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Keynote Paper

Biopolymer-based soil treatment (BPST)

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ABSTRACT

Various environmental concerns, including global warming, climate change, and desertification, have lately risen to the forefront of human concern and interest. The convergence of global climate change and accompanying land degradation is contributing to various socio-economic problems, such as the loss of farmland, air pollution (fine dust), severe famines, and water shortages. In this regard, geotechnical engineering professionals are responsible for preserving the land on earth. Current geotechnical engineering and biotechnology advancements are coupled to provide ecologically acceptable soil treatment and preservation methods. This paper reviews the biopolymer-soil treatment (BPST), as a new soil binder treatment to promote interparticle interactions in soils and support geotechnical development with weak environmental effects regarding their CO_2 emissions and groundwater disturbance. Numerous studies have been carried out on the biochemical interactions between biopolymers and soil to improve their binding strength. Furthermore, the best conditions for biopolymer treatment have been investigated while considering the various types of biopolymers and soils. Future initiatives for application of this technology to different geotechnical constructions are also considered. This paper reviews the BPST and solidifies the foundation for the future eco-friendly geotechnics.

1. INTRODUCTION

Recent increases in the number and severity of environmental issues caused by the rapid industrialization and global warming have highlighted the need for sustainable engineering techniques. Moreover, as ecological threats such as climate change threaten to cause irreversible alterations to the ecosystem, the need to reduce the human dependence on scarce resources has increased. The planet and its soil are crucial to the human survival and growth.

Nonetheless, escalating environmental changes are beginning to threaten the

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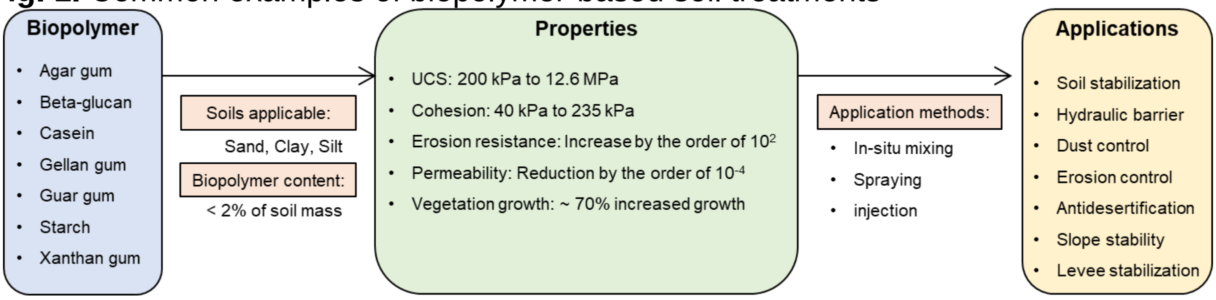
ecosystem on which humans depend. For the development of civil infrastructures, geotechnical engineers studied various soil stabilization and ground improvement methods to modify the geotechnical engineering features of soil to enhance its compressive strength, hydraulic conductivity, durability, and erosion resistance (Chu *et al.* 2009). Cement is the most often employed substance for chemical ground improvement. Nevertheless, it has various ecologically unfavorable properties, such as greenhouse gas emissions, which restrict its use as a sustainable material (Worrell *et al.* 2001; Metz *et al.* 2005; Rehan and Nehdi 2005; Larson 2011; Oss 2014). In recent years, biological soil stabilization methods such as microbe injection and byproduct precipitation (e.g., Microbially induced calcite precipitation and enzyme induced calcite precipitation) have been researched as alternatives to using chemical soil binders such as cement with substantial CO_2 emissions in geotechnical engineering procedures. In addition, biopolymers have been investigated among various biological soil stabilization means as potential building adhesives.

