Cementless Soil Stabilizer – Biopolymer

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ABSTRACT

In recent years, a number of environmental challenges, including global warming and desertification, have risen to the forefront of human focus and attention. The soil of the earth has been the basis of human life and prosperity throughout the ages in all countries around the world; however, the confluence of global climate change and the accompanying land degradation is now contributing to a variety of socio-economic problems, such as the loss of farmland, air pollution (fine dust), severe famines (e.g., in Africa), water shortages, and so on. In this context, workers in the field of geotechnical engineering are among those responsible to preserve the land on planet Earth. In addition, they also have the responsibility to identify and prepare extra-planetary territory as an alternative to earth to ensure human survival in an extreme future scenario. In this paper, recent advances in the fields of geotechnical engineering and biotechnology are combined in an environmentally-friendly approach to soil treatment and preservation. Specifically, microbial biopolymers that have been adapted as novel soil binders are discussed in terms of how they function to enhance inter-particle interactions in soils and facilitate plant growth with minimal environmental impact in terms of their CO₂ emissions and groundwater disturbance. Numbers of research have been performed to investigate the bio-chemical interactions between biopolymers and soil with the objective of increasing their binding strength, and the optimal conditions for biopolymer treatment were explored while considering different types of biopolymers and soils. Today, bio-soil technologies have been practically implemented in a number of applications, including cement-free pavement, slope and embankment stabilization, aeolian erosion reduction, and in-situ ground improvement practices. Future commercialization strategies for these technologies are also discussed.

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1. INTRODUCTION

The recent growth in the number and magnitude of environmental challenges caused by rapid development and global climate change has highlighted the need to identify sustainable engineering methodologies. As environmental hazards like global warming threaten to cause irreversible change to our environment, the necessity to reduce our dependence on limited resources has become increasingly evident. The earth and its soil are the basis of human life and prosperity. However, accelerating changes to the environment are beginning to threaten the very Earth that we as humans depend on.

In the context of global warming, there are two major climate effects that in turn create a chain of actions and reactions that result in changes to the land we live on. The first is the effects of extreme precipitation and the second is the increase in ocean levels (Huber and Knutti 2012; Yasuhara et al. 2007). Extreme precipitation is the result of a warmer climate, which enables the surrounding atmosphere to retain more water vapor. A 1 °C increase in the atmospheric temperature means that atmosphere can contain 7% more water vapor (Liu et al. 2009; Trenberth 1998, 2011; Trenberth et al. 2003). This increase in water vapor density when combined with cloud movements due to changes in the weather patterns results in localized heavy downpours in certain geographic areas and droughts in others (Ren 2015). These events may lead to the development of irregular irrigation patterns with longer intervals between the dry and wet seasons. Heavy localized raining can also cause instabilities in the properties of the ground. For example, heavy localized rain may cause significant increases in the pore water pressure in soils, and such increases can greatly reduce the stability of various local soils and lead to landslides and slope failures (Crozier and Glade 2005; F. Wieczorek et al. 2007; Keefer et al. 1987). In addition, localized heavy rainfall is more prone to cause flooding, which in turn can cause the failure of earthen structures like embankments and levees (Huang et al. 2014). At the same time, extended dry seasons can cause droughts in other parts of the world, which will reduce the amount of vegetation and increase the likelihood of erosion and thus will lead to soil degradation and desertification (Chang et al. 2015d; Williams 2014).

Increases in the sea level are a consequence of the melting of polar and inland glaciers in addition to the thermal expansion of the water (Church et al. 2011; Mimura 2013; Solomon et al. 2007). Increases in these phenomena can generate severe air currents, and thereby result in the formation of stronger storms and higher intensity rains (Yasuhara et al. 2007). Moreover, increases in the water level increase wave energy, which can result in the erosion and removal of coastal soils (Alongi 2008; Yasuhara et al. 2007).

