Proceedings of the ICBBG2025
2025 International conference on Bio-mediated and Bio-inspired Geotechnics
18-20 May, 2025 | Tempe, Arizona, USA
https://doi.org/10.53243/ICBBG2025-13

Stabilization of Dredged Marine Sediment Using Biopolymer

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ABSTRACT

The frequent dredging of sediments from port areas often leads to the rapid accumulation of excess material, potentially resulting in landfill challenges. Dredged marine sediments typically exhibit high water content, a significant proportion of fine-grained soil, limited bearing capacity, substantial settlement tendencies, and low shear strength. Addressing these issues is imperative for construction projects on such soil types. Recent trends in soil stabilization have witnessed the rising popularity of sustainable bio-binders, particularly biopolymers, owing to their environmentally friendly attributes and extensive use in various geoenvironmental applications. This study investigates the utilization of four different types of biopolymers for the stabilization of marine dredged sediment sourced from the Port of Koper, Slovenia. The research investigates the influence of biopolymer incorporation on the geotechnical properties of biopolymer-treated sediment through Atterberg limits and cone falling tests. In addition, samples were analyzed by scanning electron microscopy (SEM) to elucidate the interaction between biopolymer and the sediment. The findings demonstrate a significant enhancement of undrained shear strength with the addition of biopolymers to the sediment. The formation of hydrogel within the soil pores not only increases the sediment consistency but also positively affects the soil's shear strength.

INTRODUCTION

Soft marine soil (SMS) is characterized by its high content of fine-grained soil and in-situ water, resulting in low shear strength and bearing capacity. Consequently, soft marine soil is susceptible to substantial settlement, posing a challenge to the construction of coastal infrastructure. Therefore, there is a critical need to prioritize strength enhancement and settlement control when undertaking construction activities on soft marine soil deposits. Consequently, soil stabilization is frequently utilized to bolster the mechanical strength of these sediments. Soil stabilization can be broadly categorized into physical-mechanical, chemical, and biological methods. Among these techniques, chemical stabilization, the most traditional and widely employed, involves incorporating chemical substances like Portland cement and lime into the soil to enhance particle interfacial bonds. Despite this method's widespread use in the industry, it is crucial to recognize that soil stabilized with chemicals is frequently vulnerable to environmental risks, which is undesirable.

Biopolymers exhibit significant potential in improving soil stability and mitigating the environmental implications associated with conventional soil stabilization methodologies. Biopolymer binders represent a promising and innovative alternative to traditional soil stabilizers. Derived from plants, bacteria, and fungi, biopolymers are characterized by their biodegradability and non-toxic properties, rendering them a potentially sustainable option. The pivotal role of biopolymers in sediment stabilization is underscored by their eco-friendly attributes and their ability to enhance the mechanical characteristics of sediments. Biopolymers have been proposed as soil stabilizers capable of augmenting the mechanical properties of soft sediments through pore-filling and inter-particle binding mechanisms. Researchers investigated the utilization of various biopolymers, including chitosan (CH) and xanthan gum (XA), for soft soil stabilization. Chitosan, derived from chitin, exhibits promising properties in clayey soil stabilization, bonding particles together and improving soil cohesion (Ghadir and Ranjbar 2018). Xanthan gum, a microbial polysaccharide, has also demonstrated effectiveness in enhancing sediment cohesion (Sujatha et al. 2021). These findings suggest that the biopolymers can be applied for SMS stabilization.

Zarrad et al. (2015) worked on marine dredged sediment from Navar Repair (France) with 0, 5, 15, and 20 % portion of an atomized haemoglobin beef provided by the French company with a bulk density of 1.37 g/cm^3. It was observed that adding biopolymer to the sediments enhanced the stiffness and compressive strength of the biocomposites, particularly at higher biopolymer concentrations. However, incorporating biopolymer resulted in a slight decrease in tensile and flexural strengths, attributed to inadequate interfacial bonding between the organic and inorganic phases.