Biopolymers are organic polymers derived from natural biological processes composed of monomeric components organized into larger structures (Chang *et al.* 2020). Historically, the humankind has applied biopolymers in geotechnical engineering. For example, ancient civilizations used natural bitumen, straw, and sticky rice as binding materials for soil and soil bricks (Kemp 1989; Potts 1997; Yang *et al.* 2010; Chang *et al.* 2015). When biopolymers are incorporated into soil, they alter its physicochemical properties: increase its compressive strength, enhance its resistance to erosion, decrease its permeability, etc., making it suitable for plant growth. In addition, the direct use of biopolymers provides numerous benefits in terms of construction periods, target soils over conventional biological methods, including a faster treatment period, absence of need for microbial or nutrient infusions, and compatibility with clayey soils (De Muynck *et al.* 2010; Cole *et al.* 2012). Moreover, as biopolymers are abundant in the nature and many are nontoxic and even edible, they are considered sustainable eco-friendly building materials.

There are three primary categories of biopolymers: polynucleotides (ribonucleic acid and deoxyribonucleic acid), polypeptides (composed of amino acids), and polysaccharides. Among the biopolymer categories, polysaccharides, composed of carbohydrate chains of multiple monosaccharide units, are the most often employed biopolymers in various applications. Owing to their essential biological functions in the production of skeletal structures, reserve compounds, and water-binding chemicals, they are abundant in the nature, and thus are economically feasible in various fields (Belitz *et al.* 2009; Kalia and Averous 2011; US National Library of Medicine 2011). Therefore, most of the biopolymers produced for biopolymer-treated soil applications are polysaccharides. Polysaccharides have been mainly chosen owing to their capabilities as binders, either by directly enhancing the interparticle interaction between soil particles or forming a gel-like coating enveloping the soil particles. Several biopolymers highlighted in this research are listed in Fig. 1.

In this study, the impacts of popular biopolymers utilized in geotechnical engineering procedures and their effects on soil parameters are analyzed based on prior and contemporary studies. Methods of biopolymer in-situ application are recommended, as well as potential themes for future biopolymer-soil-related research.

Fig. 1. Common examples of biopolymer-based soil treatments



2. GEOTECHNICAL PROPERTIES AND MECHANISMS OF BPST

2.1 Shear Strength

Shear strength (i.e., the resistance of soils to shearing stress) is one of the most critical design factors for geotechnical constructions. Using different ratios of coarse to fine soil, shear strength evaluations for biopolymer-treated soils were carried out. In particular, the sand-to-kaolinite ratios were 100:0, 80:20, 50:50, and 0:100. Chang and Cho (2019) carried out laboratory vane shear tests regarding the biopolymer content in the biopolymer content in the soil mass. The experimental results indicated that, with fine particles, the overall strengthening trends were more reliant on the biopolymer-to-clay mass ratios than on the total soil mass ratio. In addition, the results of direct shear tests on gellan gum-treated soils (i.e., sand to clay) by demonstrated the impact of biopolymers on the cohesion and friction angle of the soils for varying fine soil concentrations (Fig. 2). In the case of pure sand, it was demonstrated that the influence of biopolymers on the soil enhanced the cohesiveness of the sand while the friction angle of the sands remained essentially constant. Clay-containing soils treated with biopolymers exhibited an increased cohesiveness. With the addition of biopolymers, the friction angle of the clayey soils also increased. These changes in behavior were a result of the direct and indirect interactions between the clay and biopolymers and sand and biopolymers, respectively. In cohesionless sands, biopolymers encircle the soils and provide the sand cohesion. As the friction angle of soils is mainly determined by the particle shapes and dilatation effect of the soil, it is generally constant. In contrast, clayey soils immediately interact with biopolymers, resulting in an aggregation effect. Therefore, at the moment of shear failure, clayey soils produce conglomerates with dilatation effects, which increase the friction angle.

