

Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands

Sojeong Lee^{1a}, Jooyoung Im^{2b}, Gye-Chun Cho^{2c} and Ilhan Chang^{*1}

¹*School of Engineering and Information Technology (SEIT), University of New South Wales (UNSW), Northcott Drive, Campbell, ACT, 2600, Australia*

²*Department of Civil Engineering, Korean Advanced Institute for Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

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Abstract. Gel-type biopolymers have recently been introduced as environmentally friendly soil binders and have shown substantial strengthening effects in laboratory experimental programs. Although the strengthening effects of biopolymer-treated sands have been verified in previous direct shear tests and uniaxial compression tests, there has been no attempt to examine shear behavior under different confining stress conditions. This study therefore aimed to investigate the strengthening effects of biopolymer-treated sand using laboratory triaxial testing with a focus on confining pressures. Three representative confining pressure conditions ($\sigma_3 = 50$ kPa, 100 kPa, and 200 kPa) were tested with varying biopolymer contents (m_{bp}/m_s) of 0.5%, 1.0%, and 2.0%, respectively. Based on previous studies, it was assumed that biopolymer-treated sand is susceptible to hydraulic conditions, and therefore, the experiments were conducted in both a hydrated xanthan gum condition and a dehydrated xanthan gum condition. The results indicated that the shear resistance was substantially enhanced and there was a demonstrable increase in cohesion as well as the friction angle when the biopolymer film matrix was comprehensively developed. Accordingly, it can be concluded that the feasibility of the biopolymer treatment will remain valid under the confining pressure conditions used in this study because the resisting force of the biopolymer-treated soil was higher than that in the untreated condition, regardless of the confining pressure.

Keywords: biopolymer; hydrogel-type biopolymer; triaxial testing; shear behavior

1. Introduction

Soil stabilization materials are widely used in construction sites and social infrastructures. From bitumen to natural pozzolan materials such as volcanic ash, many materials have been evaluated in an attempt to develop more effective soil-stabilizing materials (Chang *et al.* 2015, Chang *et al.* 2016). Since the Industrial Revolution, cement and gypsum have been comprehensively researched and are used extensively in construction due to their high cost-effectiveness (Sherwood 1993, Ngowi 1997, Prusinski and Bhattacharja 1999, Horpibulsuk *et al.* 2004). However, the need to develop alternative soil stabilization solutions has recently garnered attention due to growing concerns about climate change. Indeed, the global mean temperature has been increasing steadily, and approximately 2% of carbon dioxide emissions from cement usage are related to geotechnical applications (Chang *et al.* 2016). Several researchers have therefore proposed alternative materials

and methods for soil stabilization (Kamon and Nontananandh 1991, Kaniraj and Havanagi 2001, Horpibulsuk *et al.* 2011, Mortensen and DeJong 2011, Chang and Cho 2012, Al Qabany and Soga 2013).

Biopolymers have recently been introduced as an environmentally friendly construction material due to their biodegradation characteristics and low greenhouse gas emissions (Kavazanjian *et al.* 2009, Chen *et al.* 2013, Kulshreshtha *et al.* 2017). Researchers have investigated the feasibility of using biopolymer treatments as a new methodology for soil stabilization (Chang and Cho 2014, Chang *et al.* 2015, Chang *et al.* 2016, Chen *et al.* 2016, Latifi *et al.* 2016, Chang *et al.* 2017, Im *et al.* 2017, Kwon *et al.* 2017, Rashid *et al.* 2017, Chang and Cho 2018). Soil stabilization using biopolymers is expected to mitigate wind erosion in military environments (for example, during helicopter landings), and hydraulic erosion resulting from irrigation, and desertification (Orts *et al.* 2001, Kavazanjian *et al.* 2009, Larson *et al.* 2010, Chang *et al.* 2015).