Kwon et al. (2019) investigated the effects of two different biopolymers, xanthan gum (anionic) and ε-polylysine (cationic), with proportions varying from 0-2% on marine clays collected from Yeosu, Korea. The research findings illustrated the substantial influence of biopolymers, specifically XA and ε-polylysine (EPL), on the hydromechanical characteristics of marine clays. Notably, the incorporation of XA biopolymer resulted in a reduction in the α factor (shear wave velocity at the effective stress of 1 kPa) and an elevation in the β exponent (the sensitivity of the skeletal shear stiffness to the applied stress), thereby impacting the plasticity and compressibility of marine clays. The study also highlighted that the addition of XA biopolymer affected the Atterberg Limits of the sediment and increased the liquid limit (LL) and plasticity index (PI) due to the formation of a viscous hydrogel within soil pores. The research underscored the capacity of XA to enhance the geotechnical properties of marine sediments, specifically undrained shear strength and compressive strength. The XA biopolymer influenced the strength and hydromechanical properties of marine sediments by facilitating pore hydrogel formation and interparticle bonding.

The investigation conducted by Kwon, Chang, and Cho (2023) evaluated the effects of employing varying quantities of XA to amend the soil, covering a range from 0.5% to 2.0% of the XA-to-kaolinite mass ratio. This variation aimed to assess the consequential impact on the structural and mechanical attributes of kaolinite. The XA treatment-induced alterations in the structural configuration of kaolinite led to a transition from random edge-to-face (EF) associations to an increased face-to-face (FF) particle arrangement. This structural transformation was attributed to establishing XA bridges among the clay particles. As a result of this modification, a reduction in maximum dry density and an increase in optimal moisture content of the kaolinite clay were observed. The undrained shear strength exhibited a marked increase with escalating XA dosage. Notably, XA-treated kaolinite displayed elevated shear strength when compared to untreated kaolinite, which had equivalent moisture content.

Feng et al. (2023) investigated the mechanical characteristics of dredged soil from the Yellow River, which was stabilized with XA biopolymer and jute fibers (JF). The dredged soil was combined with varying concentrations of XA (ranging from 0.5% to 2%) and different lengths (10 mm, 20 mm) and proportions (0.3% to 1.2%) of JF. Unconfined compression and splitting tensile strength tests were performed following 7 and 28 days of curing. The findings indicated that incorporating XA substantially enhanced the strength by facilitating the binding of soil particles. Additionally, the incorporation of JF fibers resulted in strength improvement by shifting the failure mode from brittle to ductile. The empirical evidence from the study revealed that the unconfined compressive strength (UCS) of the solidified dredged soil (SDS) samples exhibited an increase with higher XA content.

In previous research, the impact of dominant factors such as biopolymer concentration and content on the geotechnical properties of biopolymer-stabilized marine dredged sediments was investigated. However, there has not been a comprehensive evaluation of the comparison of different biopolymers incorporated to see their effect on the physical, mechanical, and microstructure behavior of marine dredged soil. This study examined the use of four different types of biopolymers to stabilize marine dredged sediment. The research looked into how incorporating biopolymers affects the geotechnical properties of the stabilized sediment using Atterberg limits and cone falling tests.

MATERIALS AND METHODS

Materials. The base soil used in this study was sediment dredged from the Port of Koper, Slovenia. The sediment was classified as high-plasticity clay (CH) according to the unified soil classification system (USCS), with a liquid limit (LL) of 58%, a plastic limit (PL) of 21%, and a plasticity index (PI) of 37%. The mineral composition of this sediment was studied by Rogan Šmuc et al. (2018) using quantitative X-ray diffraction (QXRD). Analysis of 21 samples revealed that the sediment is primarily composed of quartz, calcite, and muscovite/illite, with smaller amounts of albite and dolomite. Standard proctor test was conducted to determine the optimal moisture content (OMC) and the maximum dry density (MDD) of the sediment. Table 1 presents the basic properties of the sediment, while the grain size distribution curve and the results of the Proctor compaction test are shown in Figure 1 and Figure 2, respectively.