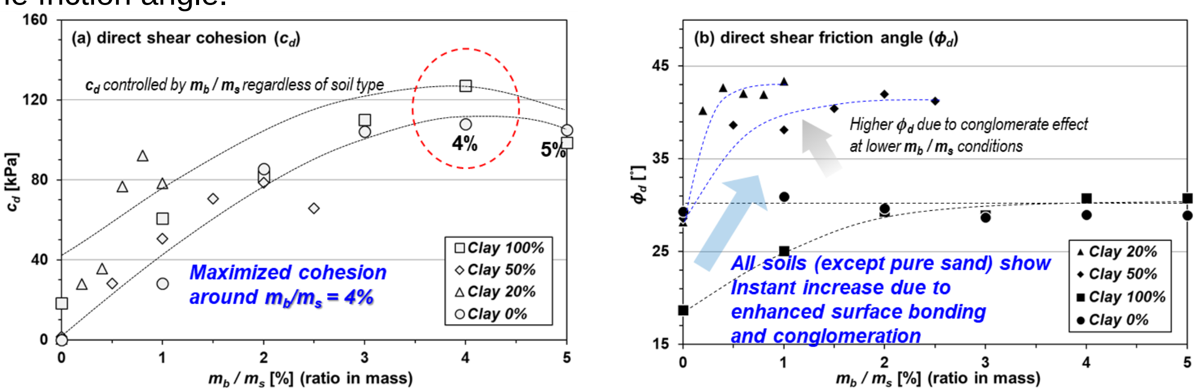


Fig. 2. Shear strength parameters from sand to clay at hydrogel state (Chang and Cho, 2019)

2.2 Compressive Strength

The dry unconfined compressive strengths of biopolymer-treated sands have been assessed (Chang and Cho 2012; Chang *et al.* 2018). Even if the stability of the biopolymer-treated sands varies, the biopolymer-treated sands (biopolymer-to-soil mass ratio < 5%) exhibit higher strengthening efficiencies than those of the cement-treated sands (even at a cement-to-soil mass ratio of 10%).

Figure 3 showed the compressive strengths of a 1% xanthan gum biopolymer added to pure sands, kaolinite clay, natural sandy soils with fines, and well-distributed fine soils (i.e., Korean Red Yellow soil). The compressive strength of the soils varied by orders of magnitude (up to 4.94 MPa (1% Xanthan gum-treated Korean Red Yellow soil)). The gel-type biopolymers react with each other to generate chain-type biopolymers that encase the soil particles in a biopolymer film that improves the soil strength for coarse soils that typically have few or no electrical charges along their surfaces. As biopolymers and fine soils tend to have electrical charges along their surfaces (Nugent *et al.* 2009), the binding mechanisms between gel-type xanthan gum biopolymers and fine soils tended to lead to a more significant increase in strength due to the links formed between the clay particles in which the biopolymers served as bridges.

However, the biopolymer vulnerability to the presence of water, induced by their natural hydrophilicity, is one of the possible negative factors for mechanical strengthening. For example, Chang *et al.* (2015) showed that the unconfined compressive strength of gellan gum and agar gum biopolymer-treated clayey soils decreased significantly as the soil water content increased. In other words, when biopolymer-treated soils dehydrate, their unconfined compressive strength largely increases. Nonetheless, when the water is absorbed back into the soil by wetting, the dipolar structure of the water interacts with the biopolymer to generate swollen hydrogels. This interaction between biopolymers and water decreases the reaction between biopolymers and soils, significantly reducing the material strength (Yakimets *et al.* 2007).

