Microbial Biopolymers as an Alternative Construction Binder

23

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Abstract

With an increasing need for civil infrastructures owing to increasing populations and growing concerns on climate change, the need for sustainable construction material has become ever more present. Worldwide sustainable development has led to various technologies and materials for various engineering practices. Among such developments, the use of biopolymers in the field of geotechnical engineering has shown great promise. Biopolymers are naturally derived organic polymers that have shown a significant engineering performance. As a new material with a low carbon footprint, the use of biopolymer as a sustainable material has been increasing in recent years. In this chapter, the engineering performances of biopolymers in geotechnical engineering practices, methods of implementation, and limitations and future prospects of this material will be investigated.

Keywords

Biopolymer · Xanthan gum · Gellan gum · Biopolymer-based soil treatment (BPST)

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23.1 Introduction

The increasing population and economic growth worldwide have led to the increased development of civil infrastructures. Coupled with the growing concerns for climate change, the need for sustainable construction materials has become ever more present. In the field of geotechnical engineering, there are two major forms of soil improvement, mechanical stabilization (e.g., compaction, vibration, anchors) and chemical stabilization (i.e., cement, asphalt, and gypsum) (Makusa 2012).

Chemical stabilization makes use of particle cementation using chemical processes to enhance the strength characteristics of the soils (Han 2015; Makusa 2012). Several commonly used materials for such purposes are cement, lime, fly ash, and asphalt. However, various environmental concerns have been expressed about the use of such materials, particularly the use of cement, which has been identified as a major contributor to greenhouse gases (Karol 2003). Cement has been the most widely used and accepted method in the field of construction and geotechnical engineering since the 1960s (Chu et al. 2009). However, as the production and use of one ton of cement lead to the emission of approximately one ton of CO_2 (Worrell et al. 2001), it has been found that the cement industry has a large impact on climate change, accounting for approximately 5–8% of global CO_2 emissions (United States Geological Survey (USGS) 2018; Metz et al. 2005). As the problems and side effects of climate change have become clearer, development and research into sustainable alternative construction materials have resulted in new technologies, such as unconventional binders, waste reuse, and biological approaches.

23.1.1 Alternative Binders

In the late twentieth century, research began on chemically synthesized polymers as an alternative method of soil enhancement. One such polymer that has been widely tested in the field of geotechnical engineering is polyacrylamide (PAM) (Malik and Letey 1991). PAM is a linear polymer that is synthesized from acrylamide ($CH_2CHCONH_2$) monomers, and it is classified as a nontoxic, hydrophilic polymer with a negatively charged surface (Kulicke et al. 1982; Malik and Letey 1991; Laird 1997). In the field of geotechnical engineering, PAM has been used for soil strengthening purposes and to help reduce soil erosion (Fox and Bryan 1992; Orts et al. 2007).

Although its polymer form is known to be nontoxic, its monomer, acrylamide, is a toxic substance that is a suspected carcinogen (Tareke et al. 2002). As the production of PAM still results in trace elements of acrylamides (Woodrow et al. 2008), and concerns exist regarding the depolymerization of PAM into acrylamides (Prajapat and Gogate 2016), the use of PAM has been greatly limited.

23.1.2 Waste Reusage

Another form of sustainable development is the reuse of waste materials such as blast furnace slag, fly ash, or demolition wastes as aggregates. Such materials are either used as additives in more conventional binders such as cement, as performance enhancers, or they are used in geopolymerization processes (Abubakar and Baharudin 2012; Bakharev 2005; Oh et al. 2010). The geopolymerization process involves the use of alkali-activated silicon and aluminum ions in either soils or waste products (i.e., blast furnace slag and fly ash) to produce a cementation effect between the soil particles (Duxson et al. 2007; Kim et al. 2006). When these waste materials are subjected to an alkaline solution, the excess oxide ions (O^{2-}), resulting from the reaction between the hydroxyl ions (OH^-) and the free water (H_2O), form monomers with the silicon and aluminum ions found in the waste products, which in turn condense around the soil particles and create a cementation effect (Hench 1998).

However, several factors limit the widespread use of these geopolymerized waste materials. The geopolymerization process generally involves heating (above 60 °C) for sufficient geopolymerization to occur, and as such, this technology is difficult to apply in the field (Rovnaník 2010; van Jaarsveld et al. 2002). Additionally, studies have found that geopolymers are susceptible to water, with a significant decrease in strength when saturated, and are especially sensitive to acidic solutions as the acid results in the depolymerization of the aluminosilicate polymers (Bakharev 2005).

23.1.3 Biological Approaches

23.1.3.1 Microbial Induced Calcite Precipitation

Among biological approaches to soil improvement, the use of microbes for soil cementing (i.e., bio-mineralization) has been widely studied. Microbial induced calcite precipitation (MICP) is the most recognized method of soil treatment, and it makes use of microorganisms that precipitate calcium carbonate, such as *Sporosarcina pasteurii* and *Bacillus pasteurii*, through biological processes to cement the soil particles together (DeJong et al. 2006; Whiffin et al. 2007).

The strengthening mechanism of MICP involves the precipitation of calcium carbonate through urea hydrolysis (Stockes-Fischer et al. 1999). Urea is supplied to ureolytic bacteria that convert urea into ammonium and carbonate, and the carbonate derived from this biological process then reacts with calcium ions supplied to the system to form calcium carbonate precipitates (Fujita et al. 2000). The calcium carbonate precipitates then bind to the soil grains and create a cementitious effect that enhances the strength and stiffness of the soil (Mortensen et al. 2011).

Although this method is a novel approach to ground improvement, studies have shown that its use in the field has several limitations. As the method used in the MICP process involves the use of a living organism, the conditions of the organism's survival greatly affect the performance. Studies have shown that the use of MICP is most applicable to coarse-grained soils, and due to several factors (i.e., limitations to food supply and unsuitable environment for bacterial growth) the use of MICP in fine-grained soils is greatly limited (Rong et al. 2011). Moreover, the use of MICP results in a byproduct of ammonium chloride in the soil, which generally requires soil flushing to remove (Pham et al. 2013).

23.1.3.2 Biopolymers

Biopolymers are defined as organic polymers that are derived from biological processes. They are generally composed of repeated units of monomers bonded together into a larger formation. Biopolymers can be categorized as polynucleotides (i.e., RNA and DNA), polypeptides (i.e., amino acids), and polysaccharides. Among these sub-categories, polysaccharides are the most widely used biopolymer in various industries because of their unique and diverse properties (US National Library of Medicine 2011; Kalia and Averous 2011).

Polysaccharides are polymers made up of carbohydrate monomers with the properties of the polysaccharides, which vary with the overall structure and chemical composition of the polymers. They are widely found in nature because of their roles in key biological processes, such as skeletal structure formation, water binding mechanisms, and reserve substance assimilation (Belitz et al. 2009). Owing to their unique properties, such biopolymers have been used as thickening agents, stabilizers, sweeteners, and gel-forming agents for food, agriculture, cosmetics, medical, and pharmaceutical purposes (Saha and Bhattacharya 2010; Lorenzo et al. 2012; Van de Velde and Kiekens 2002).

For geotechnical purposes, biopolymers, such as natural bitumen, straw, and sticky rice, were used in ancient civilizations. In ancient Chinese civilizations, sticky rice was used as a mortar with river sand for various geotechnical purposes (FuWei et al. 2009). Studies have shown that biopolymers can help stabilize the soil by acting as a cementing binder for soil particles (Akbulut and Cabalar 2014; Chang et al. 2015a; Cho and Chang 2018).

23.2 Common Biopolymers Used in Civil and Construction Engineering Practices

23.2.1 Xanthan Gum

Xanthan gum is a polysaccharide biopolymer that consists of a repeated structure of two glucose, two mannose, and one glucuronic acid (Garcıa-Ochoa et al. 2000; Milas and Rinaudo 1979). It is naturally produced from the microbe *Xanthomonas campestris* and is either in a helix or random coil formation (Butler 2016). When xanthan gum is exposed to water, it absorbs the water to form a viscous solution with a high degree of stability in a wide range of temperature, pH, and electrolyte conditions (Chang et al. 2015a).

Xanthan gum is mostly used for its highly viscose and thickening properties (Garcıa-Ochoa et al. 2000). It has often been used in the food industry because of its high stability with temperature and other food ingredients (Garcıa-Ochoa et al.

2000). It has also been used in industries as a suspending agent for drilling purposes as a mud thickener (Becker et al. 1998).

23.2.2 Gellan Gum

Gellan gum is produced during the fermentation process of the microbe *Sphingomonas elodea* (Giavasis et al. 2000). Its structure consists of a repeated chain of two D-glucose monomers with one D-glucuronic acid and one L-rhamnose residue (Stokke et al. 1993).

Gellan gum has a temperature-dependent structure that restrains the gellan molecules during the heating and cooling of the gel solution to form a double helix, resulting in a stiff hydrogel (i.e., thermogelation) (Chang et al. 2015b). At high temperatures, the gellan molecules show single helix structures, while at lower temperatures, the gellan molecules exhibit a double helix structure (Giavasis et al. 2000). Gellan gum has been used in the food and medical industries (Oliveira et al. 2010; Imeson 1992).

23.2.3 Starch

Starch is one of the most commonly found biopolymers and is mainly derived from organic foodstuffs such as seeds, grains, and roots. Starch is generally composed of two main polysaccharides: amylose and amylopectin. The properties of starch will differ based on the different ratios of amylose to amylopectin, along with the size and structure of the polymers (Mishra and Rai 2006). Different sources of starch have different ratios and structures of amylose to amylopectin.

Starches are widely used in a variety of industries such as food, textiles, cosmetics, and pharmaceuticals (Eliasson 2004). They are mainly used as disintegrants and diluents, strengtheners, and adhesives (Rodrigues and Emeje 2012; Nachtergaele 1989; Vishnuvarthanan and Rajeswari 2013).

23.2.4 Beta-Glucan

Beta-glucan is a biopolymer that mainly consists of D-glucose monomers joined together through glycosidic bonds (Bacic et al. 2009). It is a biopolymer commonly found in items such as cellulose, bran, yeasts, fungi, and bacteria (Misaki et al. 1990; Zhu et al. 2015; Lazaridou and Biliaderis 2007). Beta-glucan is mostly used in the cosmetic industry as a moisturizer (Kogan et al. 2005; Pillai et al. 2005).

23.2.5 Guar Gum

Guar gum is a polysaccharide extracted from the seeds of the plant *Cyamopsis tetragonoloba*. It has a main backbone of beta-D-mannopyronose with 1,4 linkages with side branches of alpha-D-galactose monomers (Risica et al. 2005). It has the significant characteristic of rapid hydration even in cold water and is capable of producing high viscosities even at lower concentrations (Mudgil et al. 2014).

Guar gum has mostly been used in the food industry because of its stabilizing, emulsifying, and thickening properties (Mudgil et al. 2014; Whistler and Hymowitz 1979). It has also been used as a flocculant, foam stabilizer, and aid in filtration and water treatment and as an additive in pharmaceutical applications (Khullar et al. 1998; Krishanaiah et al. 2003; Chourasia and Jain 2004; Krishnaiah et al. 2001).