However, the majority of recent studies have focused on the strengthening effects of biopolymers without considering other practical factors. Biopolymer-treated soils have mainly been evaluated through laboratory uniaxial compression tests and direct shear tests (Chang and Cho 2012, Chang *et al.* 2015, Cabalar *et al.* 2017, Lee *et al.* 2017, Fatehi *et al.* 2018, Hataf *et al.* 2018). Although the degree to which soils have been reinforced can be verified using these methods, the effectiveness of biopolymer treatments in practical conditions has not been analyzed, and the successful implementation of gel-type biopolymers

*Corresponding author, Senior Lecturer

E-mail: ilhan.chang@unsw.edu.au

^aGraduate Student

E-mail: sojeong.lee@student.unsw.edu.au

^bGraduate Student

E-mail: jooyoungim@kaist.ac.kr

^cProfessor

E-mail: gyechun@kaist.edu

for practical applications cannot be established without considering critical in situ factors.

This study therefore investigated the shear behavior of biopolymer-treated soils under confining pressures using a laboratory triaxial system. Varying confining pressures (i.e., 50 kPa, 100 kPa, and 200 kPa) were applied to represent shallow construction depths.

Different hydraulic conditions were also examined (i.e., hydrated and dehydrated conditions) because previous studies have indicated that gel-type biopolymers are significantly affected by water content. In addition, the percentage of biopolymer content was varied (i.e., 0.5%, 1.0%, and 2.0%) to determine the most effective dosage.

2. Materials and method

2.1 Tested materials

Sand

Sydney sand, which is a sub-angular quartz sand classified as SP (poorly graded sand; Fig. 1) by the unified soil classification system (USCS), was used in this study (Lo *et al.* 2010). Detailed information about this sand is shown in Table 1.

Biopolymer

Xanthan gum was used to make the cemented specimens. This polysaccharide-type biopolymer is composed of two glucose units, two mannose units, and one glucuronic acid unit. The repeated structure consists of a main chain and a trisaccharide side chain. The main chain is made by linking the beta-D-glucose units at positions 1 and 4. The side chain containing D-glucuronic acid and two D-mannose units is attached at the O-3 position of the glucose in the main chain (García-Ochoa *et al.* 2000).

2.2 Sample preparation

Varying quantities of the biopolymer powder were dissolved into deionized water (water content = 20% to soil mass) using a pneumatic mixer to prepare a biopolymer hydrogel. The biopolymer content was controlled at 0.5%, 1.0%, and 2.0% by mass ratio (m_{bp}/m_s). The biopolymer hydrogel was poured into oven-dried sand and mixed thoroughly to ensure the homogeneous distribution of the biopolymer (a process referred to herein as “wet mix”).

For the hydrated xanthan gum (HXG) condition, the wet-mixed xanthan gum sand was poured into a cylinder mold, which was set up on the bottom plate of a triaxial apparatus (diameter: 50 mm; height: 100 mm), and compacted using a compaction bar (diameter: 15 mm; weight: 180 g). This process was repeated for three layers to produce a homogeneous composition. Thereafter, the mold was disassembled without applying vacuum pressure due to the cohesion of the hydrated biopolymer hydrogel.

For the dehydrated xanthan gum (DXG) condition, the wet-mixed xanthan gum sand was poured into a paper mold (diameter: 50 mm; height: 100 mm) in the same manner as the HXG condition sample preparation. Because the paper mold had pierced holes to allow air to circulate and thoroughly dry the wet mixed samples, the samples were