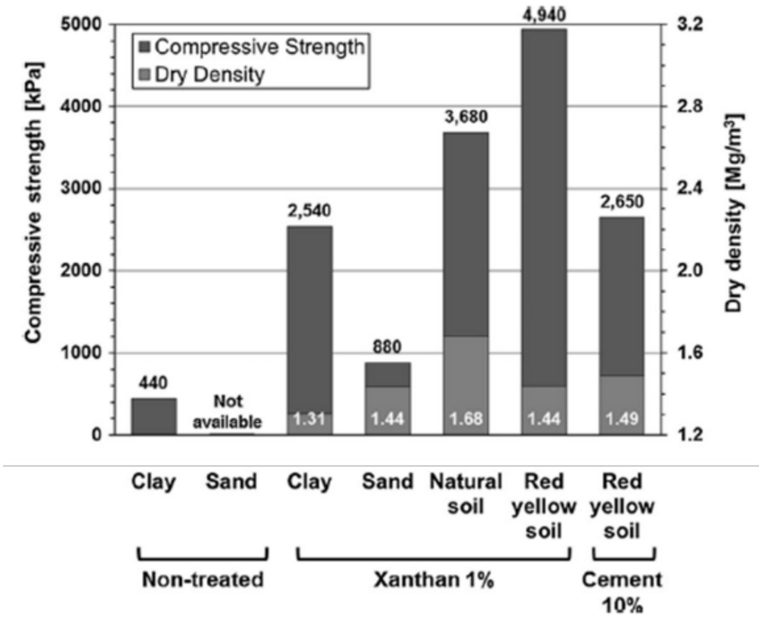


Fig. 3. Unconfined compressive strength of xanthan gum biopolymer-treated soils (Chang *et al.* 2015)

2.3 Hydraulic Conductivity

The viscous characteristics of biopolymer hydrogels and their capacity to entangle soil particles influence the hydraulic conductivity decrease (or hydraulic barrier) of soils (Ayeldeen *et al.* 2016; Cabalar *et al.* 2017), as shown in Fig. 4. When biopolymers contact and absorb pore fluids, a very viscous hydrogel forms in the pore spaces of the soil. These hydrogels are often water-retentive and delay the water transit (including diffusion) through the soil pores. When biopolymers are combined with the soil, the soil hydraulic conductivity (permeability) is largely reduced (Chang *et al.* 2016). As a result of the small activation time (i.e., immediate interaction) of biopolymer-treated soils compared to cement grouting methods, the effect of biopolymers on the hydraulic conductivity is almost instantaneous. In contrast, other methods require a period of curing before the hydraulic conductivity is affected. Chang *et al.* (2017) showed a difference in the time needed for activating a decrease in hydraulic conductivity. Gellan gum-treated soils exhibited a period smaller than 4 h to achieve the hydraulic conductivity of impermeable layers (i.e., <10^{-7} cm/s), while a cement slurry required 60 h. These results are promising for hydraulic barrier applications.