The deterioration and destruction of the earth not only causes harm to the land and infrastructure but also to human life in present and future generations. To mitigate or prevent such disasters, it is essential that appropriate steps be taken to develop sustainable geotechnical engineering methods and materials.

In this study, common biopolymers used in geotechnical engineering practices and their effects on soil properties are discussed based on numbers of previous and recent research. Methods of biopolymer in-situ application are suggested, as well as
providing prospective subjects for future research related to biopolymer-soils.

2. BIOPOLYMERS IN GEOTECHNICAL ENGINEERING FOR SUSTAINABLE DEVELOPMENT

The main purpose of soil stabilization and ground improvement activities is to alter the geotechnical engineering properties of soil to improve its design parameters, such as compressive strength, hydraulic conductivity, durability, and erosion resistance (Chu et al. 2009; Sherwood 1993). There are two widely used ground improvement and soil stabilization practices. The first is mechanical improvement whereby the properties of the soil are reinforced via physical processes, such as compaction, drainage, external loading, and consolidation. The second is to enhance the soil by applying chemical additives that bind the soil particles together by way of a chemical reaction, such as cement hydration or pozzolanic reactions. The most widely used material for chemical ground improvement is cement; however, cement has several environmentally unfriendly properties, such as greenhouse gas emissions, which limit its use as a sustainable material (Chang and Cho 2012; Larson 2011; Metz et al. 2005; Oss 2014; Rehan and Nehdi 2005; Worrell et al. 2001).

For this reason, biological approaches, such as microbe injection and byproduct precipitation, have been studied in recent years as alternatives to reduce the use of high CO₂ emitting soil binders in geotechnical engineering practices. In particular, the use of biopolymers and biologically induced polymers has been studied as prospective construction binders.

Biopolymers are polymers produced via natural biological processes and consist of monomeric units that are assembled into larger formations. There are three major types of biopolymers: polynucleotides (RNA and DNA), polypeptides (composed of amino acids), and polysaccharides. Among these, polysaccharides are carbohydrate chains that consist of numerous monosaccharide units and are the most widely used biopolymers in various applications. These are commonly found in nature due to their key biological roles in the formation of skeletal structures, reserve substances, and water binding substances (Belitz et al. 2009; Kalia and Averous 2011; US National Library of Medicine 2011).

In the field of geotechnical engineering, the use of biopolymers is not entirely new. For example, ancient civilizations were known to use natural bitumen, straw, and sticky rice binders (Chang et al. 2015b; Kemp 1989; Potts 1997; Yang et al. 2010). When biopolymers are mixed into soil they cause various changes in the physicochemical characteristics of the soil, such as increases in the compressive strength, improved erosion resistance, reduced permeability, and suitability for vegetation. Moreover, the direct use of biopolymers has several advantages over other biological approaches, such as a shorter treatment time, no requirement for microbial or nutrient injections, and compatibility with clayey soils (Cole et al. 2012; De Muynck et al. 2010). In additional, as biopolymers are found in nature and many are known to be harmless and even edible, biopolymers are considered to be a sustainable eco-friendly construction material.

Several biopolymers have now been developed for biopolymer-treated soil applications, most of which are polysaccharides. Polysaccharides were selected
primarily for their properties as a binding agent by either directly improving the interparticle bonding between soil particles or by creating a gel-like film surrounding the soil particles. The following are several of the biopolymers highlighted in this study.

**Beta-glucan** Beta-glucans are composed of D-glucose monomers linked by β-glycosidic bonds (Bacic et al. 2009; Shin et al. 2007). It is naturally found in the cellulose of plants, the bran of cereal grain, and the cell walls of various organisms, such as yeast, fungi, mushrooms, and bacteria (Cui 2001). Beta-glucans have been used in cosmetic products, superplasticizers, and water reducing agents (Chang and Cho 2014; Khayat and Yahia 1997).