Table 1. Results of basic soil characterization test

Natural water content	Specific gravity ($\boldsymbol{G_s}$)	Liquid limit (LL)	Plasticity index (PL)	Optimum moisture content (OMC)	Maximum dry density (MDD)
47 %	2.7	58 %	37	17.8%	1.75 g/cm^3

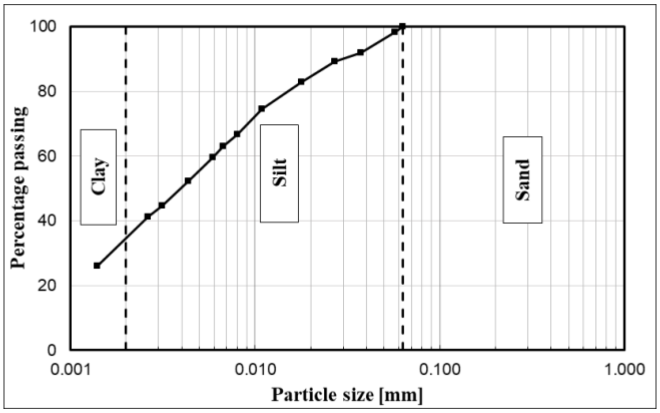


Figure 1. Grain size distribution

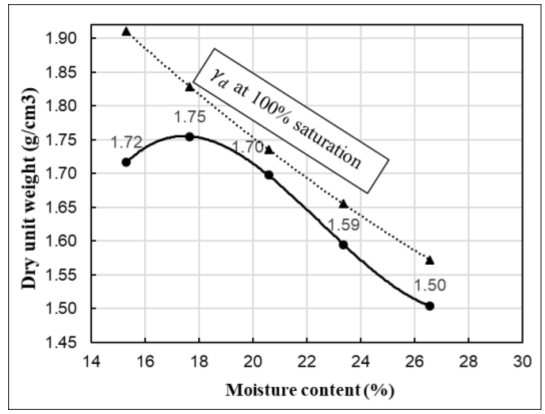


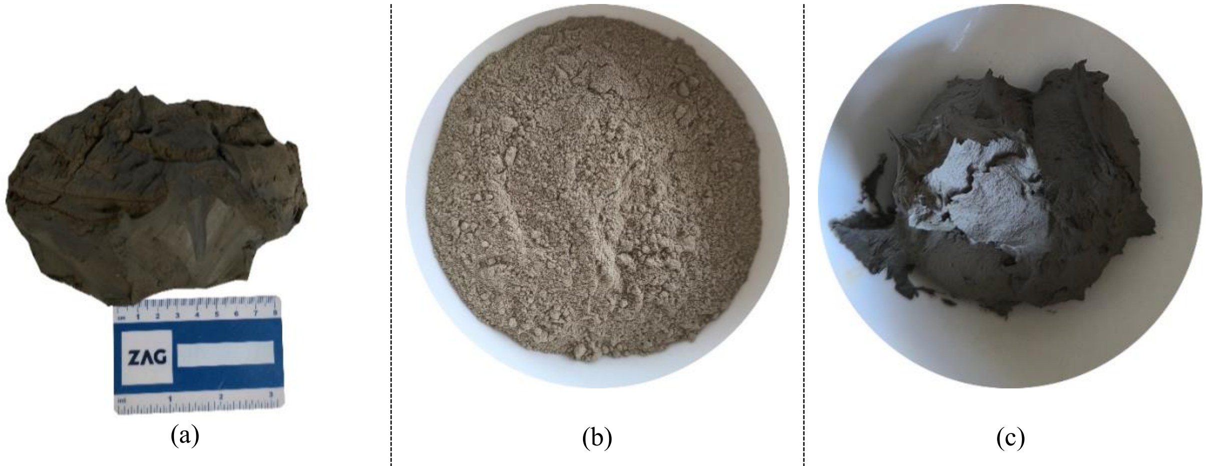
Figure 2. Proctor compaction test

Four commercially available biopolymers—xanthan gum (XA), calcium alginate (AL), guar gum (GG), and chitosan (CH)—were selected for sediment treatment. The CH biopolymer (product number 417963-100G) used in this study was purchased from Sigma-Aldrich (Merck) and derived from shrimp harvested in Iceland. Similarly, GG (G4129-250G) was obtained from Sigma-Aldrich (Merck). AL biopolymer (A0738) and XA (X0048) were purchased from Tokyo Chemical Industry Co., Ltd. (TCI).