23.2.6 Casein

Casein is a phosphorous protein biopolymer that is most commonly found in mammalian milk. Casein is a hydrophobic biopolymer found in a suspension of particles called a casein micelle (Ruhsing Pan et al. 1999). The structure of the micelles is held together by calcium phosphate particles that interact directly with the surface of the casein particles (Fox and McSweeney 2003). Due to its hydrophobic properties, casein has been used as an additive in food, industrial paints, adhesives, plastics, and various medical practices (Semenova et al. 2010; Rose 2000).

23.3 Geotechnical Engineering Behaviors of BPST

23.3.1 Microscopic Interaction Between Biopolymers and Soil Particles

23.3.1.1 Biopolymers: Coarse Particles

Biopolymers have a high specific area with electrical charges, which enable them to interact with other biopolymers, ions, and water (Dickinson et al. 2003). In the case of biopolymers in coarse-grained soils, the surface charge along the surface of the coarse grains can be considered negligible for interaction purposes with the biopolymers. Therefore, biopolymers heavily interact with water when saturated, and when dehydrated, they interact with other biopolymers to form biopolymer films (Chang and Cho 2014; Chang et al. 2016).

The SEM images in Fig. 23.1 show how biopolymers create interconnecting biopolymer films between soil particles. The biopolymers are shown to coagulate around the sand particles, encompassing the soils in a very thin layer of a biopolymer film.

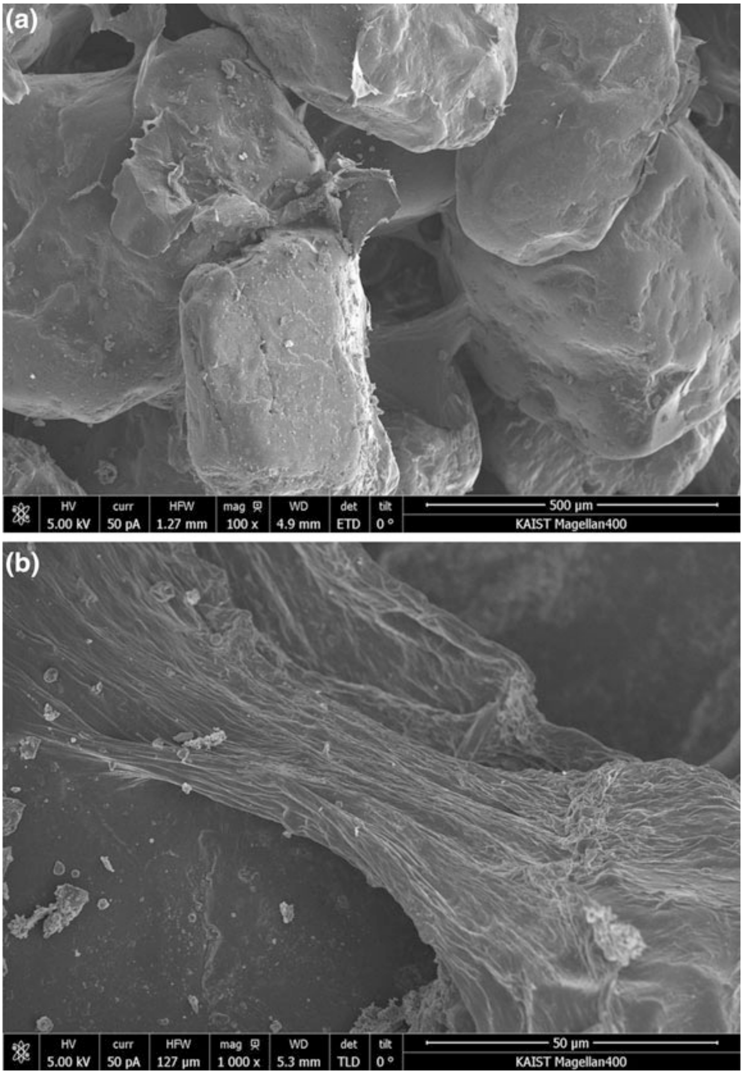


Fig. 23.1 SEM images of 1% gellan gum-treated sands: (**a**) soil-biopolymer mixtures and (**b**) biopolymer film (Chang et al. 2016)

23.3.1.2 Biopolymers: Clay Particles

In the case of biopolymers in clayey soils, as both the biopolymers and clay particles have surface charges, there is a more direct interaction between the biopolymers and clay particles than in the case of the coarse-grained soils. As most biopolymers are negatively charged due to the OH^- groups found in the carbohydrate chains, they are mostly found to interact with the positively charged edges of the clay particles, with some biopolymers forming connections between the kaolinite coagulates (Chang and Cho 2019). This mechanism is shown in Fig. 23.2.

23.3.2 Soil Consistency and Electrical Sensitivity

When we consider the effects of biopolymer-based soil treatment (BPST) on soil consistency and electrical sensitivity, studies have found that, as biopolymers are not electrically neutral, they have varying degrees of effects depending on the soil characteristics and the concentrations of biopolymers present in the soil.

Liquid limit (LL) tests performed with a xanthan gum BPST of kaolinite-sands and bentonite-sands are shown in Fig. 23.3 (Chang et al. 2018b). In Fig. 23.3a it is shown that at lower biopolymer concentrations, the addition of biopolymers increased the LL of the kaolinite, and after a certain concentration was achieved, the LL of the biopolymer kaolinite mixture was reduced. This mechanism is explained by the fact that as biopolymers are hydrophilic and are known to absorb water, at lower concentrations, the biopolymers and kaolinite particles absorb water separately, thereby increasing the water-holding capacity of the soil and increasing the LL. At higher concentrations, due to the closer proximity of the xanthan gum and kaolinite particles, it is expected that there is a facilitation of the interaction between the kaolinite particles and the xanthan gum biopolymers, thereby reducing the LL of the soil. This indicates that, in the case of xanthan gum, the tendency to interact with water molecules is greater than that of kaolinite particles.

In the case of xanthan gum BPST with bentonite soils, Fig. 23.3b shows that with an increase in the biopolymer concentration, the LL of the soil decreased slightly. As the surface charge characteristics of bentonite soils are significantly larger than those of kaolinite, it is believed that xanthan gum directly interacts with the bentonite particles even at lower biopolymer concentrations. The neutralization of the bentonite's surface charge with its interactions with the xanthan gum particles results in a slight decrease in the LL of the soil.

With regard to the soil classification changes with the addition of biopolymers, Fig. 23.4 shows the effects that xanthan gum BPST has on the soil classification based on electrical sensitivity (Jang and Santamarina 2016). The results indicate that with an increase in the biopolymer concentrations, the soils tended to have a reduced electrical sensitivity and increased plasticity (Chang et al. 2018b).

23.3.3 Strengthening Parameters

23.3.3.1 Unconfined Compressive Strength (UCS)

Previously, it was mentioned that biopolymer soil interactions were dependent on the soil type (i.e., coarse-grained or fine-grained soils) due to the surface charge characteristics of the biopolymers and soils. This difference in behavior is also observed when we examine the strengthening capabilities of biopolymers.

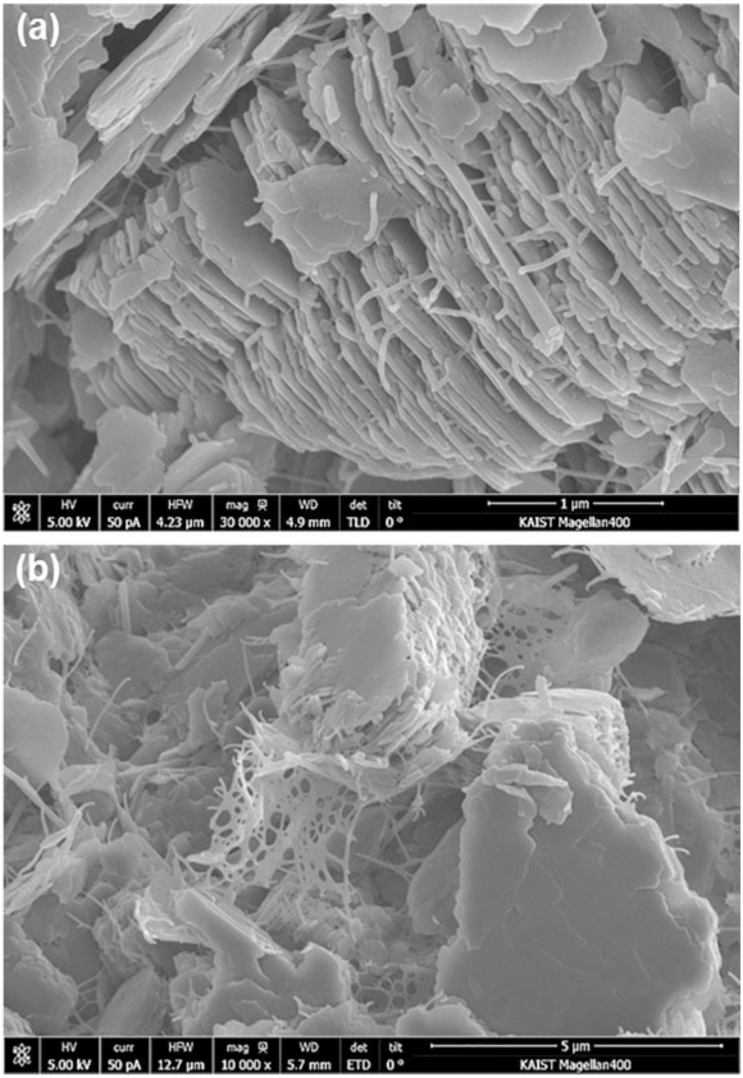


Fig. 23.2 SEM images of 1% gellan gum-treated kaolinite (**a**) biopolymers' interaction on the edges of the kaolinite particles (**b**) formation of biopolymer connections between the kaolinite coagulates (Chang and Cho 2019)

In Fig. 23.5, the various strengthening capabilities of different biopolymers with coarse and fine soils are shown. It is seen that on average, the biopolymer-treated fine soils display a higher strengthening efficiency than that of coarse-grained soils. As the electrical surface charges between the biopolymers and the fine soils allow for a more direct method of interaction, the overall strengthening capabilities are improved. It should also be noted that the biopolymer type and concentration play a large role in the strengthening behavior of the soils.

