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Slope stabilization and erosion control using a Naturally based solution with Biopolymers

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Abstract: Climate change, usually manifested by frequent and intense rainfalls, can be a main contributing factor for soil instabilities, in the form of landslides, and soil erosion. Thus, it is crucial to comprehend the process of atmospheric interaction responsible for the stability of natural and man-made slopes, the water infiltration, and shallow (local) instabilities which over time most certainly can develop into global slope instability. Nowadays, the usage of environmentally friendly materials for soil improvement has become very popular with the increased environmental awareness. The biopolymers are processed from a biodegradable substance, thus they are safe for the environment or people. The paper presents the results of research on the use of biopolymers as naturally based solutions for soil treatment and improvement. The biopolymer acts as a binding viscous agent with the soil particles providing additional adhesion, thus provides more resistance to the erosion process. The research methodology was organized into two stages, laboratory testing followed by experimental testing on a large-scale physical model. First, strength-deformation properties and saturated coefficient of permeability of the natural (untreated) and improved (treated) soil were defined. Hence, through comparison, the improvement effects or the degree of the improvement has been defined. Second, experimental tests on an untreated and biopolymer-treated slope with a slope of 1:1.5, on which rainfall of 10 liters per hour was applied for 180 minutes were performed. 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. When it rains, it becomes hydrophobic and allows the run of water without significant soil erosion. All test results confirm the efficiency of the biopolymer as an additive to the soil for stabilizing the slopes subjected to atmospheric actions.

Keywords: Slope stability, Erosion resistance, Naturally-based solution, Biopolymer stabilization.

Introduction

The influence of climate change in the infrastructure sector is becoming ever more visible and should not be ignored. Climate change creates several challenges for infrastructure that can affect their lifespan and transport safety. The high-temperature variations and intense rainfall affect the stability of soil slopes. Increased rainfall and dry periods have a great impact on slope stability because over time they cause erosion, cracking, local instabilities, and even trigger landslides.

Soil erosion is a process of detachment and transport of soil particles caused by water and wind (Song et al. 2005). Soil erosion occurs once shear stress exerted by moving fluids exceeds a critical value, referred to as critical erosion shear stress (Soo-Min et al. 2018). Generally, erosion is considered that can not affect the stability of the slope. However, this research shows that the rainfall-runoff rate and soil erodibility initiate erosion which reduces the shear capacity while increasing the pore pressure which ultimately results in erosion sometimes even sliding. Some soils are more erodible than others, but climate change may bring more frequent and more intense rainfall that will cause increased soil erosion regardless of soil type (Nikolovska et al. 2023)

In reality, the berms are partially or completely filled with eroded soil material, as shown in Fig. 1, thus runoff water flows down the slopes and creates paths that can be quite deep and over time result in surface instabilities. To prevent such situations and reduce their occurrence in the future, it is necessary to take prevention measures during the design phase, directed to increase the resistance to erosion and improve infiltration.

Some soils are more erodible than others, but in general climate change brings more frequent and intense rainfall which causes increased soil erosion regardless of soil type.

Soil water content is an important element for the growth of vegetation. Vegetation dynamics largely depend on soil water availability, which, in turn, results from several complex and mutually interacting hydrologic processes (Chen et al. 2007). Different vegetation and soil types have different water infiltration capacities. Root systems make the soil more resistant to external influences. Hence, climate change causes severe dry periods that create difficult conditions for vegetation to

Figure 1 Soil slope with expressed erosion of the Highway Miladinovci – Shtip, R.N. Macedonia.

thrive, which emphasizes the need to take measures for surface stability at the slopes in the design phase.

Today, many natural soil improvement techniques that increase erosion resistance by improving their mechanical and hydrological properties (Ham et al. 2018) are available. One of them is the biopolymeric material produced by microorganisms, algae, plants, etc., which are considered ecological and sustainable materials for soil improvement. In the past decade, natural polymers have been identified as highly effective polymers that stabilize soil surface structure and improve infiltration (Lentz et al. 1997). Natural polymers are water soluble and when mixed with soil, they can produce increased soil strength, improve cohesion, and reduce water permeability, but also retain soil moisture, and produce greater resistance to erosion forces.

Natural polymer solution

A biopolymer product is an aqueous solution containing a binding agent for soil stabilization. The product is obtained by processing a biodegradable substance of natural origin, specially designed for application on slopes exposed to climate changes and atmospheric actions (Nikolovska et al. 2022).