Sample Preparation. Initially, the dredged sediment was washed through a 1 mm sieve and then placed in an oven to dry at 50°C. Once dried, the material was ground and subsequently sieved to pass through a 0.4 mm sieve to determine Atterberg limits and undrained shear strength.

Biopolymer solutions were prepared at concentrations of 0.5%, 1%, and 2% by weight of the soil. The selected concentrations of biopolymers were dissolved into distilled water, using an amount of water associated with 40% water content for each mixture, to form a biopolymer gel. For AL and GG, the biopolymer was directly added to water at a temperature of 23±0.2°C. Both biopolymers dissolved well at this ambient temperature. In the case of XA, the water was heated to 50°C using the stirring heater, and the biopolymer was gradually added to the warm water. The solution was stirred for over 30 minutes to form a homogeneous gel, which was then allowed to cool to the reference temperature of 23°C. To dissolve CH, A 2% acetic acid solution (by weight of water) was first prepared, to which the CH was then added. The mixture was stirred for over 30 minutes using magnetic stirring to achieve a homogeneous gel.

The prepared biopolymer gels were then added to the dried sediment and manually mixed using a spatula to form a uniform mixture. The Atterberg limit tests were conducted immediately after sample preparation. Prior to each test, water content of the samples was adjusted by adding distilled water to the soil-biopolymer gel mixture. Figure 3 presents the sediment in natural condition, the dry fine sediment, and the sediment treated with 2% XA biopolymer.



(a) (b) (c)

Figure 3. Sediments at a) natural condition, b) dry condition, c) treated with 2% XA

Laboratory Tests. The Atterberg limit tests for determination of PL and LL were conducted according to EN ISO 17892-12:2018. Similar procedure was followed to prepare soil-biopolymer mixtures, which were then used in fall cone tests to estimate the undrained shear strength using Equation 1, in accordance with the guidelines provided in EN ISO 17892-6:2017.

$$C_{u,fc} = c.\,g.\frac{m}{i^2} \qquad [1]$$

where, $C_{u,fc}$ is the undrained shear strength [kPa], c is a constant that depends on the tip angle of the cone, g is the gravity acceleration, m is the mass of the cone [g], and i is the average penetration depth of the cone [mm]. A cone with a mass of 80 g and a tip angle of 30° was used in the laboratory experiments. This equation is valid for a cone penetration range of 4 mm to 20 mm.

Based on the LL and PI results, biopolymer concentrations of 0.5% and 1% were selected to estimate the undrained shear strength. The Atterberg limit tests revealed that the addition of 1% biopolymer significantly improved soil consistency. However, a higher concentration of 2% biopolymer, while effective, was excluded from further testing due to its high cost, making it impractical for large-scale applications. All tests were conducted at high water contents, ranging from 40% to 80% reflecting the naturally high moisture content of dredged sediments. Although the water content of the provided material was measured as 47% in the laboratory, in environmental conditions in Port of Koper, this moisture content vary significantly and can be much higher. This range was selected to evaluate the treatment efficiency under conditions close to the sediment's natural state.

A JEOL IT500 LV Scanning Electron Microscope (SEM) was used to visualize the interaction between the soil particles and the biopolymer. The SEM was operated at an accelerating voltage of 20 kV in low vacuum mode at a working distance of 10 mm. SEM was performed to visualize the microstructural development induced by the addition of biopolymers, which contribute to the improvement of soil consistency and shear strength.

