimental tests were conducted on an untreated and biopolymer-treated slope with a slope of 1:1.5, to which rainfall of 10 litres per hour was applied for 180 minutes. The results have shown that the natural polymer improves not only the mechanical but also the hydraulic soil parameters by forming a viscous gel matrix with a reinforcing bond between the soil grains that fills the pores. In dry conditions, the treated soil forms a solid surface crust that prevents evapotranspiration. In rain, the biopolymer becomes hydrophobic, allowing water to run-off without significant soil erosion. The results confirm the efficiency of the biopolymer as an additive to the soil for stabilising the slopes subjected to atmospheric actions.

Keywords: Biopolymers; Naturally-based solution; Soil Stabilisation; Erosion Control; Vegetation

1 INTRODUCTION

The impact of climate change has changed the factors affecting the stability and safety of soil slopes. Large temperature variations and more frequent, intense rainfall are factors that contribute to soil instability, erosion, and landslides. This phenomenon is widely known as soil-atmosphere-vegetation interaction, which is studied using biopolymers and vegetation as a natural solution, representing a green alternative to traditional methods (Josifovski et.al., 2024). The natural polymers, such as microbial biopolymers, are high-molecular polysaccharides produced by microorganisms (Sujatha and Kannan 2022). They offer an effective and sustainable solution for slope stability and erosion control. For example, polysaccharides such as xanthan gum increase shear strength, while proteins such as casein can form cross-linked networks in the soil (Cabalar et.al., 2017). Due to their water solubility, these biopolymers form stable, viscous solutions that enhance soil binding and moisture retention. Viscous solutions are hydrogels that create a binding matrix through intermolecular hydrogen bonds between biopolymer molecules and soil, connecting the soil structure (Vedovello et al., 2024; Kwon et.al., 2019) through soil particles, which mechanisms the pores in the soil, thus creating cohesion and maintaining water retention (Ivanov and Chu, 2008; Kavazanjian et al., 2009). Due to the high viscosity, it cannot penetrate deeply into the soil. Main action on the surface is through biological blocking (bioclogging) of soil particles and pores (Ivanov and Chu, 2008). In dry conditions, the soil treated in this way stands out as a surface layer with greater resistance to erosion (Atanasovska and Josifovski, 2024). The surface layer acts as a barrier, keeping soil grains bound, and controls the level of tearing under the influence of surface forces from water and wind (Sharma et al., 2024; Tugrul et al., 2019). Additionally, the microbial polymers containing sugar components support vegetation growth. For long-term stability, the viscous solution can be applied with seeds of vegetation. Hydroseeding keeps seeds on the surface, accelerating germination and improving coverage. The viscous binder increases water retention in the soil during wet periods, which is especially important for the survival of the plants in dry periods.

This study presents results from an experimental investigation of a biopolymer binder solution as an effective method for soil stabilization and erosion control.

2 METHODOLOGIES OF INVESTIGATION

For this study, the investigated silty sand soil was collected from the surface layer of the cut-slope on the Miladinovci - Stip express road in North Macedonia.

2.1 Sample preparation

The soil samples were prepared using the optimum moisture content, as determined by the Standard Proctor test. The viscous binder solution was formulated using xanthan gum (1% by mass) as the primary component, along with two additional polymers at concentrations of 1% and 0.5% by mass. The binder was prepared by dissolving polymer powder in water (pH 7.5) over 24 hours using a magnetic stirrer. The soil-binder wet mixture was prepared by manually mixing the soil with the binder until a homogeneous and uniform texture was achieved. This had ensured an even distribution of the binder throughout the soil sample. For strength-deformation and water permeability tests, the soil was compacted into the appropriate mould in three successive layers; each layer being tamped using a small steel hammer to ensure uniform compaction. Hence, two types of soil samples were prepared: untreated samples (Series 0) and binder-improved samples (Series 1 to 4).