**Xanthan Gum** Xanthan gum is a polysaccharide derived from the bacterium *Xanthomonas campestris*, and is produced by the fermentation of glucose or sucrose (Davidson 1980; Rosalam and England 2006). It is composed of D-uronic acid, D-mannose, pyruvylated mannose, 6-O-acetyl D-mannose, and 1,4-link glucans (Cadmus et al. 1982). This biopolymer is commercially available and has been used in numerous fields as a viscosity thickener due to its pseudo plasticity and hydrocolloid properties (Barrére et al. 1986; Casas et al. 2000; García-Ochoa et al. 2000).

**Agar Gum** Agar gum is a biopolymer extracted from *rhodophyceae* that consists of linked galactose molecules (Ivanov and Chu 2008) with a structure that alternates between (1-4)-linked 3,6-anhydro-α-L-galactose and (1-3)-linked β-D-galactose residues. It has been widely used in the food industry as a stabilizer, thickener, flavor enhancer, and absorbent (Duckworth and Yaphe 1971; McHugh 2003). One important characteristic of agar gum is its thermogelation property, which means that it is easily dissolved at temperatures close to that of boiling water and forms a stiff hard gel when cooled back to room temperature of 20°C (Duckworth and Yaphe 1971).

**Gellan Gum** Gellan gum is extracted from the microbe *Spingomonas elodea* and is a linear polysaccharide composed of (1,3)-β-D-glucose, (1,4)-β-D-glucuronic acid, (1,4)-β-D-glucose, and (1,4)-α-L-rhamnose molecules (Jansson et al. 1983). Gellan gum has characteristics very similar to those of agar gum in that it is also used as a stabilizer/thickener with the thermogelation properties, and it is commonly used as a substitute for agar gum in some industries (Imeson 2010).

**Casein** Casein is a family of phosphoproteins that are found in mammalian milk. In bovine milk, 80% of the protein is composed of casein (Ruhsing Pan et al. 1999). Casein is normally in a suspension of particles called “casein micelles” that are held together through hydrophobic interactions with water and calcium ions (Dalglish 1998). Casein is used in a wide variety of industries, including foods, paints, glues, plastics, and medical and dental products (Rose 2000; Sutermeister 1940).

### 3. EFFECTS AND MECHANISMS OF BIOPOLYMERS ON SOIL IMPROVEMENT

#### 3.1 Strengthening Characteristics

**Compressive Strength** The dry compressive strengths of various biopolymer-treated sands are shown in Fig. 1. Even though the strengths of the biopolymer-treated sands
are various, the biopolymer-treated sands (even lower concentrations) exhibit larger strengthening efficiencies in comparison with 10% cement-treated sands.

Biopolymers can be classified into three main categories. The first is long chain type biopolymers, such as beta-glucan biopolymers. These biopolymers tend to react with themselves to create a sort of film that surrounds soil particles and thereby enhances their strength. This mechanism can be seen in the scanning electron microscope (SEM) images shown in Fig. 2(a). The second category is gel-type biopolymers, to which Xanthan, gellan, and agar gums all belong. Gel-type biopolymers react differently depending on the soils. Due to the electrical charge properties of the gel-type biopolymers themselves, the presence of other charged particles can greatly enhance the strength of the resulting combination (Fig. 2 b&c).

As shown in Fig. 3, when the biopolymer Xanthan gum was applied to soils ranging from pure sands, kaolinite (clay), sandy soils with fines (natural soil), and well distributed fine soils (red yellow soil), the strength of the soils differed by orders of magnitude. As both biopolymers and fine soils tend to have electrical charges along their surfaces (Chang et al. 2015a; Nugent et al. 2009), the binding mechanisms between the gel biopolymers and soils with fines tended to have a larger increase in the strength due to the links formed between the clay particles in which the biopolymers served as bridges (Fig. 2c) (Chang et al. 2015a). Meanwhile, for coarse soils that tend to have little to no electrical charges along their surfaces, the gel-type biopolymers react among themselves to form chain type biopolymers that encompass the soil particles in a biopolymer film that enhances the strength of the soils (Fig. 2b) (Chang et al. 2015c).