Fig. 2 shows the erosion resistance model of polymer-treated soil. The gel structure of the natural solution fills the pores and cavities, which reduces the potential for infiltration, and coats the grains, improving their mutual adhesion and connection, which increases the strength of the material (Ivanov et al. 2008). Soils treated with polymer solutions form a solid surface crust that prevents water infiltration and allows free surface runoff without soil erodibility (Cheng et al. 2015). Polymer-treated soils have an additional positive effect on plant life, primarily due to the absorption of moisture and its retention in the soil, which supports and stimulates the growth of vegetation for a longer period (Chung et al. 2018).

Testing methodology

The testing in this study was organized into two phases: the first phase where the physical, strength-deformation characteristics and coefficient of the permeability were determined for the untreated and biopolymer-treated soil, and the second phase, when experimental testing on physical models was performed for the untreated and biopolymer-treated slope subjected to intense rainfall

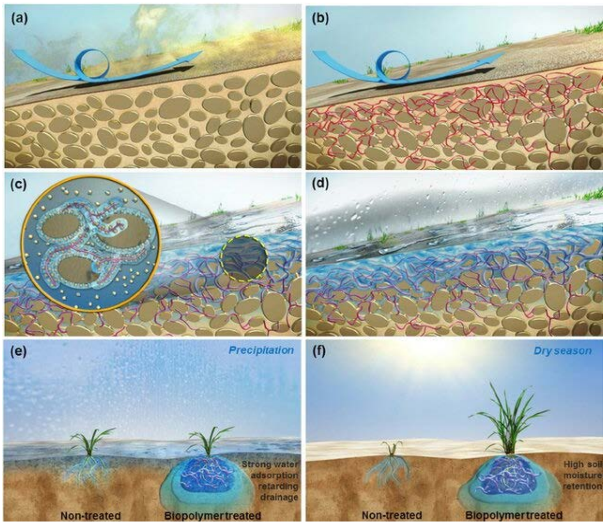

Figure 2 Erosion resistance model of polymer-treated soil (Chang et al. 2015).

Laboratory testing

To determine the physical and mechanical properties of the soil around 60 laboratory tests have been performed. Fig. 3 shows the grain size distribution curve of the investigated soil, which is classified as silty sand soil (SM according to the USCS).

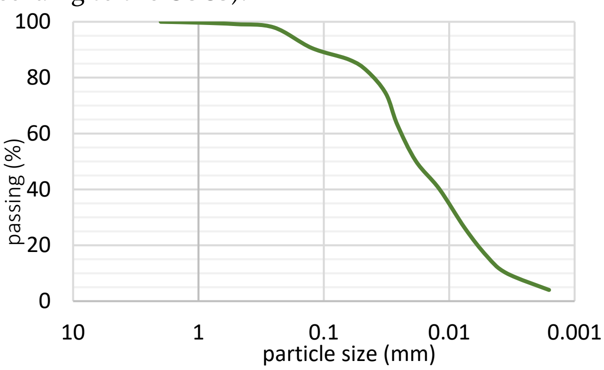

Figure 3 Grain size distribution curve.

The strength and compressibility parameters were obtained through the Uniaxial Compressive Strength CEN ISO TS 17892-7), Direct shear (MKTC CEN ISO/TS 17892-10), and Oedometer tests (MKTC EN ISO/TS 17892-5), respectively. The coefficient of water permeability (CEN ISO TS 17892:11) is determined for a constant pressure of 0.5 bar for samples saturated with water from top to bottom.

Experimental testing

The physical model was built in a box 0.5m in length 0.5m in height, and 0.1m. For better contact with the soil on the bottom, the model has an adhesive mesh positioned (see fig. 5). Also, drainage holes were used to simulate water flow out when the soil is saturated. The model was placed at an angle representing a slope with an inclination of 1:1,5. The untreated and biopolymer-treated slopes were subjected to rainfall with an intensity of 10 l/h for 180 minutes. Additionally, untreated and biopolymer-treated slopes with an inclination of 1:2 were planted with vegetation and subjected to rainfall intensity of 12 l/h after 27 days of curing time (Fig. 8).

Results

Laboratory results

In Tab. 1 are presented results of the physical properties of surface layer soil characterized as silty sand (SM).

Table 1. Physical properties of silty sand soil.