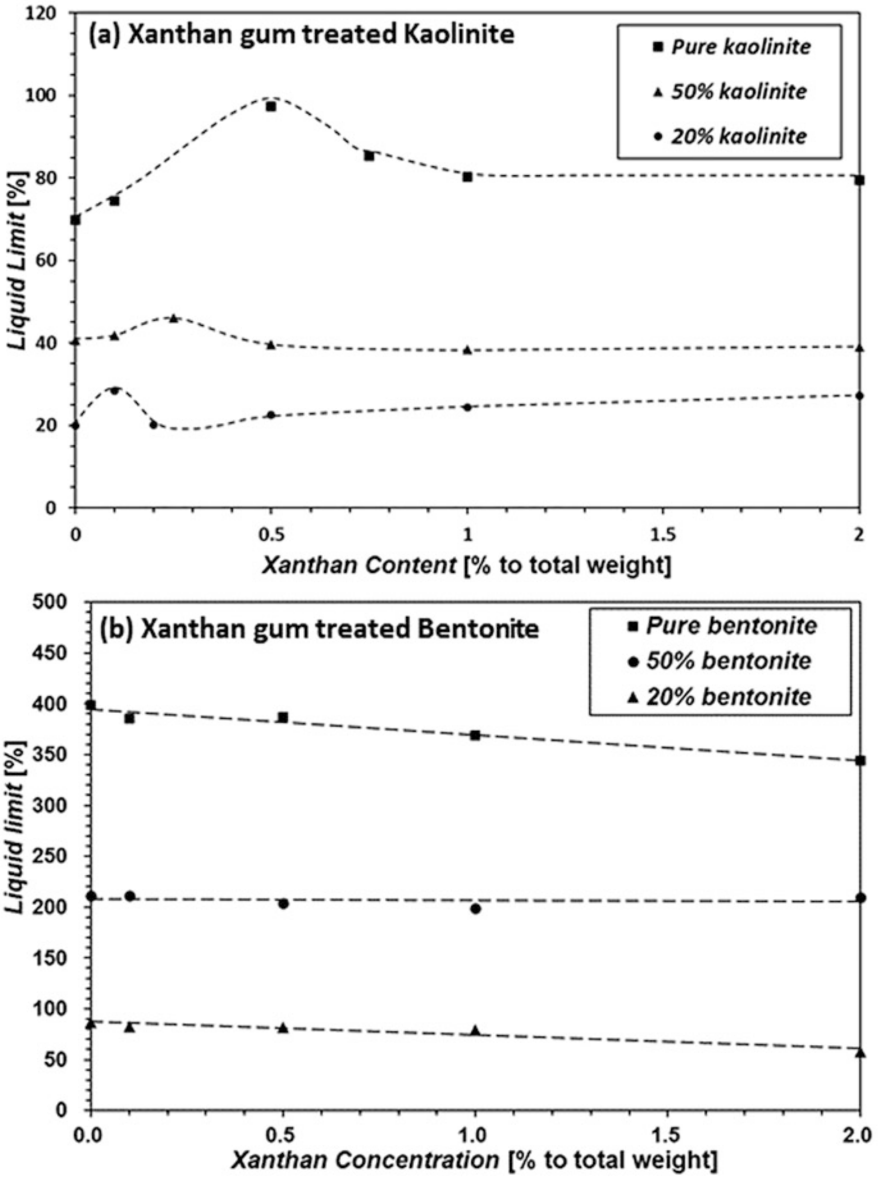
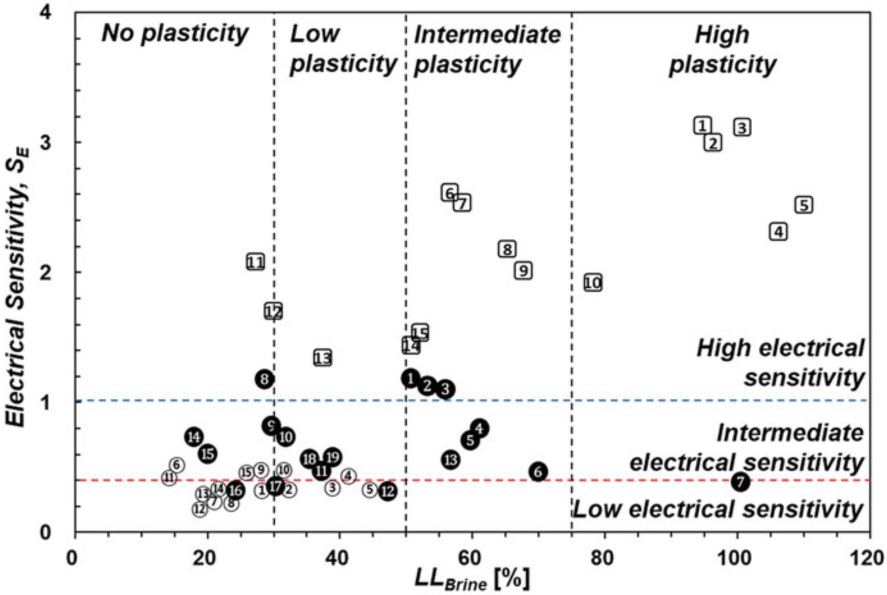


Fig. 23.3 Liquid limit tests of xanthan gum-treated (**a**) kaolinite-sand mixtures and (**b**) bentonite-sand mixtures (Chang et al. 2018b)

Moreover, as biopolymers are known to be hydrophilic materials, they are highly sensitive to the presence of water, and their strengthening capabilities have been shown to be directly related to the water content of the soils (Fig. 23.6) (Chang et al. 2015b).



	0	0.1	0.2	0.25	0.5	0.75	1	2	5
Pure Kaolinite	❶	❷			❸	❹	❺	❻	❼
50% Kaolinite	❽	❾		❿	⓫		⓬	⓭	
20% Kaolinite	⓮	⓯	⓰		⓱		⓲	⓳	
Pure Illite	①	②			③		④	⑤	
50% Illite	⑥	⑦			⑧		⑨	⑩	
20% Illite	⑪	⑫			⑬		⑭	⑮	
Pure Bentonite	[1]	[2]			[3]		[4]	[5]	
50% Bentonite	[6]	[7]			[8]		[9]	[10]	
20% Bentonite	[11]	[12]			[13]		[14]	[15]	

Fig. 23.4 Effects of xanthan gum biopolymer treatment on the soil classification based on electrical sensitivity (Chang et al. 2018b)

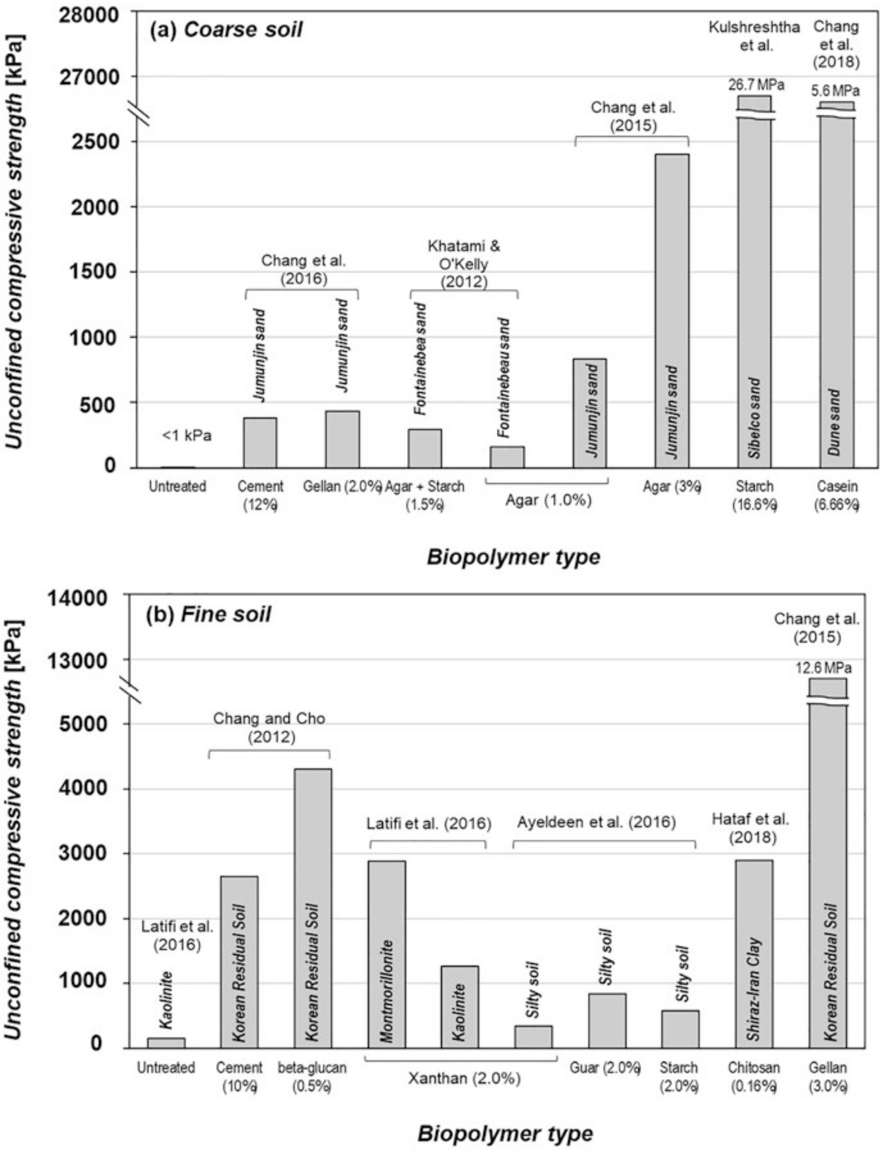


Fig. 23.5 Unconfined compressive strengths of biopolymer-treated (**a**) coarse soils and (**b**) fine soils (Chang et al. 2015b, 2020; Khatami and O'Kelly 2012; Fatehi et al. 2018; Kulshreshtha et al. 2017; Chang and Cho 2012; Ayeldeen et al. 2016; Latifi et al. 2016; Hataf et al. 2018)

23.3.3.2 Interparticle Cohesion

In the case of coarse-grained soils, the BPST encompass the soil particles while forming biopolymer-film connections between them. This mechanism results in an increase in soil cohesion. With fine-grained soils, the charge characteristics of