The third biopolymer category is proteins. Casein is a protein which, when used to enhance the strength of soils, exhibits strengthening characteristics similar to those of chain type biopolymers. Protein solutions surround the soils and bond them together, and thereby enhance their strength (Fig. 2d). Unlike most other biopolymers, casein exhibited a stronger resistance to water due to the lower hydrophilicity of casein proteins (Chang et al. 2018).

Fig. 1 Unconfined compressive strength of biopolymer-treated sands (Chang and Cho 2012; Chang et al. 2018; Chang et al. 2015a; Chang et al. 2015c).
Fig. 2 SEM images of biopolymer-treated geomaterials: (a) beta-glucan-treated glass beads; (b) gellan gum-treated sands; (c) gellan gum-treated kaolinite soils; and (d) casein-treated soil (Chang and Cho 2012, 2018; Chang et al. 2016; Chang et al. 2018).

Fig. 3 Unconfined compressive strength of xanthan gum biopolymer-treated soils (Chang et al. 2015a).
One major drawback of biopolymers is their susceptibility to the presence of water. As shown in Fig. 4, the unconfined compressive strength of gellan gum and agar gum biopolymer-treated clayey soils can be seen to reduces greatly with the water content increase of the soils. That is, as biopolymer-treated soils lose moisture via dehydration, their unconfined compressive strength increases significantly. However, as the water is absorbed back into the soil through wetting, the dipolar characteristic of the water interferes with the biopolymer to form swelled hydrogels. This reaction between the biopolymers and water weakens the reaction between the biopolymers and soils, and greatly reduces the corresponding strength of the material (Chang et al. 2017b; Chang et al. 2015c; Yakimets et al. 2007).

Fig. 4 Compressive strength of gel-type biopolymers versus the water content: (a) gellan gum, and (b) agar gum (Chang et al. 2015c).
The strength (i.e., the unconfined compressive strength) and durability of gellan gum-treated sands when subjected to repeated wetting and drying cycles are shown in Fig. 5. It can be seen that the repeated drying and wetting cycles gradually reduced the overall strength. At the end of 10 wetting and drying cycles, the dry strength was reduced to approximately 70% of the initial value and the wet strength was reduced to between 30–50% of its initial strength based on the biopolymer concentration (Chang et al. 2017b). However, it was observed that with each drying stage, the biopolymer-treated soils recovered a large percentage of their strengthening efficiency, which demonstrated that the strength of the biopolymer-treated soils was largely based on the water content rather than the curing time.

Fig. 5 Strength of gellan gum biopolymer-treated sands with repeated wetting–drying cycles: (a) dry strength, and (b) wet (saturated) strength (Chang et al. 2017b)
Shear Strength Evaluations of the shear strength were performed using various ratios of coarse to fine soils. Specifically, the ratios of sand to kaolinite were 100:0, 80:20, 50:50, and 0:100. The results of vane shear tests versus the biopolymer concentration in the total soil mass and versus the biopolymer concentration in only the clay mass are shown in Fig. 6. As shown, the general strengthening trends were more dependent on the biopolymer to clay mass ratios than the total soil mass ratio in the presence of fine particles.

In addition, the results of direct shear tests on gellan gum-treated soils (sand to clay) (Fig. 7) show the effects of biopolymers on the cohesion and friction angle of the soils for various fine soil concentrations. It was found that in the case of pure sand, the effect of biopolymers on the soil increased the cohesion of the sand whereas the friction angle of the sands remained relatively constant. Soils containing clay exhibited an increase in cohesion when treated with biopolymers. However, the friction angle of the clayey soils also increased when biopolymers were added.