Classification tests			Proctor test	
Natural moisture ω [%]	Natural unit weight γ [kN/m³]	Specific gravity Gs [/]	Optimal moisture ω_{opt} [%]	Max dry unit weight γ_d [kN/m³]
23.62	18.82	2.67	17.60	15.20

Strength-deformability properties

The representative values of the angle of initial friction and cohesion were calculated as the average value of two series with three samples for untreated and biopolymer-treated soil.

Tab.2 presents the results of strength-deformation parameters, the angle of initial friction, and cohesion, where an improvement ratio of 9.52 % and 7.5 % is registered, respectively. The compressibility modulus has been calculated for 240 kPa load and represents an improvement ratio of 36.64 % compared with the modulus of untreated soil, under saturated conditions.

Table 2 Strength-deformable properties.

Natural soil			Polymer-improved soil		
ϕ [°]	c [kPa]	M_v [kPa]	ϕ [°]	c [kPa]	M_v [kPa]
29.2	25.9	4648	32.3	28.0	2945

The uniaxial compressive strength (UCS) was determined on samples with dimensions of 5.0 cm by 10.0 cm in series on 1, 7, 14, and 28 days. In Fig. 4 the biopolymer-treated sample before and after testing is shown, while in Tab. 2 and Tab.3 the results of untreated and treated samples are presented.

Table 3 Compressive strength parameters of natural samples.

Day of testing	Normal stress σ [kPa]	Deformation ε [%]
1	435.3	4.0

Table 4 Compressive strength parameters of treated samples.

Day of testing	Normal stress σ [kPa]	Deformation ε [%]
1	257.1	3.5
7	1749.9	2.9
14	1132.4	2.6
28	2000.6	2.9

Figure 4 Compressive strength of treated samples before and after testing, series of 28 days old.

Water permeability

The volume of infiltrated water in the treated sample was 6.71 cm³ /day, which is 6 times higher than the amount of the untreated sample, 1.06 cm³/day. Hence, biopolymer-treated soil has hydrophobic effects on the soil that allow free flow, unlike natural soil where the water is retained. Therefore, the water coefficient was tested where the following values of the coefficient were obtained: for treated soil, the coefficient is 2.20 x 10^{-6} m/s and for the natural soil is 3.47 x 10^{-7} m/s.

Experimental results

In the second phase, experimental testing (Fig. 5) of erosion was performed on an inclined slope of treated and untreated soil after 24 hours of needed time for the biopolymer solution to bond with the soil, Fig. 5.

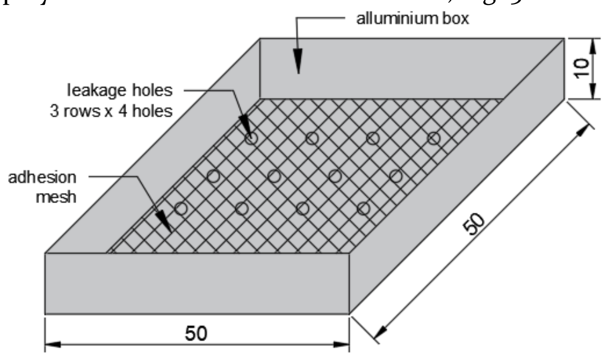

Figure 5 Experimental model

The biopolymer solution was applied by spraying evenly over the surface of the slope. The solution with a high viscosity fills the pores and cavities in the soil while the grains are coated with a bio-film creating a surface crust. The duration of the rainfall was 180 minutes, while every 60 minutes snapshots were made to register the changes on the surface of the slopes. The rainfall was simulated through a system of sprinklers which were installed above the model and connected to the water supply system.

Before the test began, there was no visual difference between the treated and untreated slopes. The interaction between the biopolymer solution, soil, and water creates a specific soil rheology characterized by hydrophilic absorption, and binding of water molecules. In contact with water, the surface crust becomes a hydrophobic surface that allows surface water to flow freely with high resistance against the erosive forces of water visible in Fig. 5 where practically no erosive changes were observed on the polymer-treated slope in 180 minutes (Nikolovska et al. 2022).

During the test, it was observed how the surface crust absorbs the water, thus becoming a hydrophobic surface, after which the surface water starts to run freely over the surface without causing surface erosion (Nikolovska et al. 2022). After the soil was completely saturated, the water started to drain through the boreholes at the base, and movement paths of the eroded soil were observed on the surface. After 180 minutes, there was muddy water with fine fractions in the base of the slope, which was not the case with the treated slope. The eroded soil is shown in Fig. 7 with the granulometric content: 69.4% silt, 21.2% sand, and 9.0% clay. In the following series of tests untreated and treated slopes with vegetation grown were tested on 120 minutes of rainfall with an intensity of 12 l/h. During the rainfall, no erosion was observed on the treated slope, hence, the biopolymer-treated slope has a higher stability and resistance to erosive force (Nikolovska et al. 2023). Moreover, the water absorption of the viscous solution proves to have a positive effect on vegetation growth (Fig. 7).