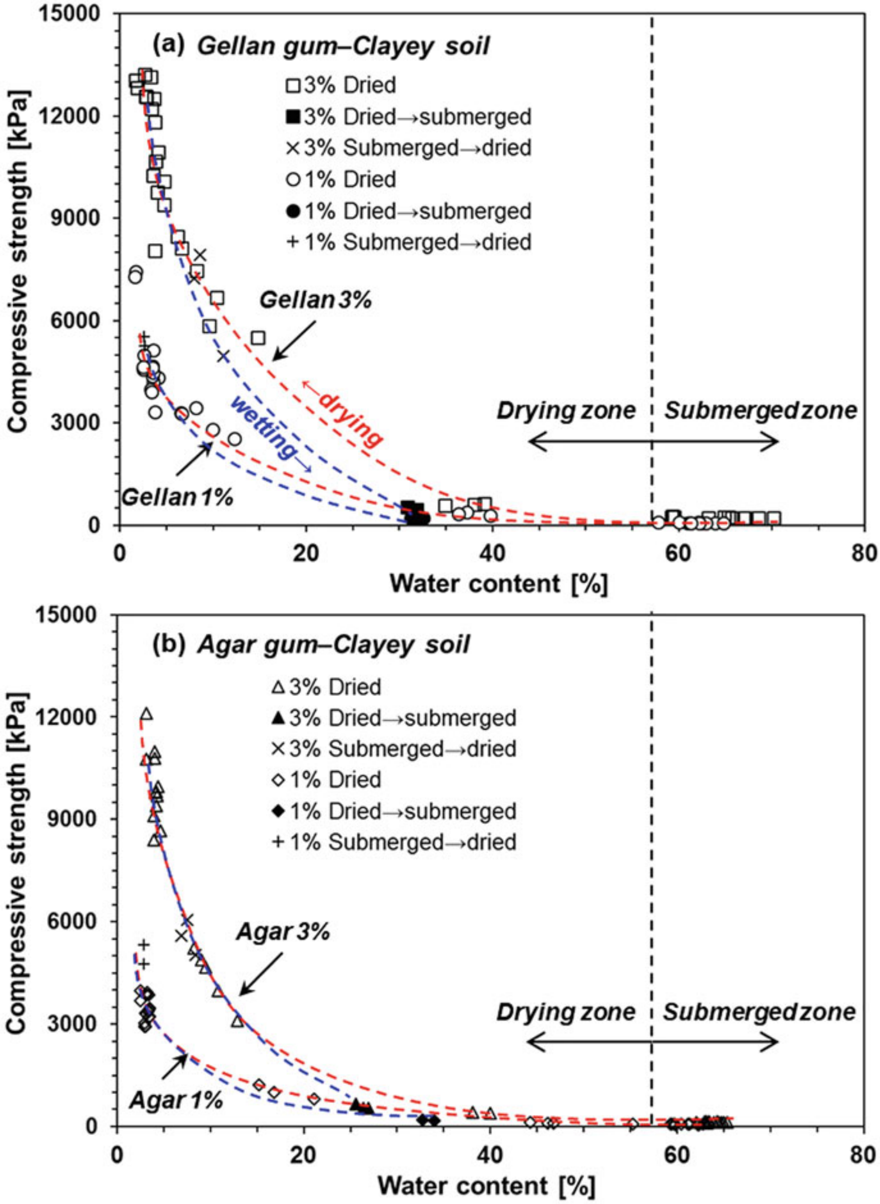


Fig. 23.6 Uniaxial compressive strength variations of (**a**) gellan gum and (**b**) agar gum-treated clayey soils at different water contents (Chang et al. 2015b)

biopolymers interact directly with the surface charge of the clay particles through hydrogen bonding. With this bonding mechanism, the cohesion of the soil is enhanced. Direct shear tests have shown this trend with biopolymer-treated sands

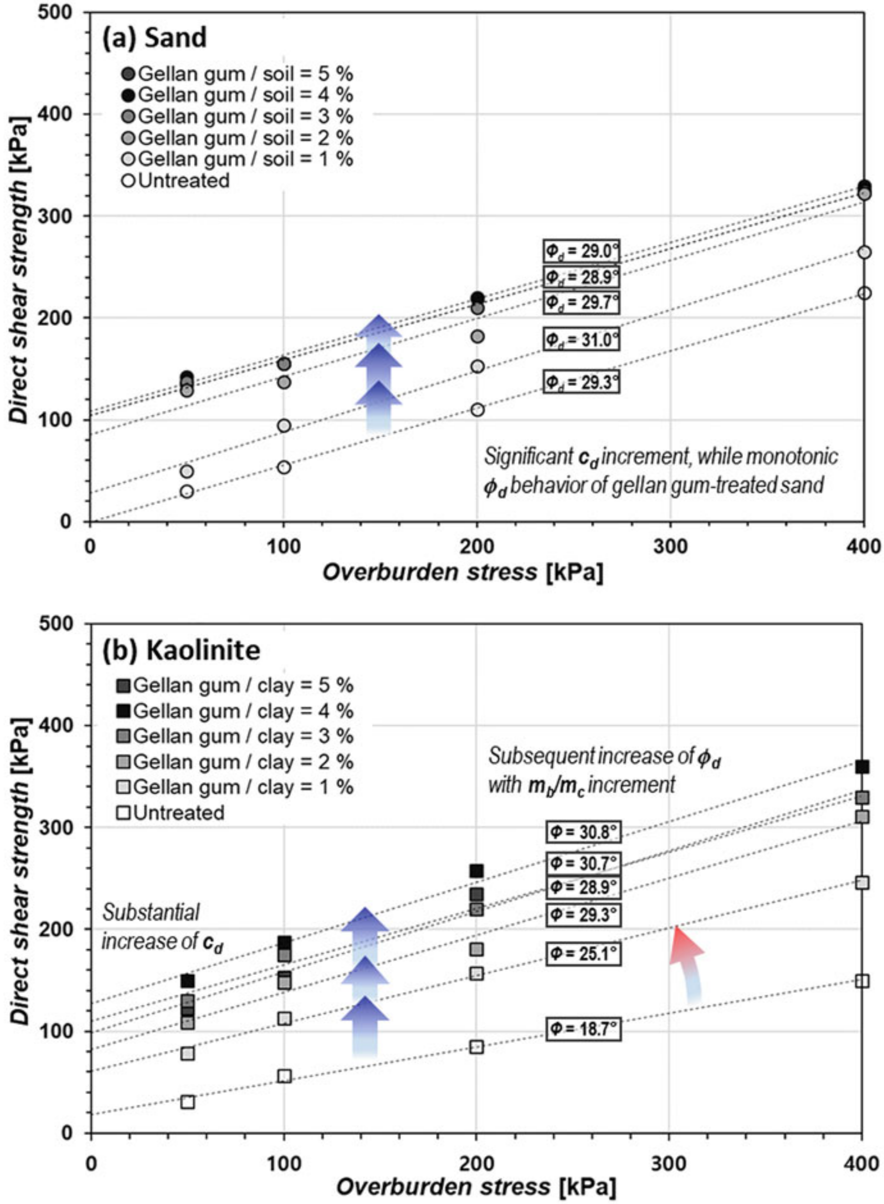


Fig. 23.7 Direct shear results for gellan gum-treated (**a**) sand and (**b**) kaolinite (Chang and Cho 2019)

and kaolinite samples, Fig. 23.7 (Chang and Cho 2019). As shown, there is a definitive increase in the cohesion for both sandy soils and clayey soils. It should be noted that the increase in cohesion can vary greatly depending on the biopolymer used for BPST.

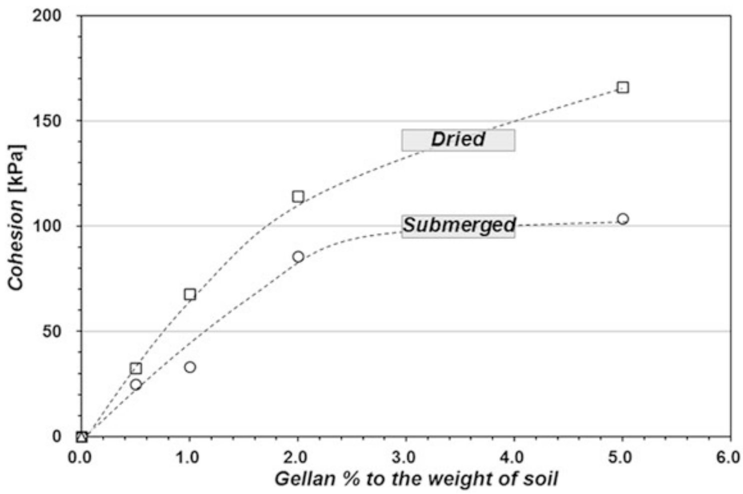


Fig. 23.8 Increase in cohesion with dehydration of gellan gum-treated sands (Chang et al. 2016)

The use of biopolymers in soils has also been known to vary based on the degree of hydration of the biopolymer–soil mixtures. As biopolymers are generally hydrophilic in nature, they tend to easily absorb water, and with the absorption of water, there is a decrease in the strengthening efficiency of BPST. Conversely, with the dehydration of the biopolymers, there is a large increase in the strengthening capabilities of the biopolymer (Chang et al. 2016). This effect is shown in Fig. 23.8, in which the cohesion of the gellan gum-treated sands increases when completely dried.

The overall strengthening capabilities of BPST on soil cohesion shows that the increase in cohesion is directly related to the concentration of the biopolymers used in the soil (Fig. 23.9) (Chang and Cho 2019). The efficiency of the strengthening mechanism will differ based on the soil and biopolymer types used in the soil treatment process.

23.3.3.3 Dilatancy and Interparticle Friction Angle

With regard to the effects of biopolymers on the dilatancy and interparticle friction angle of the soil, the results of direct shear tests shown in Fig. 23.10 show the effects of gellan gum treatment on the sand. With an increase in the biopolymer concentration, the direct shear tests showed an increase in the dilative properties of the soil (Chang and Cho 2019). This behavior was shown to be especially true for soils with clay particles (Fig. 23.11).

Clay soils are known to have low friction angles owing to the shape of their particles. With a platelet-like particle shape, its dilative properties, and thereby its friction angles, are low. However, BPST increases the friction angle of these clay particles (Chang and Cho 2019). It is believed that, owing to the electrical surface charges of both the biopolymers and clay particles, there is a high degree of

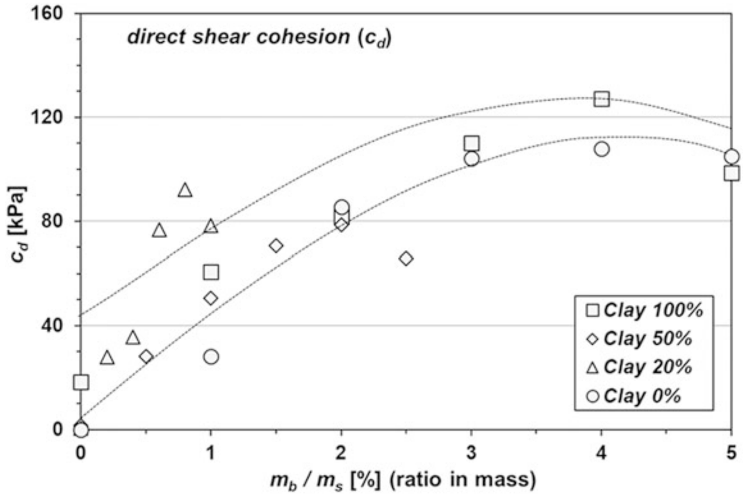


Fig. 23.9 Increase in the cohesion of gellan gum-treated sands from direct shear tests (Chang and Cho 2019)

interaction between them. With a strong connection between the biopolymers and the clay particles, the biopolymers help bridge and connect the clay particles into a bulk conglomerate. These conglomerates then act as large coarse-grained particles exhibiting larger dilatancies and friction angles. This behavior is illustrated in Fig. 23.12.

In the case of coarse-grained soils, BPST does not seem to have a dominant effect on the friction angle. However, with dehydration, the biopolymer connections between the soil particles strengthen enough to overcome the force generated by the dilatancy of the soil. As such, under dry conditions, there is an increase in the friction angle, as shown in Fig. 23.13, as the biopolymer-treated coarse-grained soils form larger conglomerates (Chang et al. 2016).

23.3.4 Hydraulic Conductivity

The use of BPST has also been known to decrease the hydraulic conductivity of soils. The behavior of the biopolymers with regard to the hydraulic conductivity (Fig. 23.14) shows that up to a certain biopolymer concentration, the hydraulic conductivity decreases at an exponential rate and then levels off (Chang et al. 2016). This behavior can be explained by the fact that as the biopolymers take up more and more space within the pores of the soil (e.g., pore-clogging), the hydraulic conductivity decreases rapidly. After a certain concentration of biopolymers is present in the soil, the pore spaces within the soil are completely filled up with the biopolymers, and any additional increase in the biopolymer concentration does not significantly decrease the hydraulic conductivity of the soils.