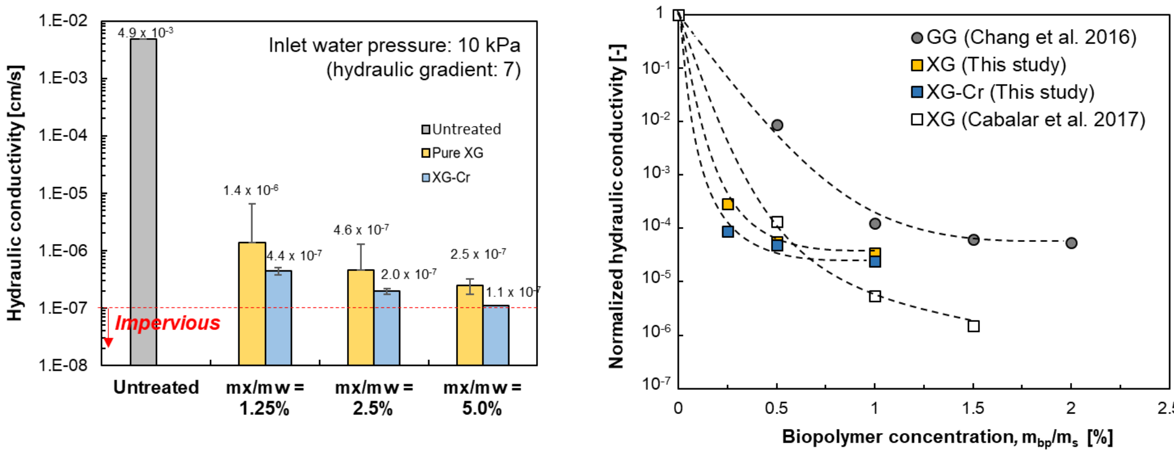


Fig. 4. Pore-clogging induced by xanthan gum treatment on sand

2.4 Soil Erosion Resistance

Biopolymers enhance the erosion resilience of soils. Chang *et al.* (2015) analyzed the erosion of natural and biopolymer-treated soils and quantity of surface runoff. In this study, the use of biopolymers significantly reduced the rate of soil erosion. Although the strength of biopolymer-treated soils largely diminishes in the presence of water, biopolymers tend to improve the viscosity of pore fluids owing to their hydraulic absorption. Consequently, the development of biopolymer hydrogels that fill the soil pore spaces with very viscous hydrogels increases the interparticle adhesion (Khachatoorian *et al.* 2003; Ivanov and Chu 2008; Bouazza *et al.* 2009). Even under extreme fluid (i.e., water or air) flow conditions (Fig. 5), this hydrogel-induced interparticle bonding enhances the erosion resilience of soils (Ham *et al.* 2016; Kwon *et al.* 2020; Kwon *et al.* 2021). Moreover, biopolymer hydrogels cause pore clogging, restricting the rapid water infiltration into the ground and increasing the pore pressure.

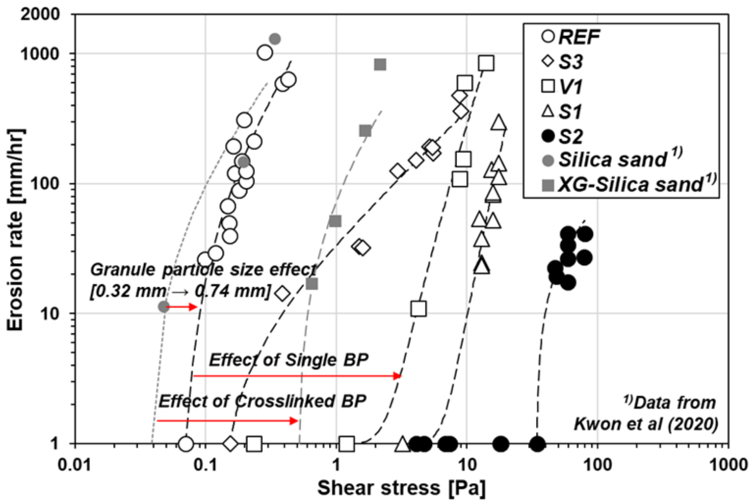


Fig. 5. Erosion curves of soils treated with biopolymers (Kwon et al. 2021)

<u>*2.5 Aids on Vegetation Growth: Antidesertification Purposes*</u>

Given their hydrophilic properties and natural composition, biopolymers encourage plant growth (Fig. 6). Chang *et al.* (2015) illustrated the effect of biopolymers on the development of oat seeds in natural and cultivated soils. Their experiment demonstrates that the addition of biopolymers to soils enhanced the plant growth in numerous manners. The first was that biopolymers in the form of microorganism-produced polymers are predominantly composed of glucose, a plant nutrient. In addition, as biopolymers are very hydrophilic, biopolymer hydrogels may hold water for a considerably longer period than that of untreated soils. Finally, as biopolymer-treated soils have more water than untreated soils, this provides plentiful water and nutrients to plants, stimulating their development. These findings are encouraging for antidesertification efforts.