RESULTS AND DISCUSSION

The liquid and plastic limits were determined for the soil treated with each biopolymer at three different biopolymer-to-soil weight ratios. The results for soil treated with each biopolymer are displayed in Figure 4.

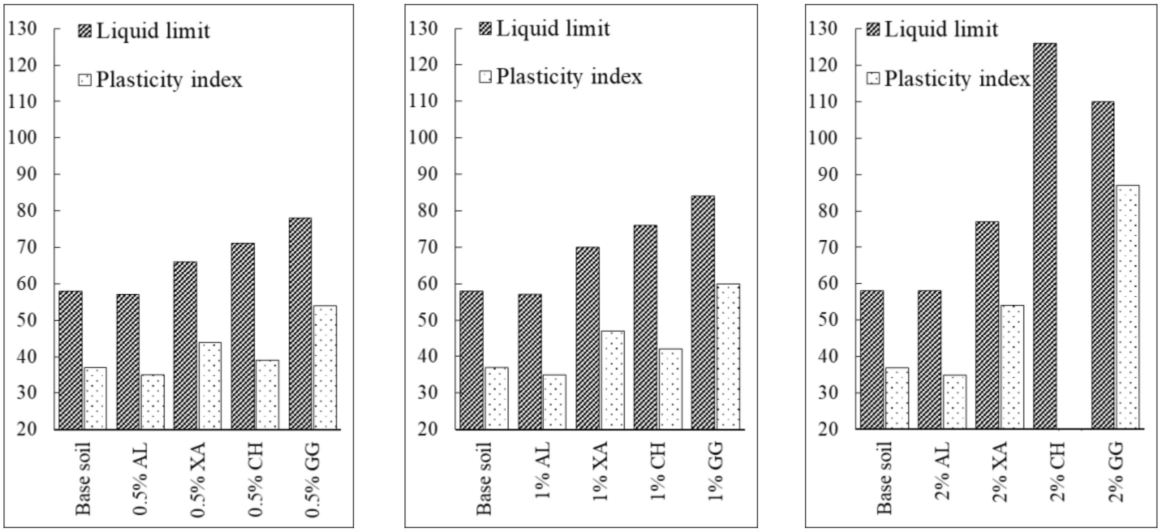


Figure 4. Liquid limit and plasticity index of biopolymer-treated soil

AL, even at concentrations up to 2% of the soil weight, does not significantly affect the consistency limits of the sediment. The liquid and plastic limits of sediment treated with AL remain almost identical to those of the untreated sediment. In contrast, the other three biopolymers cause a significant increase in the LL. This effect is particularly pronounced in soil treated with CH and GG, due to their high water-holding capacity (Liu et al. 2013; Doğan, Toker, and Göksel Saraç 2011). At 2% CH a dispersed paste was formed which prevent the rolling behavior for plastic limit determination. Therefore, the test could not be performed as the soil failed to exhibit the typical plastic behavior under rolling at this percentage.

Among the biopolymers tested, CH significantly increases the PL of the sediment, while the other three biopolymers result in only a slight increase in PL. The PI of the sediment treated with all biopolymers, except for AL, is higher than that of the untreated sediment.

Generally, greater water absorption increases a soil's susceptibility to instability. However, in the case of dredged sediment, where excessively high water content is a primary concern, the application of biopolymers can be beneficial. As demonstrated in this study, biopolymers help the soil remain in a plastic state rather than transitioning to a liquid state, even across a wide range of water contents. This means that the soil can withstand high water content without experiencing significant loss of strength. This behavior is reflected in the soil's consistency index, which indicates the relative firmness or stiffness of a soil sample.

The natural water content of the dredged sediment measured in the laboratory was 47%, though in environmental conditions, this moisture content could be significantly higher. Considering the 47% natural water content, the consistency index was measured for each sample, as shown in Figure 5.