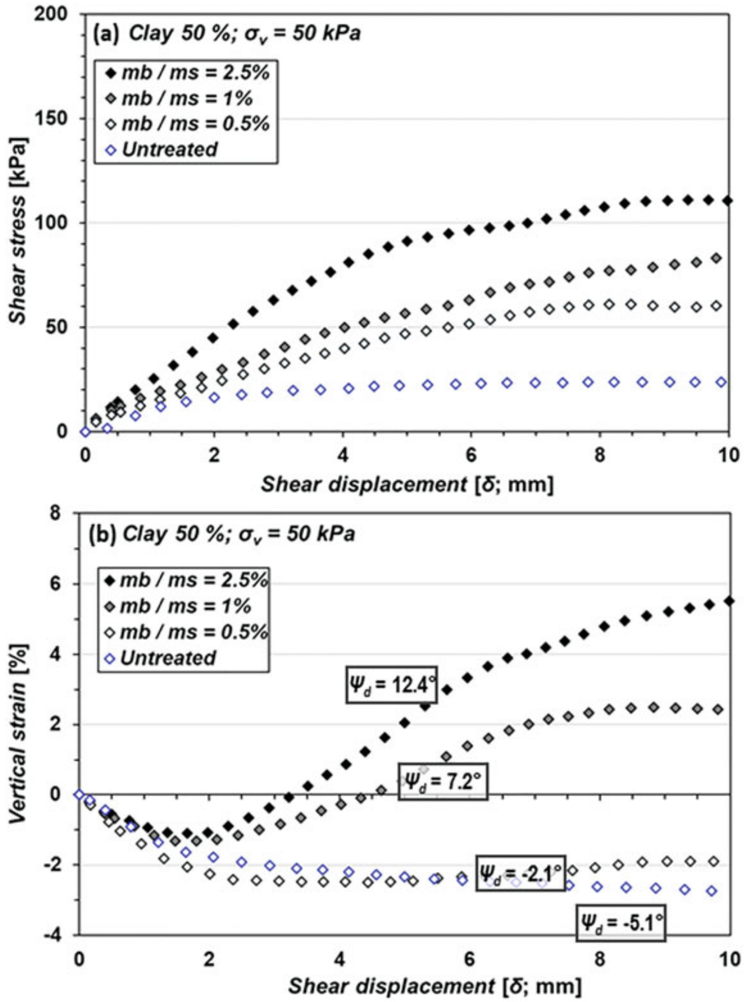


Fig. 23.10 Direct shear behaviors of gellan gum-treated sand (**a**) Stress–strain curves (**b**) Dilatancy (Chang and Cho 2019)

23.3.5 Erosion Behavior

The use of biopolymer has been shown to increase the cohesion of soils and facilitates the formation of larger soil conglomerates, where BPST shows sufficient soil erosion reduction effects. The effects of BPST on sandy soils (Fig. 23.2) show how the addition of biopolymers to the soil reduces the cumulative erosion that the soil exhibits to rainfall to nearly negligible levels (Chang et al. 2015c) (Fig. 23.15).

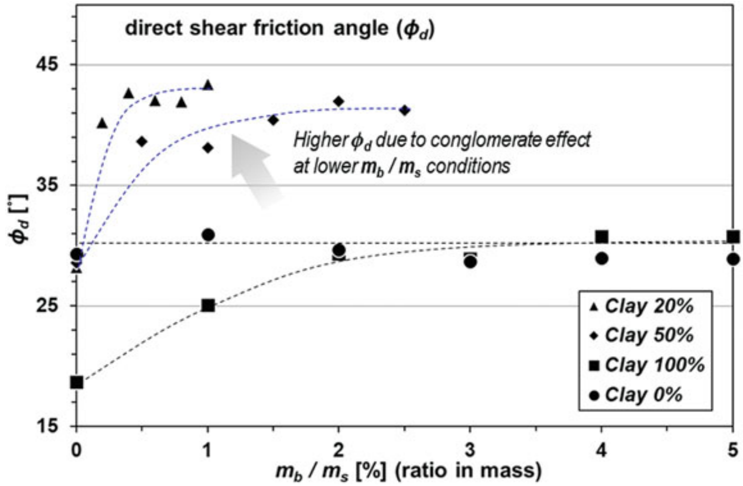


Fig. 23.11 Changes in the friction angle of the soil with gellan gum treatment (Chang and Cho 2019)

Additionally, erosion conditions tested at higher fluid flows using the erosion function apparatus (EFA) show similar results: BPST significantly increases the resistance of soils to erosion (Kwon et al. 2020). As shown by the addition of biopolymers, there is a significant improvement in the soil's erosion resistance to fluid flow, showing signs of erosion at flow rates higher than 1 m/s (Kwon et al. 2020) (Fig. 23.16).

23.3.6 Durability

One major concern for BPST is the durability of biopolymers. As a material that is highly sensitive to water, seasonal changes and repeated wetting and drying cycles may hinder and degrade the engineering capabilities of biopolymers in soils. Experimental tests (Fig. 23.17) showed that with repeated drying and wetting cycles, the strength and stiffness of the biopolymers show a slight degradation with each loading cycle (Chang et al. 2017).

23.3.7 Vegetation Growth

As the majority of biopolymers are carbohydrate polymers, biopolymers are non-toxic to the environment. In addition, due to the high water-holding capability and natural origin of biopolymers, BPST has shown optimistic effects in the promotion of vegetation growth. In Fig. 23.18, we can see the effects of biopolymers on germination rate of oats and the survival efficiency of oat sprouts under severe drought conditions (Tran et al. 2019; Chang et al. 2015c). The results show that

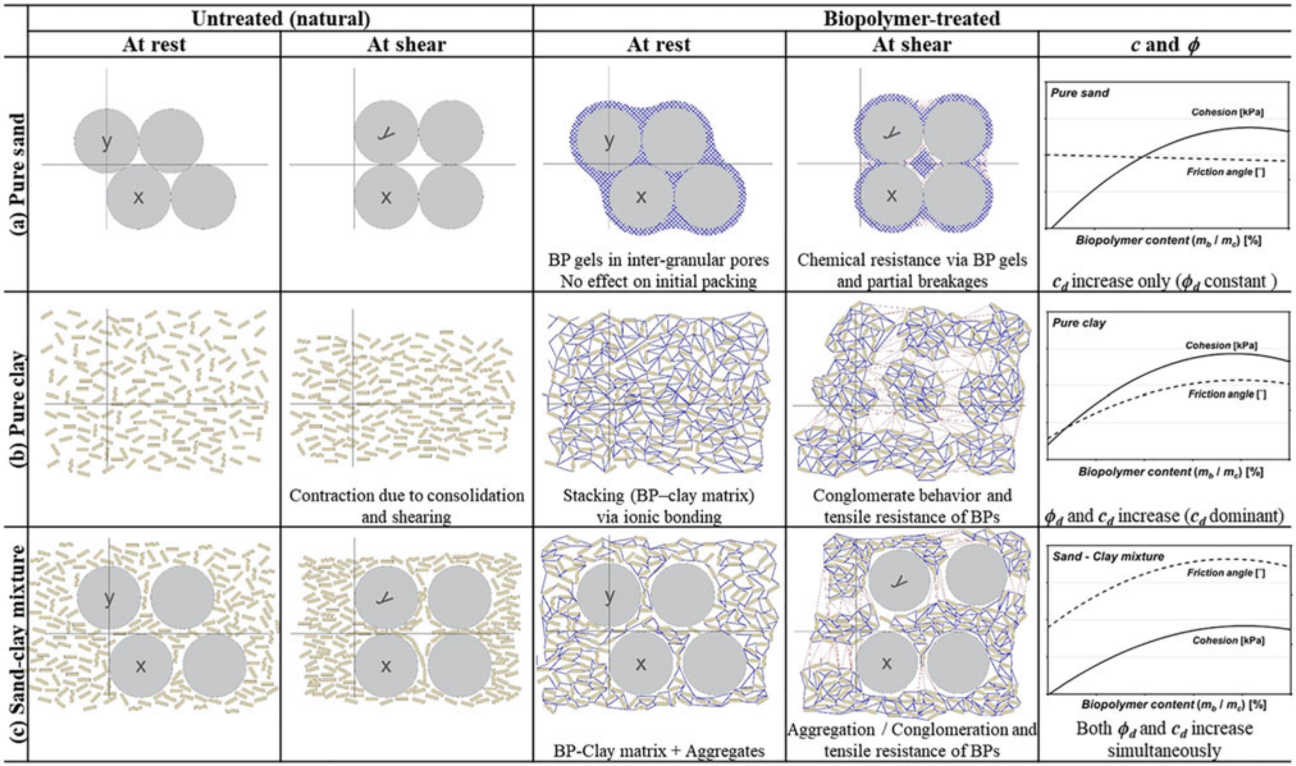


Fig. 23.12 Schematic model of the shearing behavior of gellan gum-treated coarse and fine-grained soils (Chang and Cho 2019)

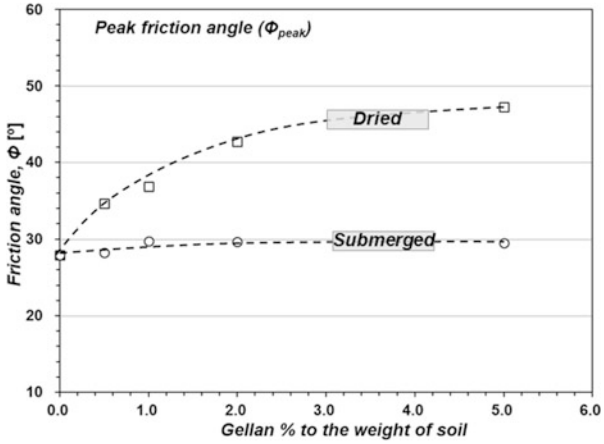


Fig. 23.13 Change in friction angle of gellan gum-treated sands with dehydration (Chang et al. 2016)

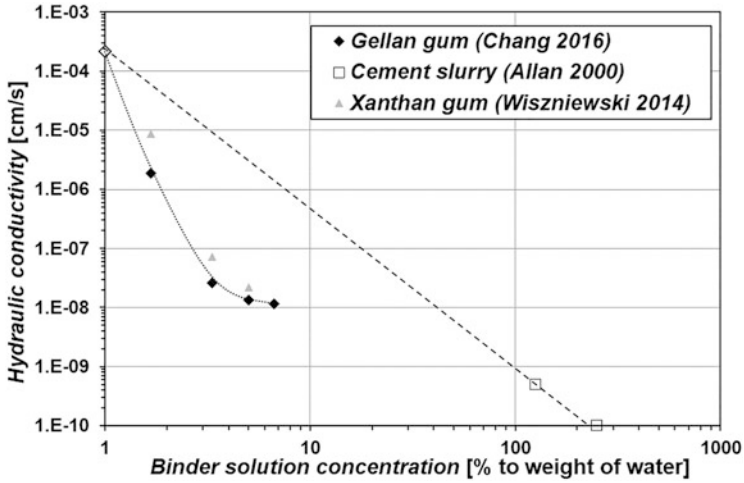


Fig. 23.14 Hydraulic conductivity reduction comparison between biopolymers and cement (Chang et al. 2016; Allan 2000; Wiszniewski and Cabalar 2014)

with BPST, the germination rate of a plant can increase to close to two times than that of the control (Larson et al. 2013). Moreover, the plant survivability against drought conditions is greatly improved by the addition of biopolymers (Tran et al. 2019; Larson et al. 2013). However, it should be noted that a different type of biopolymer and plant species may react differently from the results shown in Fig. 23.18.