![Fig. 6 Vane shear strengths of soils with fines when compared to the: (a) biopolymer to total soil ratio, and (b) the biopolymer to clay ratio (Chang and Cho 2018).](image)
Fig. 7 Direct shear test results of gellan gum biopolymer-treated soils for different sand to clay ratios (sand:clay): (a) 100:0, (b) 80:20, (c) 50:50, and (d) 0:100 (Chang and Cho 2018).

These behavioral differences were due to the differences in the direct interaction between the clay and biopolymers and the indirect interaction between the sand and biopolymers. In cohesionless sands, the biopolymers surround the soils and provide cohesion to the otherwise cohesionless sand. However, the friction angle remains relatively constant as the friction angle of soils is largely based on the particle shapes and the dilation effect of the soil. In contrast, clayey soils interact directly with the biopolymers, which in turn results in a conglomeration effect. Therefore, at the point of shear failure, clayey soils create conglomerates that exhibit dilation effects and thereby increase the friction angle. These effects are shown in Fig. 8.

3.2 Soil Erosion Resistance

The use of biopolymers has also been shown to increase the erosion resistance of soils. The results of measuring the erosion of natural and biopolymer-treated soils are shown in Fig. 9(a), while Fig. 9(b) shows the results of measuring the degree of surface runoff with respect to the water content of the soils as increasing amounts of rainwater were absorbed. The use of biopolymers was found to drastically reduce the erosion rate of the soils in this test.
### Inter-particle interaction and strengthening mechanisms of gellan gum-treated soils

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Fig. 8 Inter-particle interaction and strengthening mechanisms of gellan gum-treated soils (Chang and Cho 2018).
Although the strength of biopolymer-treated soils significantly degrades in the presence of water, biopolymers generally tend to increase the viscosity of pore fluids due to hydraulic absorption. And thus, accompanying biopolymer hydrogel formation in which the pore spaces within the soil are filled with highly viscous hydrogels enhances the inter-particle adhesion (Bouazza et al. 2009; Ivanov and Chu 2008; Khachatoorian et al. 2003). This hydrogel induced inter-particle bonding characteristic increases the erosion resistance of soils even in the presence of severe fluid (i.e., water or air) flow conditions (see Figs. 10 a&b) (Chang et al. 2015d; Ham et al. 2018; Ham et al. 2016). Moreover, biopolymer hydrogels also cause pore-clogging, which restricts the rapid infiltration of water into the ground and retains pore pressure increase (see Figs. 10c and d) (Chang et al. 2015d).
3.3 Hydraulic Conductivity

The viscosity properties of biopolymer hydrogels and their ability to entangle soil particles have been shown to have a positive effect on the hydraulic conductivity reduction (or hydraulic barrier) of soils (Ayeldeen et al. 2016; Cabalar et al. 2017; Chang et al. 2016). As mentioned above, when biopolymers come into contact with water, this results in the formation of a highly viscous hydrogel in the pore spaces in the soil. These hydrogels tend to have strong water holding capabilities and slow the transport (including diffusion) of water through the pores in the soil. When biopolymers are mixed into soil, the hydraulic conductivity of the soil is significantly reduced (Fig. 11a). As one benefit of biopolymer-treated soils as opposed to cement grouting methods is their incredibly short activation time, the effect of biopolymers on the hydraulic conductivity is almost immediate, whereas other methods require a period of curing before the hydraulic conductivity is affected (Fig. 11b) (Chang et al. 2017a).

3.4 Vegetation Growth

In addition to various engineering properties of biopolymers in soils, it has also been found that the use of biopolymers has positive effects on the growth of vegetation. The effects of biopolymers on oat seed grown in natural and cultured soils are shown in Fig. 12 (Chang et al. 2015d). In that test, it was observed that the addition of
biopolymers promoted growth in the soils in several ways. The first was that biopolymers in the form of microbially produced polymers are primarily composed of glucose, which provides nutrition to the plants. In addition, as biopolymers are highly hydrophilic, biopolymer hydrogels can hold water for extended periods of time compared to non-treated soils (Chang et al. 2015d). As soils that have been treated with biopolymers contain more water, this provides the vegetation with plenty of water and nutrition and thereby promotes growth. These effects, when combined with erosion resistance, are promising in anti-desertification applications.