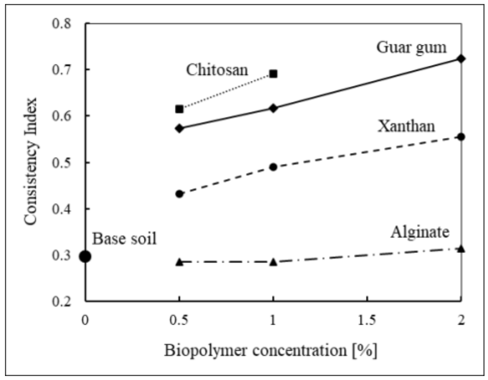


Figure 5. Consistency index

As seen in this figure, the soil consistency increased significantly even with 0.5% biopolymer concentration. While AL had no noticeable effect on enhancing sediment consistency, both CH and GG increased the consistency index by around 100% at a 1% biopolymer concentration.

The results of the undrained shear strength, estimated using the fall cone test, are presented in Figure 6 for biopolymer concentrations of 0.5% and 1%. In all cases, a strong correlation between the estimated undrained shear strength and the soil's water content is observed.

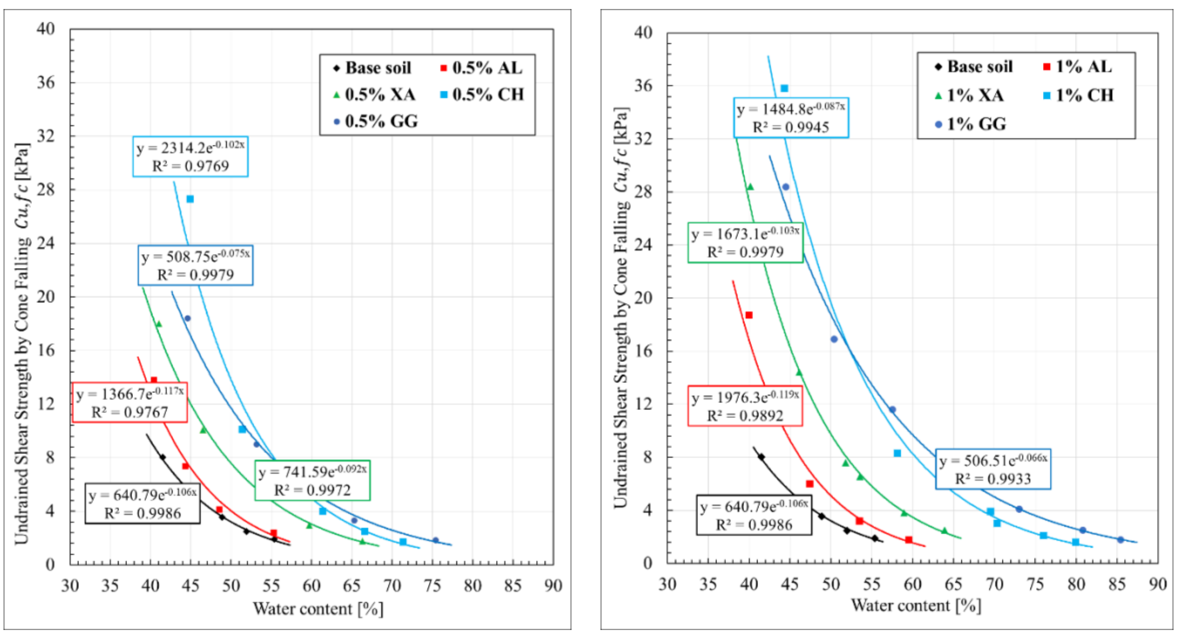


Figure 6. Estimated undrained shear strength using cone falling test

The findings demonstrate a significant enhancement of undrained shear strength with the addition of biopolymers to the sediment. The formation of hydrogel within the soil pores not only increases the sediment consistency but also positively affects the soil's shear strength. As more biopolymer is added, the viscosity of the biopolymer solution—and consequently, the shear strength of the soil—increases, as shown in Figure 6 for the 0.5% and 1% concentrations. The results indicate that CH and GG are particularly effective in enhancing shear strength at higher water contents, which is relevant for the dredged sediment materials. Based on the observed trendlines, it is expected that XA and AL biopolymers will provide significant shear strength enhancement at lower water contents.