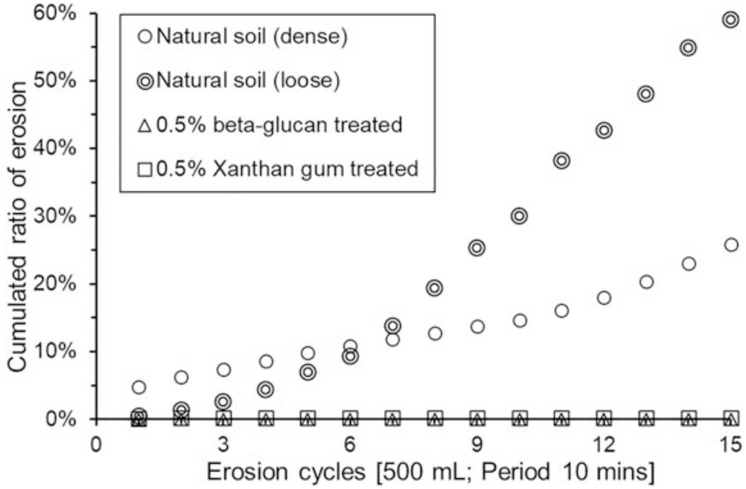


Fig. 23.15 Erosion response of biopolymer-treated and untreated sandy soils to repeated precipitation simulations (Chang et al. 2015c)

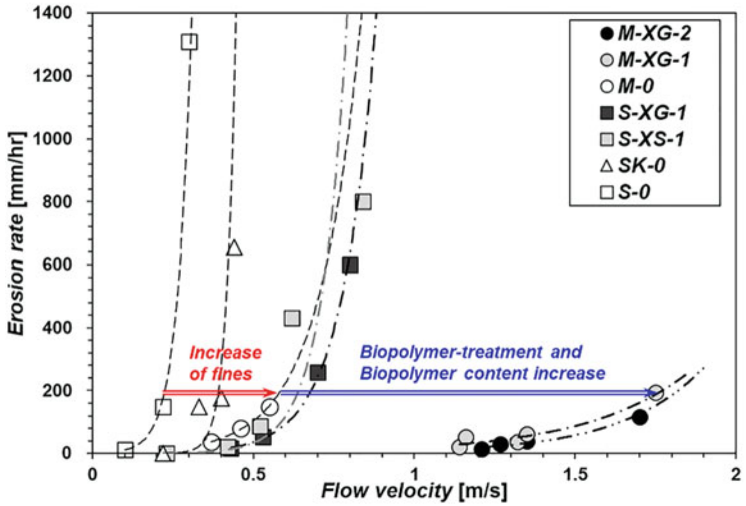


Fig. 23.16 EFA test results for xanthan gum (XG), xanthan-starch (XS), and untreated silica sand (S), silica 90%–kaolinite 10% (SK), and soft marine soil (M) at biopolymer contents (biopolymer to soil ratio in mass) of 0, 1, and 2% (Kwon et al. 2020)

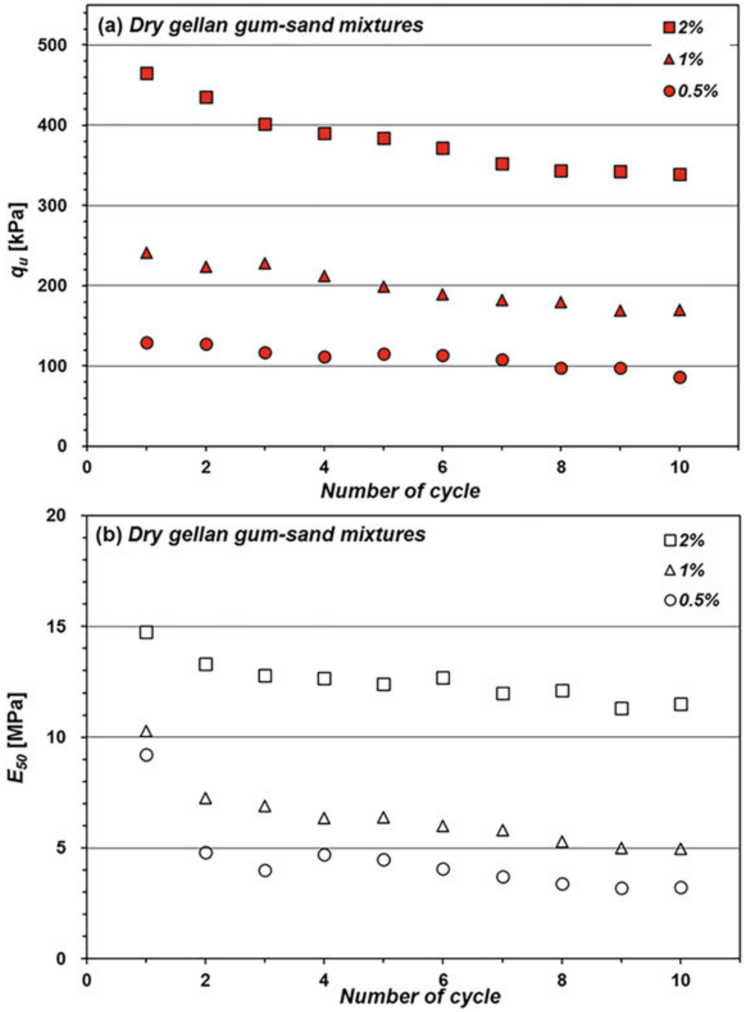


Fig. 23.17 Degradation of (**a**) uniaxial compressive strength and (**b**) Young's modulus of gellan gum-treated sands with repeated drying and wetting cycles (Chang et al. 2017)

23.4 BPST Implementation in Geotechnical Engineering Practices

23.4.1 Implementation Methods

The implementation methods of BPST in the field have not been thoroughly studied. However, the following three methods—spraying, grouting, and direct mixing—are regarded to be the most applicable form for BPST practical implementation.

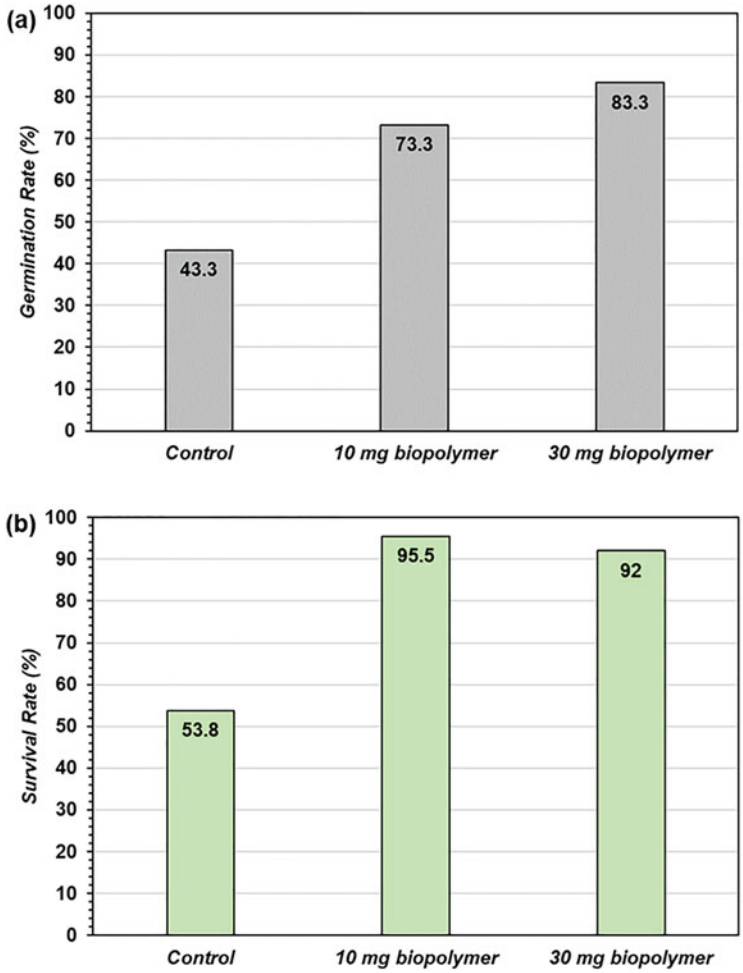


Fig. 23.18 Effects of biopolymers on the (**a**) germination rate, (**b**) survival rate during drought conditions, (**c**) wilting rate during drought conditions, and (**d**) vegetation growth promotion (Larson et al. 2013; Tran et al. 2019; Chang et al. 2015c)