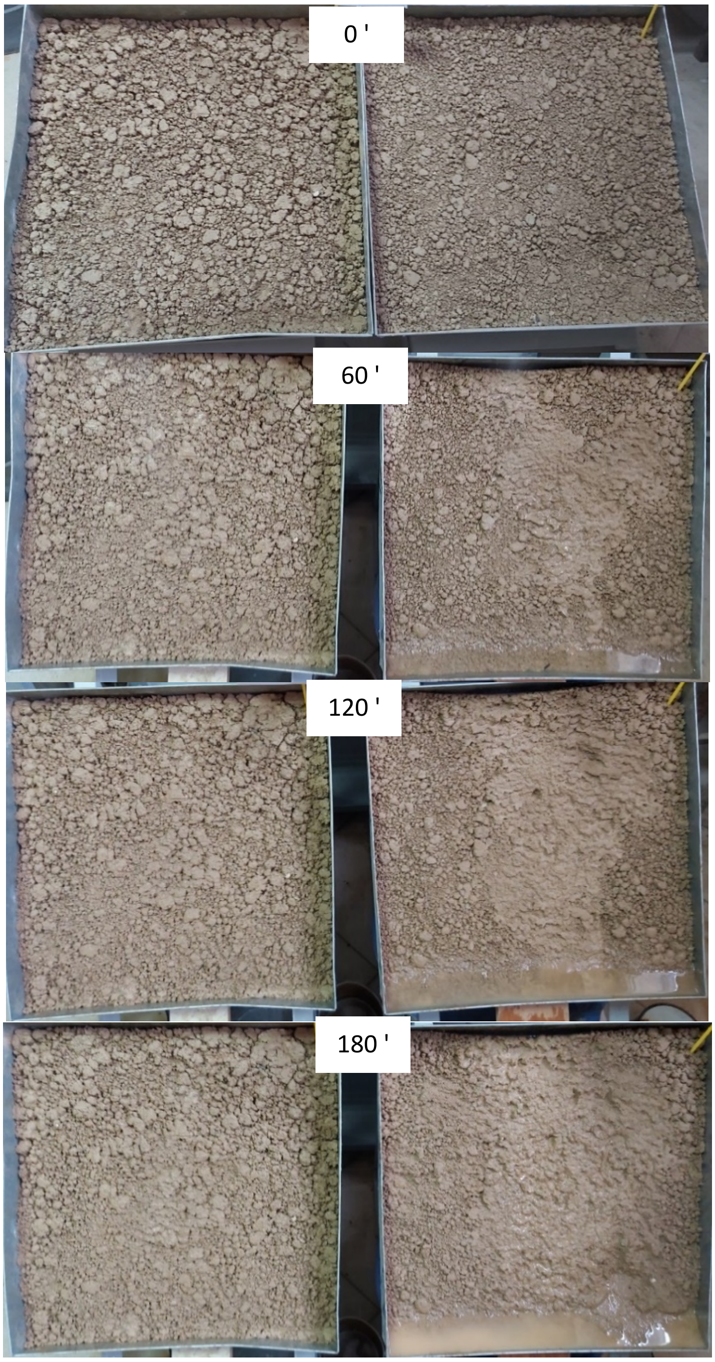

Figure 6 Erosive changes of polymer-improved slope (left side) and natural slope (right side).

Figure 7 Eroded soil in 180 minutes of rainfall for polymer-improved slope (left side) and natural slope (right side).