Table 1 Properties of Sydney sand

e_{max}	e_{min}	D_{50} [mm]	C_u	C_c	G_s	USCS
0.92	0.60	0.36	1.18	0.96	2.60	SP

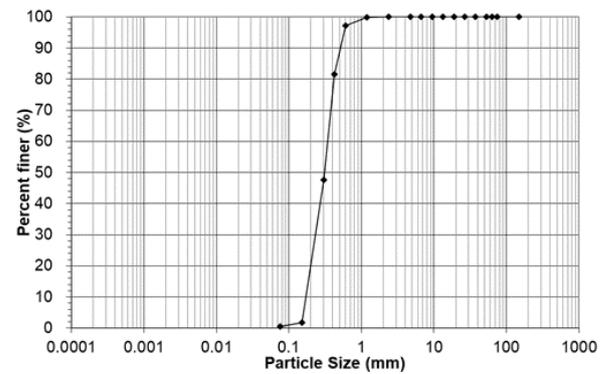


Fig. 1 Particle size distribution of Sydney sand

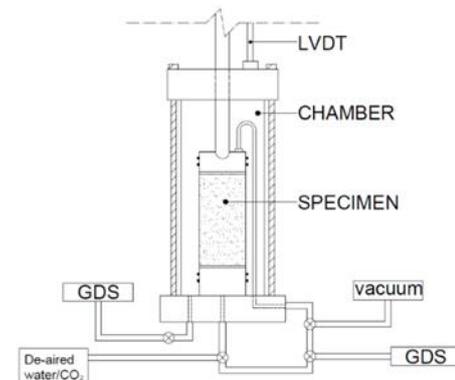


Fig. 2 Laboratory triaxial testing system

dried in a 50°C oven for 14 days without demolding, and the specimen itself was dried for an additional 14 days after demolding.

In the sample preparation process for both the hydrated and dehydrated conditions, it was presumed that the xanthan gum sand proportion would be constant since it was mixed homogeneously and only the water dried during oven drying.

2.3 Test procedure

The experiment was conducted using laboratory triaxial testing apparatus. The experimental apparatus is depicted in Fig. 2. Test samples were mounted on the bottom plate within a rubber membrane to isolate them from the pressurized chamber fluid, and porous stones were placed above and below them. A computer-controlled triaxial device was connected to the experimental system. A GDS Standard Pressure Volume Controller (GDS Product Code: STDDPC) was used to measure the pressure and volume changes in the chamber/pore fluid. The axial strain was measured using an external linear variable differential transformer (LVDT), which was attached to the top of the chamber. The confinement conditions were 50 kPa, 100 kPa, and 200 kPa, and the applied strain rate was 0.1 mm/min.

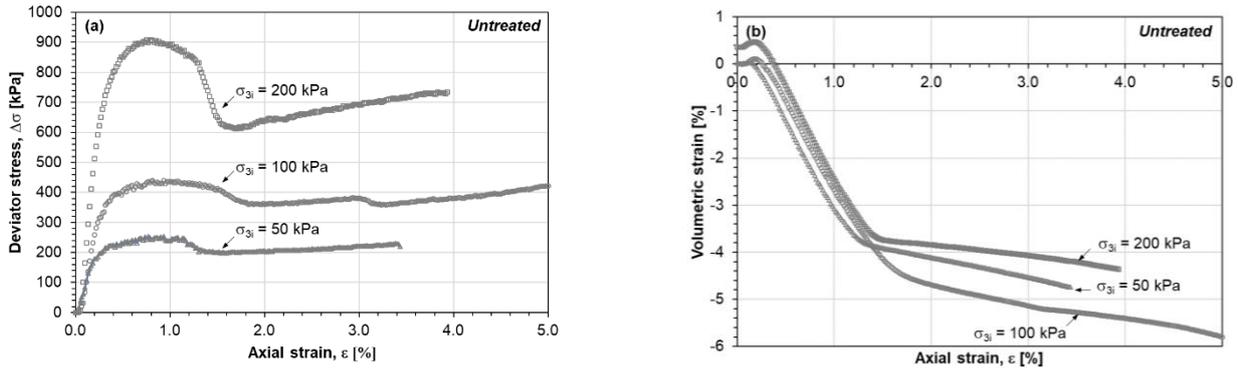


Fig. 3 Stress-strain relationship, and volumetric change of untreated soils during the test

Consolidated Drained Test

For the untreated soil, negative pressure was applied to derive the self-standing force, then the dry mounting method from ASTM D7181 was implemented (ASTM 2011). After assembly, the specimens were saturated by circulating de-aired water and CO₂ gas through the sample, sequentially and repeatedly. Thereafter, a back pressure of 500 kPa and a cell pressure of 520 kPa were applied until the B value reached 0.9. Consolidation proceeded after saturation, and the isotropic consolidation pressure varied according to the confining pressure. After these processes were completed, the specimens were sheared with a shear rate of 0.1 mm/min. The relative density (D_r) of the untreated sand was controlled at 0.22.