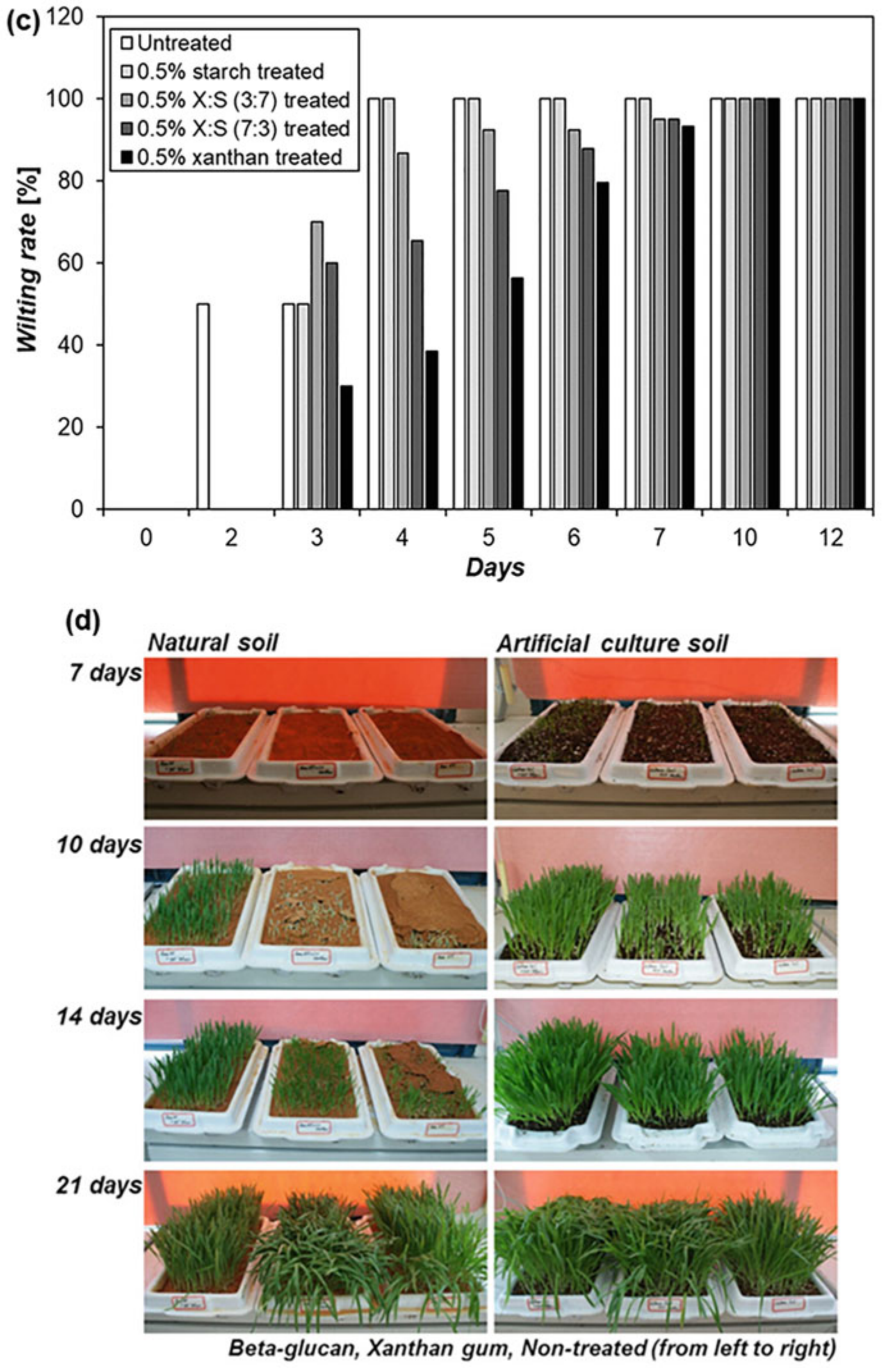


Fig. 23.18 (continued)

Fig. 23.19 Wet spraying method in which a biopolymer solution is mixed directly with the soil before spraying (**a**) In-situ wet mixing system (**b**) Biopolymer-soil mixture spraying

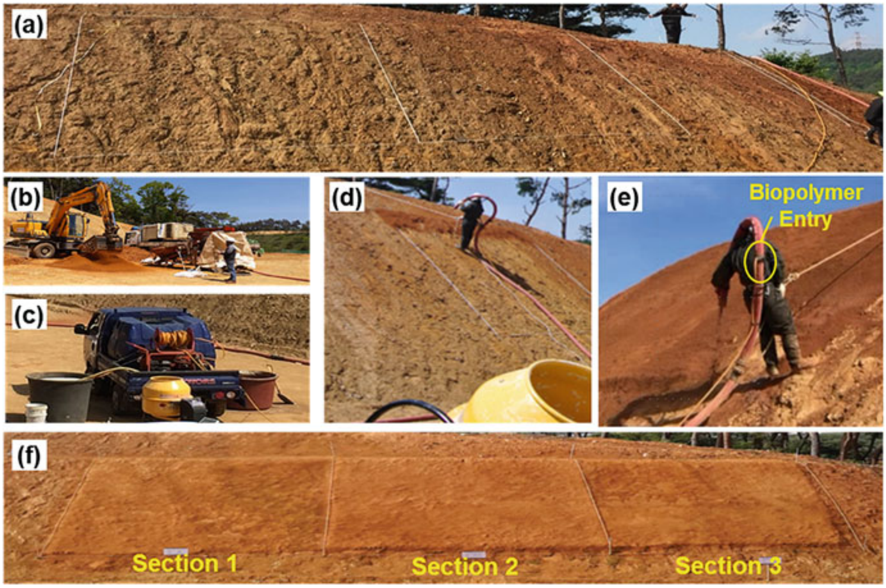


Fig. 23.20 Procedure for biopolymer implementation using the dry spraying method (**a**) Test site overview (**b**) Site soil supply via pneumatic pressure (**c**) Biopolymer solution preparation (**d**) Dry soil and biopolymer solution spraying (**e**) Multiple spraying nozzle (**f**) Completion of BPST on embankment surfaces (Chang et al. 2020)

23.4.1.1 Spraying: Wet and Dry

In the case of spraying, there are two considered methods: (1) wet spraying (Fig. 23.19) and (2) dry spraying (Fig. 23.20). In the case of wet spraying, either the biopolymer solution or a biopolymer solution mixed with soil is directly sprayed on the applicable area.

Wet Spraying

When spraying only the biopolymer solution, a device such as a hydroseeder can be used to apply the solution on the soil, and the infiltration of the biopolymer can be relied on to treat the soil. When the biopolymer solution is mixed with the soil before spraying, a very viscous and fluid mixture is necessary for reliable spraying. Additionally, heavy-duty pumps are required to push the mixture through the spraying nozzle (Fig. 23.19).

Dry Spraying

In the case of dry spraying (Fig. 23.20), a pneumatic compressor is used as the transport mechanism to deliver the soil to the site (Fig. 23.20b). A relatively dry soil is used to prevent clogging in the pipes, and a biopolymer solution is pumped (Fig. 23.20c) into the main pipe at approximately 2–5 m behind the exit nozzle (Fig. 23.20d). The rate of biopolymer pumping must be regulated to achieve the desired mixing concentrations.

23.4.1.2 Injection: Grouting

Biopolymer injection is a possible implementation method that can be used for hydraulic conductivity control purposes. Grouting is a method in which a material is injected into the voids in the ground through the use of fluid pressure. To utilize biopolymers for grouting purposes, a careful method of injection will be necessary, as the use of biopolymers can drastically increase the viscosity of a fluid. Moreover, the initial mixing concentrations of the injected biopolymer will need to be considered as the engineering properties of biopolymer-treated soils will differ based on the mixing concentrations (Fig. 23.21).

23.4.1.3 In Situ Soil Mixing and Compaction

The last possible methods of BPST implementation are (1) direct mixing of the biopolymer into the soil (like deep cement mixing; DCM) or (2) mixing and compacting biopolymer-treated in-situ soil at the desired location (e.g. pavement using site soil) (Fig. 23.22). However, in-situ mixing and compaction method may require specialized equipment for biopolymers as a sufficient kneading of the biopolymer-treated soils maximizes the engineering performance. Additionally, as biopolymer-treated soils react almost immediately and form a sticky viscous mixture, a sufficiently powerful mixer will be required (Fig. 23.22).

23.4.2 Erosion Control

Several erosion control tests using biopolymers have been performed under in situ conditions. In one case study performed by Larson et al. (2013), a biopolymer solution was sprayed over a berm to test the changes in erosion resistance. The biopolymers were applied using a hydroseeder with a single spray, double spray, and double spray at a two-foot depth (Larson et al. 2013). The results of observations over a 6-month period showed that the use of biopolymers sufficiently reduced the erosion of the soil, in particular the surface roughness of the slopes (Fig. 23.23) (Larson et al. 2013).

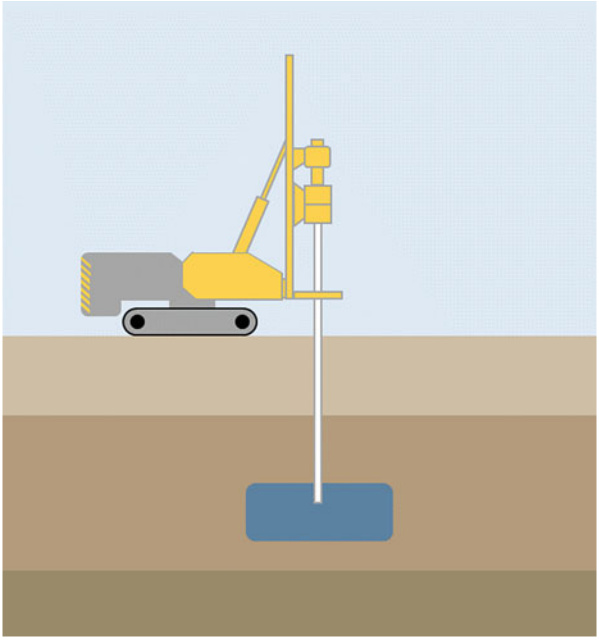


Fig. 23.21 Schematic diagram of biopolymer grouting methodology

Fig. 23.22 Direct mixing and compaction procedure (**a**) Site overview (**b**) Site cleaning and trimming (**c**) Biopolymer-site soil mixing (**d**) Biopolymer-site soil mixture distribution (**e**) Compaction (**f**) Completion (Chang et al. 2020)

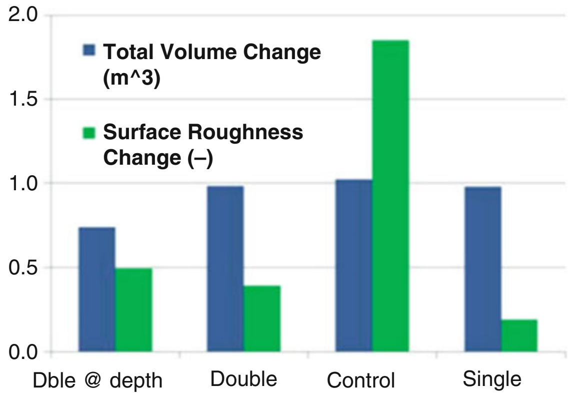


Fig. 23.23 Performance of biopolymer hydroseed spraying on erosion control of a berm (Larson et al. 2013)

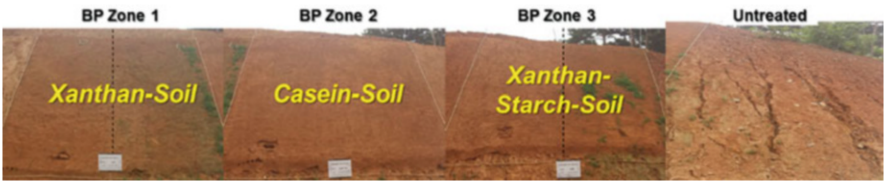


Fig. 23.24 Reduction of surface erosion on target slope after heavy rainfall

In another case study, a dry mixing method (Fig. 23.20) was attempted to assess the erosion resistance of a biopolymer-treated slope (Chang et al. 2020). The target soil of the slope, silty sand, was transported using an air compressor, and a biopolymer solution was mixed with the soil close to the exit nozzle. The surface erosion, shown in Fig. 23.24, was significantly reduced in the cases with biopolymer treatment.

Both biopolymer spraying and dry spraying methods of application have been shown to be viable for the purposes of erosion control.

23.4.3 Grouting Control and Injection

The grouting and injection of biopolymers into the soil can help to immediately reduce the transport mechanisms within the soil due to the high viscosity of the biopolymers. In one study conducted by Khatami and O'Kelly (2018), biopolymers were used for grouting purposes to inhibit the bleeding of particulate grouts such as granulated blast furnace slags (GGBS) (Khatami and O'Kelly 2018). In this case, the grouting material was prepared as a solution and added to a biopolymer solution, as the direct addition of a grouting powder resulted in an uneven mixing of the solution.