2.2 Laboratory test

All laboratory tests were performed according to standard procedures. The classification test was made to determine the physical parameters of the soil. To determine the strength-deformation parameters of untreated and binder-improved samples, the following tests were conducted: uniaxial compressive strength (UCS), direct shear test (DST), and oedometer test (OED). The water permeability test was performed to determine the amount of leaked water from untreated and binder-improved samples.

2.3 Experimental testing

An experimental test was conducted on a physical slope model with dimensions of 500 mm in length and width, and a depth of 100 mm. The aluminium box has three rows of 5 holes on the bottom to drain water, Figure 1. To ensure effective interaction between the aluminium bottom and the soil, an adhesion PVC mesh was placed between them. The adhesion mesh enhances contact and minimises slippage.

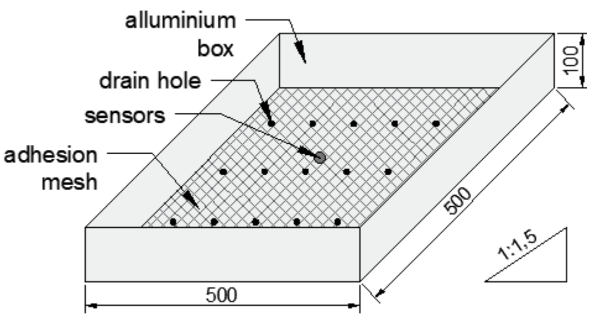

Figure 1. Physical model

Each slope was built by lightly compacting the soil, and the binder was applied with a pressure pump by evenly spraying it over the surface. The pipe and sprinkler system (Figure 2a) was installed above the slope model and connected to the water supply system. The sprinkler system (Figure 2b) was set to simulate a rainfall with an intensity of 40 mm/h and a duration of 180 minutes.

(a) (b)

Figure 2. Equipment for experimental test (a) Rainfall simulation equipment, and (b) Sprinkler

3 RESULTS AND DISCUSSION

3.1 Strength-deformation results

This study was performed on silty sand soil. The results from the Proctor test indicate a maximum dry density of 15.20 kN/m³ at an optimum moisture content of 17.60%. The results of the physical parameters of the soil are shown in Table 1.

Table 1. Material parameters of the silty sand soil

Test	Symbol	Result
Natural moisture	ω [%]	23.62
Specific Gravity	G_s [kN/m3]	2.67
Density	γ [kN/m^3]	18.22
Liquid Limit	LL [%]	53.62
Plasticity limit	PL [%]	32.81
Index of Plasticity	IP [%]	20.81
USCS Classification		MH

The UCS samples were cured under controlled laboratory conditions (t=20-22°C, ω=40-45%), then tested according to the curing program defined for each series. The results of the UCS test are shown in Table 2. Test Series 0 was tested on two untreated samples. The third sample was damaged during the assembly procedure for testing. Test Series 1 shows an average compressive strength of 257 kPa, which is lower than the strength observed in Test Series 0 at the same curing interval (437 kPa). This indicates that the hydration process has a significant influence on compressive strength, and the strength continues to improve with a longer curing duration. Test Series 2 shows a more than 6 times increase in compressive strength compared to Test Series 1. Interestingly, there is a decrease in the strength of Test Series 3. However, the samples in this series have similar strength values reached at a lower strain compared to the other series. In contrast, both strength and strain values vary in Series 4. This may be the case due to an inconsistency in soil compaction or testing conditions.

Table 2. UCS results

Test series No.	Curing time [days]	Axial stress [kPa]	Axial strain [%]
0	1	509.29	4.00
		364.65	4.00
	1	260.20	3.00
1		231.94	3.60
		279.14	3.80
		1720.27	3.00
2	7	1829.01	2.80
		1683.85	3.00
3	14	1162.02	2.80
		1139.65	2.60
		1095.61	2.40
4	28	1446.83	3.40
		1756.53	2.70
		2798.60	2.50

The results of the DST test are shown in Table 3.