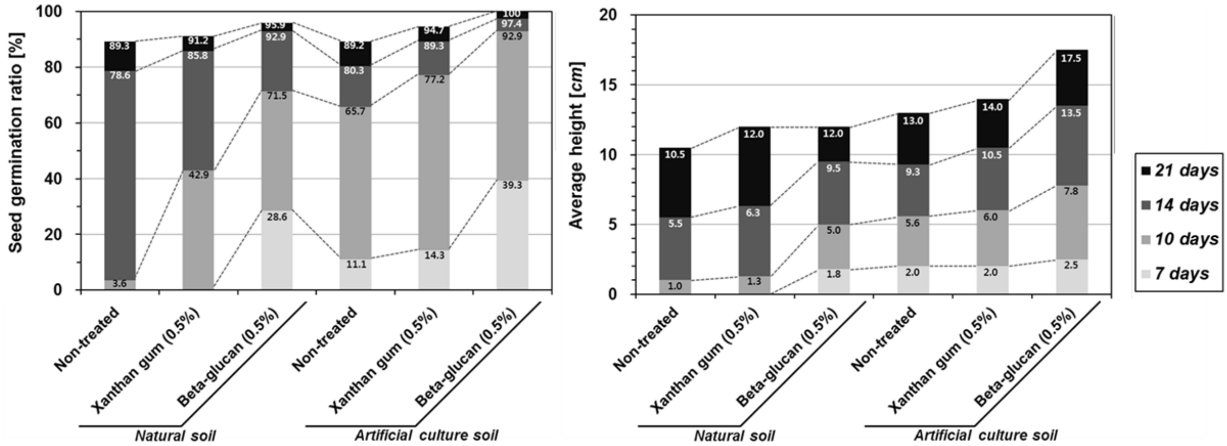


Fig. 6. Effects of biopolymers on the seed germination ratio and average height of vegetation (Chang et al. 2015)

3. FUTURE PROSPECTS OF BPST APPLICATION

3.1 Strength Enhancement: Biopolymer Cross Linking

The degradation of the biopolymer in water is a severe drawback. Therefore, it is crucial to devise a method to minimize this decline. The weakening results from the interaction between water molecules and biopolymers, which reduces their contact with other biopolymers and soil. Im *et al.* (2021) assessed the effect of malonic acid to enhance the wet resistance of starch biopolymers for soil improvement (Fig. 7). Cross linking, a method for increasing the number of interparticle bonds between two chemical compounds, is a possible solution to this problem. When malonic acid is applied to biopolymers, the interaction between biopolymer molecules and water molecules is largely reduced, resulting in an increased strength under wet and dry conditions. However, it is necessary to ensure that the cross linking does not compromise the overall workability of biopolymer soil mixtures.

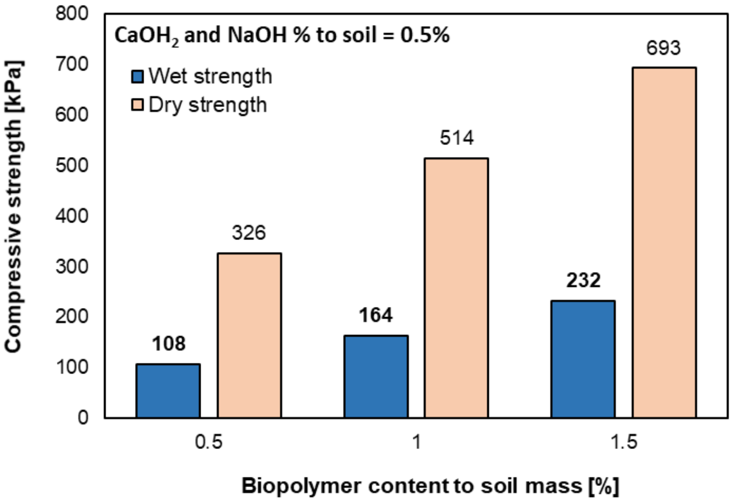


Fig. 7. Effect of xanthan gum cross-linking on the compressive strength

3.2 Seismic mitigation and Liquefaction control

Im *et al.* (2017) carried out resonant column/torsional shear (RC/TS) tests on a biopolymer-treated sand (Fig. 8). The biopolymer enhanced the sand shear modulus and damping ratio. This outcome most likely originated from the thin biopolymer film coating and interparticle bonding that enabled a superior energy dissipation through material damping during seismic events.

Thus, it is projected that biopolymer treatment would enhance the sandy soil earthquake and liquefaction resistance. However, to establish viability of this approach, it is necessary to evaluate the effects of biopolymers in bulk media under various conditions utilizing seismic event simulation test methods, such as the cyclic triaxial and simple shear tests and geo-centrifuge seismic test.