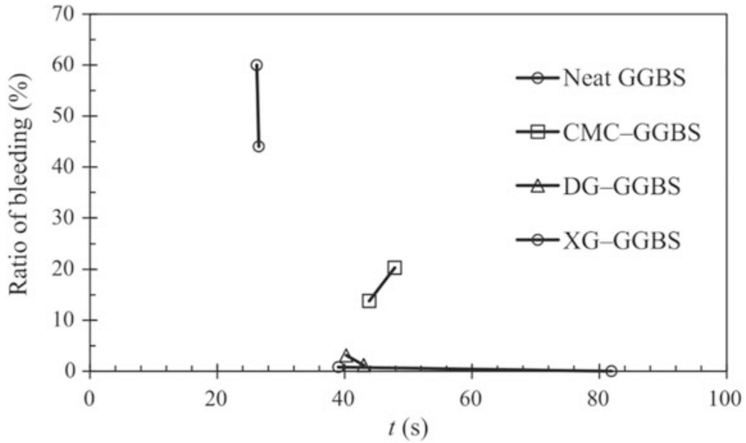


Fig. 23.25 Reduction of GGBS bleeding using carboxymethylcellulose (CMC), diutan gum (DG), and xanthan gum (XG) biopolymers (Khatami and O'Kelly 2018)

The results, shown in Fig. 23.25, showed that the use of biopolymers greatly reduced the effects of bleeding of the grout material (Khatami and O'Kelly 2018).

23.4.4 Vegetation Promotion and Degraded Site Recovery

As biopolymers have shown sufficient vegetation enhancement properties, a site application has been attempted to verifiy the vegetation growth promotion effect of BPST in the field. In a particular study, a biopolymer solution was mixed with cultivated soil and natural sandy soils to test its vegetation enhancement capabilities (Chang et al. 2020). The method used for implementation was the wet spraying method (Fig. 23.19), in which the biopolymer solution was mixed with the target soil before spraying was commenced. The results from this test showed that the use of biopolymers had a large effect on the germination rate of the plants (Chang et al. 2020). Additionally, it was observed that the wet spraying method was an adequate method for BPST implementation for vegetation growth promotion (Fig. 23.26).

23.5 Future Prospects of BPST

23.5.1 Economic Feasibility

The price per unit of biopolymers is significantly higher than that of conventional materials, such as cement. However, biopolymers are used at significantly lower concentrations than are conventional binders. If we compare the prices of one of the more commercially available biopolymers, xanthan gum, with cement (Table 23.1), the prices per unit are 2300 USD/ton and 123.5 USD/ton for xanthan gum and cement, respectively. If we consider that xanthan gum biopolymer can be used at

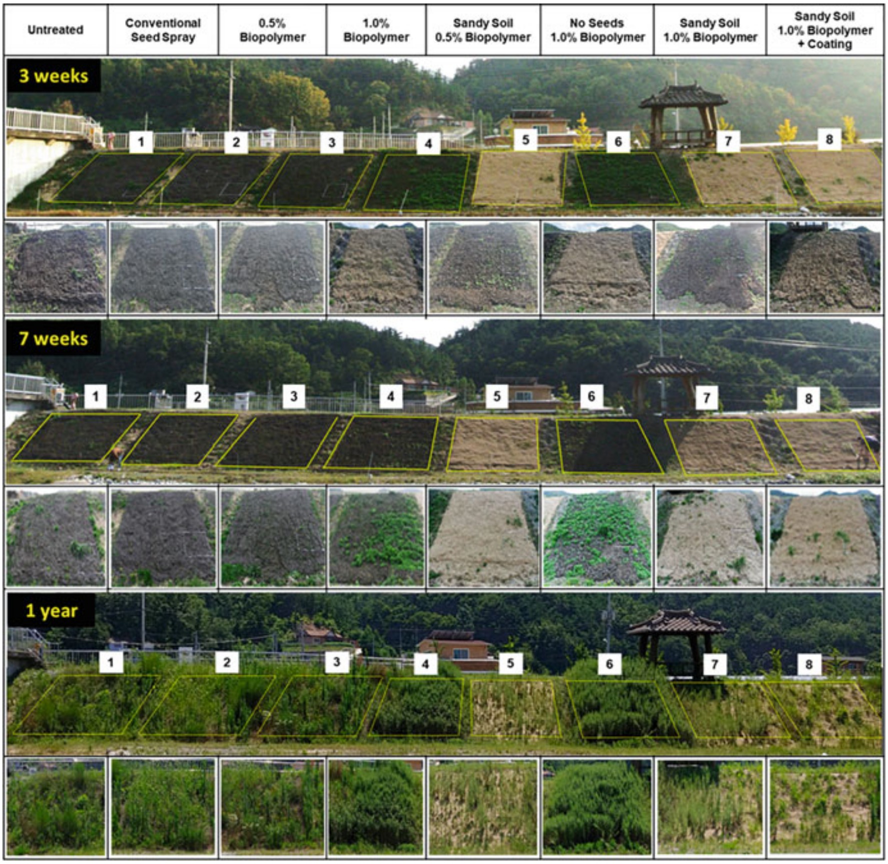


Fig. 23.26 Biopolymer-treated soils for vegetation growth (Chang et al. 2020)

Table 23.1 Economic feasibility of xanthan gum and beta-glucan BPST in comparison with cement-based ground improvement

	Cement	Xanthan gum	Beta-glucan
Market price of material per ton	123.5 USD[a]	2300 USD[b]	50,000 USD[b]
Required amount for 1 ton of soil treatment	100 kg (10% to soil mass)	5 kg (0.5% to soil mass)	5 kg (0.5% to soil mass)
Material price for 1 ton of soil treatment	12.34 USD	11.5 USD	250 USD

[a]Price of cement in the United States, in 2019 (www.statista.com)
[b]Average price found in 2020 (www.alibaba.com)

concentrations of 0.5% to the soil mass, while the typical cement treatment uses approximately 10% of cement to the soil mass, the prices per unit of treated soil are 11.5 USD/ton and 12.35 USD/ton of soil treated using xanthan gum and cement,

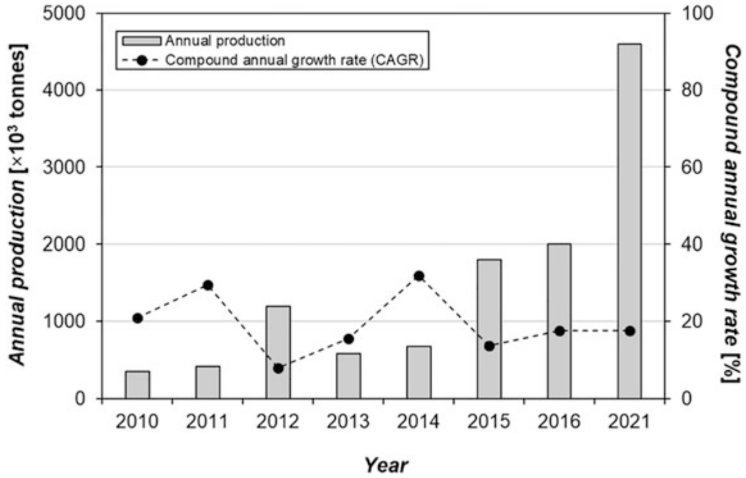


Fig. 23.27 Global biopolymer market (status and growth) (Chang et al. 2020)

respectively. This shows that the price of xanthan gum is comparable to that of conventional soil binders.

However, it should be noted that the cost of the biopolymer treatment of soils is highly dependent on the biopolymer used for the treatment. If we compare xanthan gum and beta-glucan, we can see from Table 23.1 that there is an extremely large disparity between their prices. However, as biopolymer use has been increasing over the past few years, it is expected that the overall price of biopolymers will drop to levels comparable to that of xanthan gum treatment (Chang et al. 2020) (Fig. 23.27).

23.5.2 Limitations and Challenges

Although BPST has shown several beneficial engineering properties in soils, the use of biopolymers in geotechnical engineering has also been limited by several challenges. The use of biopolymers in soils has always resulted in a certain degree of inconsistency. Owing to the highly hydrophilic nature of biopolymers, their engineering capabilities are highly reliant on the moisture content within the soil. Studies have shown that with biopolymer usage, the saturated strength can decrease to 10% of the dry strength (Chang et al. 2015b). With such a large variation in their engineering performance, their use and applicability in the long term are called into question.

There are several methods that can be used to overcome this limitation, such as the use of hydrophobic biopolymers. In one study, the use of casein proteins, a hydrophobic protein commonly found in mammalian milk, was used as a binder in soils (Chang et al. 2018a). The results of this study showed that with this method, the saturated strength of the soils was greatly enhanced (i.e., up to 650 kPa), and although there was a decrease in strength from the dry to saturated soils, the decrease was not as significant as for previously studied biopolymers (Chang et al. 2020).

Another viable method may be through the alteration and enhancement of the biopolymers themselves using methods such as a cross-linking of the biopolymers. Through such techniques, the biopolymer's mechanical strength, ductility, and even water absorption capabilities can be altered to fit the required engineering criteria for various geotechnical applications.

23.6 Conclusion

Biopolymers that are used as a soil enhancement material have been introduced as a sustainable, environmentally friendly construction material. The use of biopolymers, such as xanthan gum, gellan gum, starch, guar gum, beta-glucan, and casein, have been studied by various researchers worldwide. The current findings of biopolymer behaviors in soils are as follows:

- Biopolymer interactions—The surface charge characteristics of biopolymers allow for the biopolymer molecules to interact with (a) other biopolymers, (b) water, and (c) surface charges on fine soils. In the case of coarse soils, the biopolymer molecules interact with other biopolymer molecules to create a biopolymer film that encompasses the soil particles. In the case of fine soils, the biopolymer molecules interact with the surface charges on the fine soils and other biopolymer molecules to create a net interaction between the soil particles.
- Soil consistency—Biopolymers have water absorption capabilities that can alter the LL and PL of different soils. The addition of biopolymers provides the soils a higher plasticity and lower electrical sensitivity.
- Strength—Biopolymers are capable of significantly enhancing the strength of soils mostly through an increase in cohesion. The biopolymers either encompass the soil particles or interact directly with the fine particles to create a large conglomerate. These conglomerates tend to increase the dilatancy and friction angle of the soils. The efficiency of the strengthening capability is largely dependent on the presence of water.
- Erosion—As biopolymers enhance interparticle interactions, biopolymer-treated soils have been shown to have significant resistance to erosion. The highly viscous nature and binding properties of biopolymers have been shown to inhibit soil particle movement.
- Hydraulic conductivity—Biopolymers are generally hydrophilic and have water absorption capabilities. When biopolymers are present in the pore spaces of soil, they can absorb water and fill the pore spaces within the soil. Through this mechanism, the use of biopolymers can greatly reduce the hydraulic conductivity of the soil.
- Vegetation—The water-holding capabilities of biopolymers, along with their natural origin, have been shown to enhance the germination, growth rate, and drought survival rate of plants. Different combinations of plants and biopolymer types may show varying results.

As biopolymer-based soil treatment (BPST) has various beneficial engineering properties, along with the fact that biopolymer use is a sustainable and environmentally friendly approach to construction activities, its use as a future engineering material shows great promise. However, to fully incorporate BPST technology into current engineering practices, the limitations of biopolymer use need to be addressed.

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