Table 3. DST results

Test series No.	Curing program [days]	Angle of internal friction [°]	Cohesion [kPa]
0	1	25.95	28.50
1	1	31.66	27.75
2	7	32.01	25.13

In the Series 0, the maximum shear stresses of 35.8 kPa, 46 kPa, 54,8 kPa were registered for the applied normal stresses of 15 kPa, 30 kPa, 60 kPa. The Series 1 maximum shear stresses of 37 kPa, 46 kPa, and 65 kPa were registered for the applied normal stresses. Compared to Series 0, an increase of 5.7° in the angle of internal friction was observed. The Series 2 samples were not exposed to normal stress for 1 day. Following a 7-day curing period, the samples were found to have absorbed the water from the shear boxes, where maximum shear stresses were 34.5 kPa, 43.5 kPa, and 63 kPa for six days of loading. The shear strength parameters of Series 2 are 32° and 25.13 kPa. It was expected that the viscosity binder would influence the improvement of the shear strength parameters; however, the DST results show that it does not affect the cohesion.

The OED results of the corresponding module–load curves are shown in Figure 3. At a load of 7.5 kPa, the same value of the modulus is registered for both series. The modules decrease as the load increases. For a load of 15 kPa, or a 37% increase in the modulus of compressibility is registered. First settlements are registered for a load of 30 kPa. The compression modulus of Series 1 is twice that of Series 0 for a load of 60 kPa. For the same load, settlements larger by 0.2 mm occur for Series 0. For a load of 120 kPa, the difference in settlement between the two series is less than 1 mm. For the last loading step, of 240 kPa, the difference in modulus between the Tests is 1700 kPa. For Test No. 0, a settlement of 1.26 mm is registered, which is 0.45 mm larger than the settlement for Test No. 1 (0.81 mm).

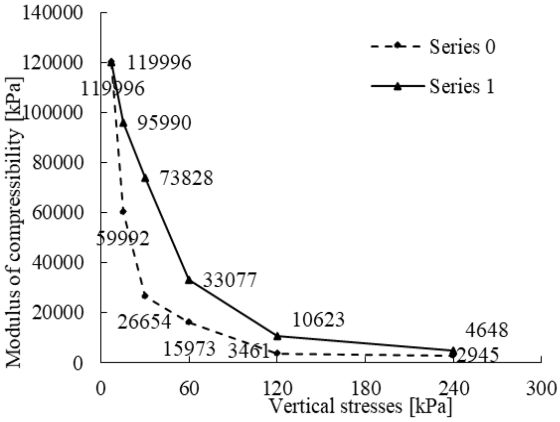

Figure 3. Modulus of compressibility-vertical normal stress

3.2 Permeability results

The results from the permeability tests are presented in Table 4, where the permeability coefficient was determined by measuring the amount of water flow in 24 hours. Test Series 1 has higher permeability than Test Series 0. Hence, the water passes easily through Test Series 1, while it is retained in Test Series 0. Over 24 hours, a higher flow amount of 84% was measured in Test Series 1. It can be concluded that the viscous binder alters the soil's structure, thereby limiting water flow.

Table 4. Permeability test results

Test No.	Water seepage [ml]	Permeability coefficient [m/sec]
0	1.06	1.71^10-7
1	6.71	1.08^10-6

3.3 Experimental results

Figure 4 shows erosion progress over time for the untreated and treated slopes. Visually, there is no noticeable difference between the two slopes; they appear the same. However, upon touch, a difference can be observed: the improved slope has a hard and compact surface crust, formed as a result of the interaction between the viscosity binder and soil particles. As the test progresses, a visual difference in surface erosion becomes increasingly apparent. In the treated slope, changes are minimal and difficult to notice. The untreated slope shows more evident signs of erosion. In this slope, soil saturation was observed around the 60th minute, when the leaking started through the holes in the model. Following this, sandy sediments became more prominent on the surface, while fine silty particles accumulated at the lower part of the slope. Around the 120th minute, water began to flow over the sides of the model, and this process continued until the end of the test at 180 minutes. The treated slope demonstrated strong resistance to rainfall. It was confirmed that the surface crust acts as a protective barrier. Upon contact with water, the crust temporarily loses its firmness and becomes a hydrophobic surface. This means it does not allow infiltration but instead enables surface run-off. A characteristic of the hydrophobic crust is that its water-repellent action is temporary and activates in contact with water.