Fig. 11 Hydraulic conductivity of biopolymer-treated soils versus the (a) biopolymer concentration (Chang et al. 2016) and (b) time (Chang et al. 2017a).
Fig. 12 Effects of biopolymers on the growth of vegetation (oats): (a) growth over a period of 21 days; and (b) the seed germination ratio and average height. (Chang et al. 2015d).
4. CASE STUDIES (SITE APPLICATIONS)

4.1 Earth Stabilization / Soil Pavement

A testbed application was developed in which biopolymer-soils were used to establish a pedestrian trail via in-situ soil stabilization. The target site (KAIST, Daejeon, Korea) was cleared, shaped, and compacted before the biopolymer-soil mixtures were applied. The biopolymer and in-situ soil were directly mixed using an on-site mortar mixer, moved with a backhoe, and then compacted using roller- and vibro- compactors (Fig. 13). The resulting biopolymer-soil surface layer was left to cure and dry before use.

When evaluated, the biopolymer-soil surfaces in the testbed implementation exhibited a higher surface stiffness and less surface erosion than untreated surfaces. However, the overall workability (mixing and application methods) of the biopolymer-soil mixtures was limited by the high viscosity of the biopolymer-soils. Thus, further studies are recommended to determine how best to modify common construction equipment or develop new specialized equipment for use in the implementation of biopolymer-soils by considering the rheology of biopolymer hydrogels and biopolymer-soil mixtures.

![Fig. 13 Construction sequence of Earth stabilization / soil pavement using biopolymer-treated in-situ soils.](image)

4.2 Cut Slope Surface Stabilization

Another example is the slope surface stabilization of an embankment at a national highway construction site in Seosan, Korea. The target site was a slope that had been artificially cut. The objective at this site was to apply biopolymer-soil materials to provide erosion control for the surface of the slope, to stabilize the slope, and to promote in-situ vegetation growth.

In this application, biopolymers were indirectly mixed with soil via an integrated spraying system in which premade biopolymer solution and dry in-situ soil were...
separately pumped into a pressurized piping system and then combined via a combination nozzle at the time of spraying. The aqueous biopolymer solution was transported via a hydraulic pump while the dry, sieved in-situ soil was sprayed via a high pneumatic pressure. The combination nozzle was connected to the ends of the biopolymer and soil transportation pipes to combine both flows, and the resulting biopolymer-soil mixture was sprayed in an aerosol phase onto the target ground (Fig. 14).

The site was observed for a period of one year after construction to determine the erosion response of the exposed biopolymer-soil surface under real climate conditions, and it was found that the higher biopolymer concentrations imparted a higher resistance.

Fig. 14 Dry mixing method for biopolymer-treated slope stability
to surface erosion (Sections 1, 3; Fig. 15) while lower concentrations provided moderate protection against surface erosion (Section 2; Fig. 15). However, in terms of promoting vegetation growth, while sprouts were seen in the soil, the overall density resulting from the pressurized spraying prevented the roots of the plants from penetrating sufficiently deep into the soil and thereby stunted their growth. Therefore, the particle size distribution of in-situ soils also plays an important but reciprocal role in the surface erosion versus vegetation.

4.3 River Levee Surface Stabilization

As biopolymer-treated soils exhibit significantly increased erosion resistance, reduced hydraulic conductivity, and enhanced vegetation growth, biopolymer-soil has been attempted to be used in the construction of a river levee structure along the Nakdong river near Andong, Korea. In this situation, a wet mixing method was employed for favourable vegetation growth by thoroughly mixing biopolymer, water, and soil in a badge chamber. Low pressure hydraulic pumps were then used to transport and spray the wet biopolymer-soil mixture onto the surface of the slope (Fig. 16). Compared to the dry mixing method (Fig. 14), the wet mixing method provides lower spraying pressure but more flexibility to control the water content and thereby optimize the density for efficient spraying.