Figure 8 Erosive changes of slopes with vegetation, polymer-improved slope (left side), and natural slope (right side)

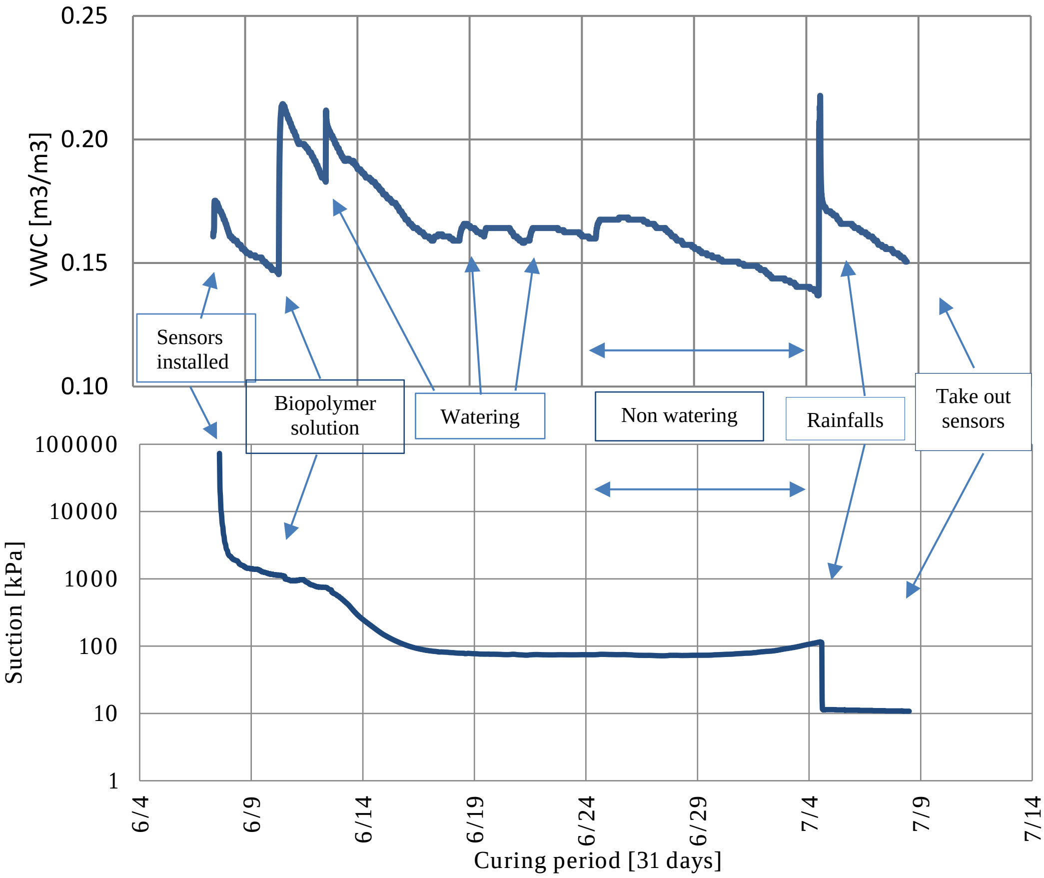

Figure 9 Results of Volumetric water content and suction for silty sand soil

The biopolymer-treated slopes with vegetation were tested after 27 days of curing period. The curing period is a needed time when vegetation roths create a strong connection with the soil and hydrophobic layer. In these slopes, were installed sensors that measured volumetric water content, suction, and temperature. The sensors were taken away after 31 days, were that period all laboratory conditions were registered, such as watering, non-watering, laboratory works, temperature changes, etc. When watering the curve for volumetric soil moisture has an increase. When the rainfall was applied, the value of the volumetric water content from 0.137 m3/m3 increased to 0.218 m3/m3. Inversely of volumetric water content, in the periods when there is non-watering for vegetation, a decrease in suction is registered. When rainfall was applied, the suction value of 110.1 kPa decreased to 11.3 kPa, or a that is decrease of 98.8 kPa.

Conclusions

The use of biopolymers has proven to be an effective measure to improve and stabilize soil material. The surface crust formed by the polymer reduces erosion and restricts the runoff water from infiltrating into the ground, thus providing surface stability to the slopes and promoting the growth of vegetation. The biopolymer as a high viscosity solution fills the pores and colds the soil particles with bio-films thus creating a 1-2 cm thick surface crust. Thus, layer improves infiltration and creates hydrophobic flow ways which provide greater resistance of erosion. Hence, adhesion between the soil grains reduces the infiltration of water into the soil.

The polymer solution improves the deformation and strength parameters of the soil. The laboratory tests have shown not just an increase in the cohesion of the treated soil, but also in the friction angle and modulus of compressibility. Moreover, the experimental tests treated and untreated material subjected to rainfall had also visibly shown the effects and the efficiency of the biopolymer solution. The use of biopolymers as a naturally based solution for erosion control, has great potential because of represents an efficient, economical, and environmentally sustainable engineering.

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