Figure 4. Experimental testing - erosion resistance test

4 CONCLUSIONS

This study investigates the potential of using biopolymers as an effective method for improving soil stabilisation. The experimental investigation shows that the binder-treated soil has higher resistance to surface erosion compared to the untreated soil. Future evaluation in real in-situ applications is needed using the hydroseeding method, assessing the effectiveness under natural factors that directly influence erosion and slope stability. The use of biopolymer solutions presents an innovative approach for a wide range of geotechnical and environmental engineering applications, offering a combination of efficiency, cost-effectiveness, and environmental sustainability.

5 REFERENCES

Atanasovska N.A., Josifovski J. 2024. Slope Stabilization and Erosion Control Using a Naturally Based Solution with Biopolymers, 271–276. doi:https://doi.org/10.18485/resylab.2024.6.ch41.

Cabalar, A.F., Wiszniewski, M., Skutnik, Z. 2017. Effects of Xanthan Gum Biopolymer on the Permeability, Odometer, Unconfined Compressive and Triaxial Shear Behavior of a Sand, *Soil Mechanics and Foundation Engineering* **54**(5), 356–361. doi:https://doi.org/10.1007/s11204-017-9481-1.

Ivanov, V., Chu, J. 2008. Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ, *Reviews in Environmental Science and Bio/Technology* **7**(2), 139–153. doi:https://doi.org/10.1007/s11157-007-9126-3.

Josifovski, J., Susinov, B., Atanasovska, A.N. 2024. Experimental and Numerical Modeling of Soil-Vegetation-Atmospheric Interaction on Slopes and Erosion Control Using Biopolymers and Vegetation, *Proceedings of the 4th European Regional Conference of IAEG (EUROENGEO),* Dubrovnik, Croatia.

Kavazanjian, E., Iglesias, E., Karatas, I. 2009. *Biopolymer soil stabilization for wind erosion control*. IOS Press eBooks. doi:https://doi.org/10.3233/978-1-60750-031-5-881.

Kwon, Y.M., Chang, I., Lee, M., Cho, G.C. 2019. Geotechnical engineering behaviour of biopolymer-treated soft marine soil, *Geomechanics and Engineering* **17**(5), 453–464. doi:https://doi.org/10.12989/gae.2019.17.5.453.

Sujatha, E.R., Kannan, G. 2022. An Investigation on the Potential of Cellulose for Soil Stabilisation, *Sustainability* **14**(23), 16277. doi:https://doi.org/10.3390/su142316277.

Sharma, M., Tellili, N., Kacem, I., Rouissi, T. 2024. Microbial Biopolymers: From Production to Environmental Applications—A Review, *Applied Sciences* **14**(12), 5081–5081. doi:https://doi.org/10.3390/app14125081.

Yakupoglu, T., Rodrigo-Comino, J., Cerdà, A. 2019. Potential Benefits of Polymers in Soil Erosion Control for Agronomical Plans: A Laboratory Experiment, *Agronomy* **9**(6), 276–276. doi:https://doi.org/10.3390/agronomy9060276.

Vedovello, P., Sanches, L.V., da Silva Teodoro, G., Majaron, V.F., Bortoletto-Santos, R., Ribeiro, C., Putti, F.F. 2024. An Overview of Polymeric Hydrogel Applications for Sustainable Agriculture, *Agriculture* [online] **14**(6), 840. doi:https://doi.org/10.3390/agriculture14060840.