The primary purpose of this test was to confirm the erosion resistance and surface vegetation growth behavior of biopolymer-treated soils sprayed with seeds and naturally occurring plants from the local region. Long-term observations over a one-year period (Fig. 17) found that the biopolymer-treated soils had a beneficial effect on the growth of vegetation in the soils, especially for the naturally occurring vegetation (i.e., no applied seeds, Section 6; Fig. 17).
Fig. 16 Wet mixing method of biopolymer-treated slopes

Biopolymers were first mixed with soil and water in a chamber before spraying onto the slope.
5. FUTURE PROSPECTS OF BIOPOLYMER APPLICATION

5.1 Embankment Slopes and Levee Structures

As the amount of rainfall has increased in many regions of the world over the past few years, the stability and safety of embankment slopes and levee structures have become of growing concern as the damage or loss of such structures can cause severe physical and economic loss in the surrounding areas. In the case of levee structures, failure occurs mainly due to overtopping and piping. With either of these failures, the progressive erosion and washout of soil reduces the overall stability of the structure. In such applications, biopolymers can be used to allow the overtopping of water as well as to provide surface protection and prevent erosion. As has been discussed, biopolymers have a high resistance toward erosion while also lowering the permeability of soils. In overtopping failures, water turbulence at the lower end of the slope results in an erosion-related failure that progressively increases in size until the entire slope fails. Biopolymer-treated soils have been shown capable of resisting water turbulence by limiting the initial erosion of the soil. At the same time, the lower hydraulic conductivity of biopolymer-treated soils can help prevent piping within the soil.

In order for biopolymers to be accepted in this field, it is essential that the durability and resistance of biopolymer-treated soils be tested in a large-scale environment (Fig. 18) to validate the limitations of the technology. Moreover, it is also critical that the details of the interactions between the biopolymer-treated soils and water be studied to ensure accurate application in the field.
Fig. 18 Testing the overtopping of biopolymer-treated embankment models at a river-flood simulation test facility (Courtesy of the River Experiment Center, Korea Institute of Civil Engineering and Building Technology).

5.2 Seismic Ground Response Control

The results of a recent study in which a resonant column/torsional shear (RC/TS) test was conducted on biopolymer-treated sand demonstrate that the biopolymer enhanced the both the shear modulus and damping ratio of the sand (Fig. 19) (Im et al. 2017). This effect was most likely due to the thin biopolymer film coating and inter-particle bonding that provided a higher energy dissipation via material damping under seismic events.

Thus, it is expected that biopolymer treatment will improve the seismic and liquefaction resistance of sandy soils. However, to ensure the viability of this approach, the effects of biopolymers in bulk media under varying conditions should be studied via seismic event simulation test methods, such as the cyclic triaxial test or geocentrifuge seismic test.
5.3 Sedimentation or Aggregation

Certain biopolymers have also been found to affect the sedimentation (or aggregation) of clayey soils. Generally, the sedimentation behaviour of kaolinite clays is known to be less sensitive to the aqueous phase water than to the solid concentration (i.e., initial water content) due to their particle shape and relatively low specific surface area (Imai 1980). However, a recent study shows the use of $\varepsilon$-polylysine biopolymer to enhance the sedimentation of kaolinite in a suspended solution in terms of sedimentation time and accumulated density (Fig. 20) (Kwon et al. 2017).

Sedimentation is an important parameter in certain soil applications. As such, accelerated sedimentation behaviors may reduce the construction time and cost of offshore reclamation projects and the size of sedimentation depots in construction sites. These behaviors can be also applied in the compaction of clayey soils and the construction of artificial islands. However, for accurate application of such biopolymers, details of their interactions with the soils, water, and ions within the water should be clearly identified by way of further studies.