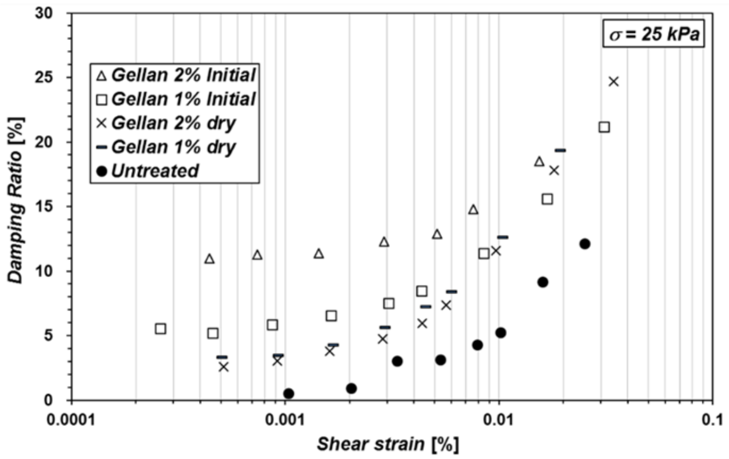


Fig. 8. Damping efficiencies of biopolymer-treated sands (Im *et al.* 2017)

<u>*3.4 Dredging and Reclamation*</u>

In several applications involving soil, sedimentation is a crucial variable. Owing to the particle structure and relatively small specific surface area of clays, their sedimentation behavior is often less sensitive to the aqueous phase water than to the solid concentration (i.e., initial water content) (Imai 1980). Despite this, studies indicate that cationic biopolymers such as ε-polylysine could be utilized to enhance the sedimentation of clays (e.g., kaolinite, marine clays) in a suspended solution regarding the sedimentation time and accumulated density, as shown in Fig. 9 (Kwon *et al.* 2017; Kwon *et al.* 2019). Therefore, quicker sedimentation behaviors may reduce the construction time, cost, and sedimentation depot size of offshore reclamation projects and construction sites. These qualities may also be used to compact clayey soils and construct artificial islands. However, further studies on their interactions with soils, water, and ions in water are required to properly use these biopolymers.

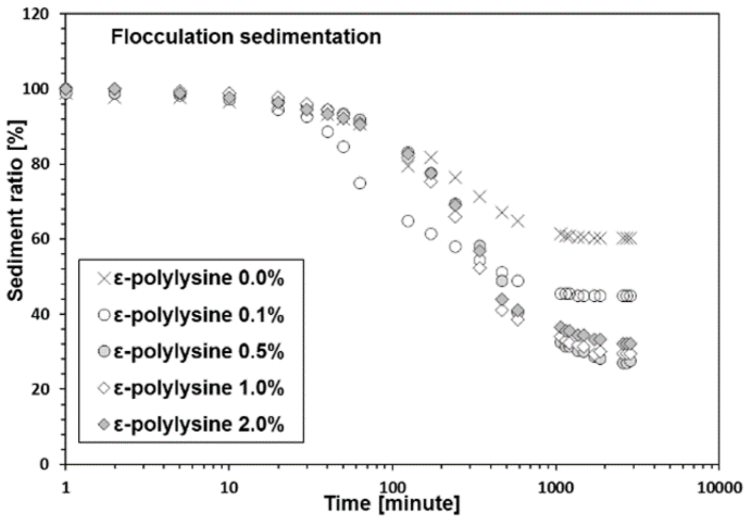


Fig. 9. Settling behavior of ε-polylysine-treated kaolinite clays (Kwon et al. 2017)

3.5 Antidesertification

Desertification is a serious environmental and societal problem, particularly in the arid and semiarid regions of the globe. In these areas, soil erosion and land degradation are generally accompanied by loss of fine particles (Chang *et al.* 2015). The desertification is comparable to the movement of fine soils through Aeolian or stream movements. The remaining soil layers consist primarily of coarse sands, resulting in loss of nutrient-rich soils that hinder vegetation growth and drier environment (Lal 2001). Therefore, an increased vegetation is necessary to prevent desertification; before this, the soil must retain sufficient nutrients and their loss must be regulated (Cao 2008).