Figure 7(a) shows the sediment microstructure without biopolymer and Figure 7(b) shows the microscopic interaction between sediment particles and the CH biopolymer as observed through SEM images. The CH forms connective chains between the soil particles, creating a cohesive soil-biopolymer matrix.

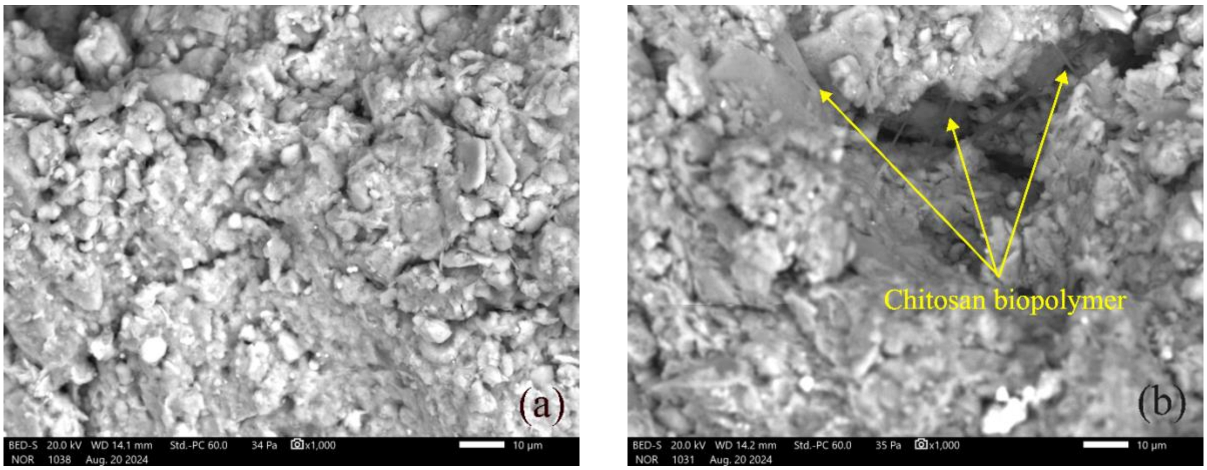


Figure 7. SEM images of (a) sediment with no biopolymer and (b) sediment treated with 1% chitosan biopolymer

CONCLUSION

This study investigated the consistency and undrained shear strength of dredged sediment treated with four types of biopolymers. The findings underscore the significant role of biopolymers in enhancing sediment consistency and undrained shear strength. The addition of biopolymers led to an increase in the LL of the treated sediment, resulting in a higher consistency index. Among the biopolymers tested, CH and GG showed the greatest ability to absorb moisture, making them particularly effective for stabilizing dredged sediment with high water content.

The study also revealed that the undrained shear strength of the sediment was significantly improved with the addition of biopolymers, with a strong correlation observed between shear strength and water content. CH and GG, in particular, showed significant enhancements in shear strength at higher water contents. Furthermore, the trendlines observed in the study suggest that XA and AL biopolymers could offer effective shear strength enhancement at lower water contents.

The results suggest that biopolymer treatment can improve the consistency and mechanical properties of dredged sediments, particularly in environments where high water content poses a challenge.

This study was conducted under laboratory conditions, with dried sediment and distilled water. The marine ecosystem, with its high salt concentrations, may affect biopolymer behavior. Acknowledging this limitation, it is recommended that future research should explore biopolymer applications for stabilizing marine sediment in its natural state.

Acknowledgments. The authors acknowledge the project FunGENESIS financially supported by the Slovenian Research and Innovation Agency through the Development funding pillar (RSF). The authors also acknowledge the financial support of the Slovenian Research and Innovation

Agency (ARIS) through the project L2-60150: Bio- and alkali- activated stabilization of dredged marine sediments for inland, shore and offshore construction purposes (BAST) and the bilateral project BI-VB/23-25-010: Microbial soil stabilization.

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