5.4 Anti-desertification

Desertification is a growing environmental and socioeconomic concern, especially in arid and semi-arid regions around the world. In these regions, soil erosion and land degradation is mainly accompanied by the loss of fine (especially clay) particles (Chang et al. 2015d), and the mechanism of desertification is quite similar to the transport of fine soils via Aeolian or water flows. As more and more fine particles are lost, the remaining dense soils mostly consist of coarse sands, and the loss of nutritional soils
stunts the growth of vegetation in the area, resulting in a more arid climate (Cao 2008; Lal 2001).

To prevent the effects of desertification, increased vegetation must be provided; however, before this can happen, the soil must contain sufficient nutrition and its loss must be contained (Cao 2008; Chang et al. 2015d). The use of biopolymers as an anti-desertification material shows promise as they have high erosion resistance (Chang et al. 2015d; Ham et al. 2018; Kavazanjian et al. 2009), are capable of providing nutrition, and can contain large amounts of water (Fig. 21).

Fig. 21 Scheme of biopolymer application as a countermeasure for desertification (Chang et al. 2015d).

However, this technology is still in the early stages of development and large-scale tests over a long period of time are required to determine the effects of biopolymers in such conditions. In addition, as various plants require different growing conditions, different biopolymers must be designed to suit various climates and vegetation types.

5.5 Wet Strength Improvement

One major drawback to biopolymers is the degradation of their strength in water. Thus, it is desirable to identify a method to mitigate this degradation. The underlying mechanism behind the reduction in strength is due to the interaction between the water molecules and biopolymers, which decreases its interaction with other biopolymers and the soil. On this basis, one possible method to alleviate this problem is the use of cross-linking, which is a method of increasing the number of inter-particle bonds between two chemical compounds. When applied to biopolymers, the overall interaction between the
biopolymers and water molecules is greatly reduced, which provides an overall increase in the strength in both wet and dry conditions. However, it will be important to ensure the implementation of the cross-linking does not negatively affect the overall workability of the biopolymer soil mixtures.

5.6 Water Retention Characteristics

As geotechnical engineering materials, there are a number of properties of biopolymers that are not fully understood, including their properties as a hydrophilic material, behavior in soils and water, high water holding capability, effects on the permeability of soils, and effects on the plasticity and overall water related behavior of clayey soils. In addition, the effects of pore pressure and ground pressure on biopolymers are not well understood.

To better understand the behavior of biopolymers in soils and the behavior of water in soils where biopolymers have been applied, additional testing is required. At a minimum, these should include an evaluation of the drainage conditions as per the soil-water characteristic curve (SWCC) and consolidated-drained (CD) triaxial tests. The results of preliminary tests on the SWCC of biopolymer-treated soils have shown that the air entry value is either extremely high or non-existent. Under such conditions, it is expected that the biopolymer-treated soils may not exhibit the basic properties of water with respect to the localization of pore pressures during soil consolidation or drainage. As such, further tests on the water-soil related effects of biopolymers are needed. In so doing, the values of certain testing parameters may need to be adjusted during development to better elucidate the effects of biopolymers in geotechnical engineering applications.

6. CONCLUSIONS

Environmental effects, such as global warming, are affecting ever larger regions of the world. To surmount the geotechnical hazards arising from such environmental effects, it is essential to develop and apply sustainable materials. Biopolymers have shown promise as sustainable materials to improve the stability and strength of various soils and have been found to possess certain advantages over conventional materials, such as being environmentally friendly and effective at low concentrations.

Studies have shown that biopolymer-treated soils exhibit a strength that is maximized by the presence of fine soils. Biopolymers have also been shown to have various properties, such as reducing the permeability of soil, increasing the resistance to erosion, and promoting the growth of vegetation. However, despite the above list of benefits, the detailed behavior of biopolymers and their effect on soils are not well understood. Although biopolymers have been demonstrated to have properties that are different from conventional strengthening materials, further research is required to understand how they can best be applied.

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