In terms of erosion mitigation and vegetation growth, biopolymers as antidesertification materials are promising owing to their high resilience to erosion (Kavazanjian *et al.* 2009; Ham *et al.* 2018), ability to supply nutrition, and capacity to retain substantial amounts of water. However, this technology is still in its infancy. A significant testing over a long period is required to determine the effects of biopolymers in such circumstances. In addition, various biopolymers must be developed to handle varying climatic conditions and plant species as different plant species need distinct growing circumstances.

Fig. 10. Possible biopolymer application for mitigate global desertification (Chang et al. 2015)

3.6 Slopes and Levee Construction

The stability of embankment slopes and levee constructions has been a significant issue as the rainfall amount has increased in many parts of the globe over the last few years as the destruction or loss of such structures may result in severe physical and economic losses in the surrounding area. Overtopping and piping are the leading causes of levee collapse. With any of these problems, the increasing erosion and washout of soil threaten the building overall stability. In some instances, biopolymers may be utilized to enable water to overflow while protecting the surface and preventing erosion. As mentioned, biopolymers have a high erosion resistance and minimize the soil permeability. In overtopping failures, water turbulence at the base of the slope causes an erosion-related loss that grows until the whole slope fails. Biopolymer-treated soils may withstand water turbulence by preventing an early soil erosion.

Additionally, the reduced hydraulic conductivity of biopolymer-treated soils may aid in preventing soil piping. However, to implement biopolymers in this business, it is essential to analyze the durability and resilience of biopolymer-treated soils on a broad scale to determine the material technological limitations. In addition, it is necessary to evaluate the interactions between biopolymer-treated soils and water to ensure practical field application. Seo *et al.* (2021) sprayed biopolymer solutions on a slope to improve the soil surface stability (Fig. 11). The biopolymers significantly improved the mechanical characteristics of the slope soil and plants. In addition, Ko and Kang (2020) constructed biopolymer-treated embankments and evaluated the influence of biopolymers on the overflow resistance of dams. The findings indicate that biopolymers are promising for retaining the wall stability.

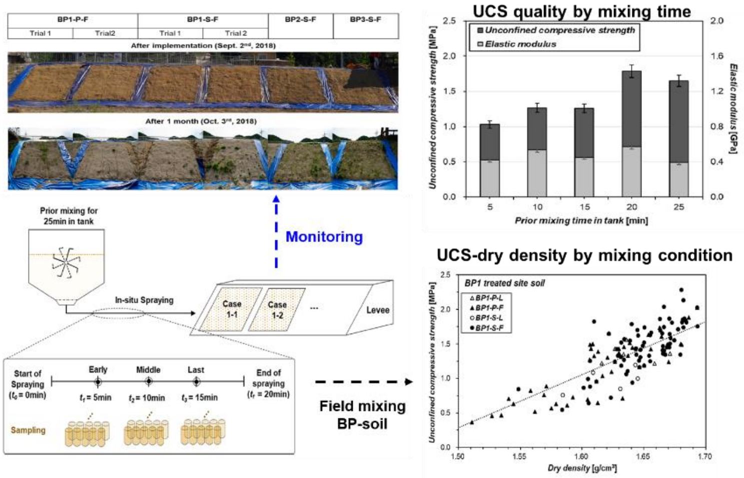


Fig. 11. Quality analysis of biopolymer-treated levee slope

4. CONCLUSIONS

An increasing number of geographic regions are affected by environmental effects such as global warming. Development and use of sustainable geomaterials are essential to avoid geotechnical concerns induced by such ecological effects. Biopolymers are promising for use as sustainable materials to increase the stability and strength of various soils. They have advantages over conventional materials, such as environmental friendliness and effectiveness at low concentrations. In addition, the fine soils enhance the shear and compressive strength of biopolymer-treated grounds. Biopolymers also possess various valuable properties: they reduce the soil permeability, increase its resistance to erosion, and promote plant growth. Despite the advantages, no extensive studies have been carried out on the behavior and effect of biopolymers on soils. Although it has been demonstrated that biopolymers possess properties distinct from those of conventional reinforcing materials, future BPST studies should concentrate on their optimal use, including biopolymer cross linking, water-holding properties, applications for antidesertification, liquefaction mitigation, dredging and reclamation, and embankment constructions.

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