Drained Test

The HXG specimens were mounted directly onto the apparatus; however, no negative pressure was applied because these samples could maintain their shape without any pressure due to the cohesion derived from the hydrogel biopolymer. After assembly, isotropic confining pressure was applied to the cell fluid. Thereafter, shearing commenced. In this case, D_r was controlled at 0.72-0.87 due to the characteristics of the biopolymer hydrogel.

The dried specimens could stand up without negative pressure because of their sturdy biofilm. Saturation was not performed on the dried specimens whilst maintaining and testing under DXG conditions. Shearing was therefore performed directly after the consolidation process.

However, there was no consolidation effect because the biopolymer film had already been established within the specimen. Accordingly, the experimental method conducted in this study is hereafter referred to as the drained test. D_r was controlled at approximately 0.92 regardless of the biopolymer content.

3. Results and analysis

The stress-strain curve and the volumetric strain curve of the untreated sand are described in Fig. 3. As shown, the higher the confining pressure applied, the higher the strength. For instance, the deviatoric strength increased from 412 kPa to 893 kPa when the confining pressure (σ_3) was increased from 100 kPa to 200 kPa. As a result, a

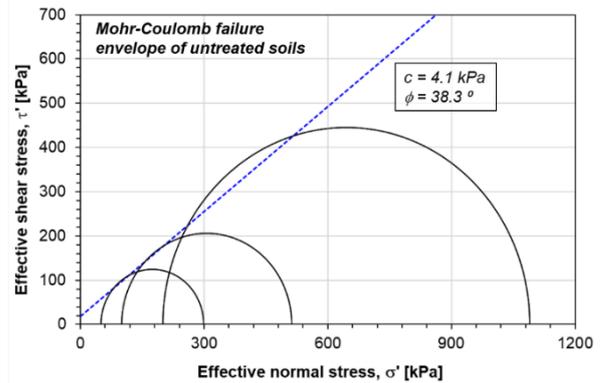


Fig. 4 Mohr-coulomb failure envelope of untreated soils

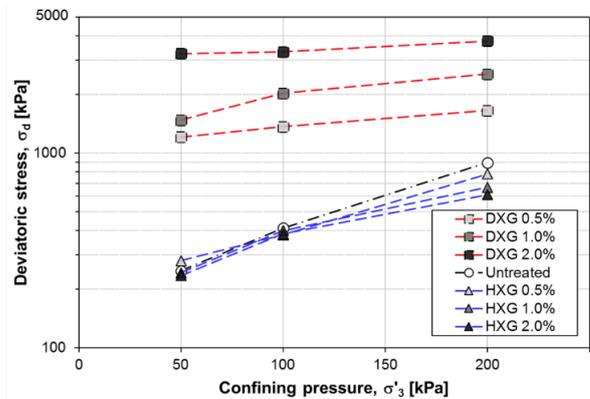


Fig. 5 Reinforcing trend with different biopolymer treatment conditions

cohesion value of 4.1 kPa and a friction angle of 38.3° (shown in Fig. 4) were derived from the experiment's analysis. As the cohesion was negligible, the untreated sand was regarded as cohesionless soil.

Overall, it was obvious that the strengthening effect was enhanced as the confining pressure increased when the sand was treated with biopolymer, regardless of the hydraulic conditions and biopolymer content (Fig. 5). This was indicated by the shear resistance of the soil, which rose as the confining pressure increased during geotechnical engineering.

However, the biopolymer treatment showed different trends depending on the hydraulic conditions, as shown in

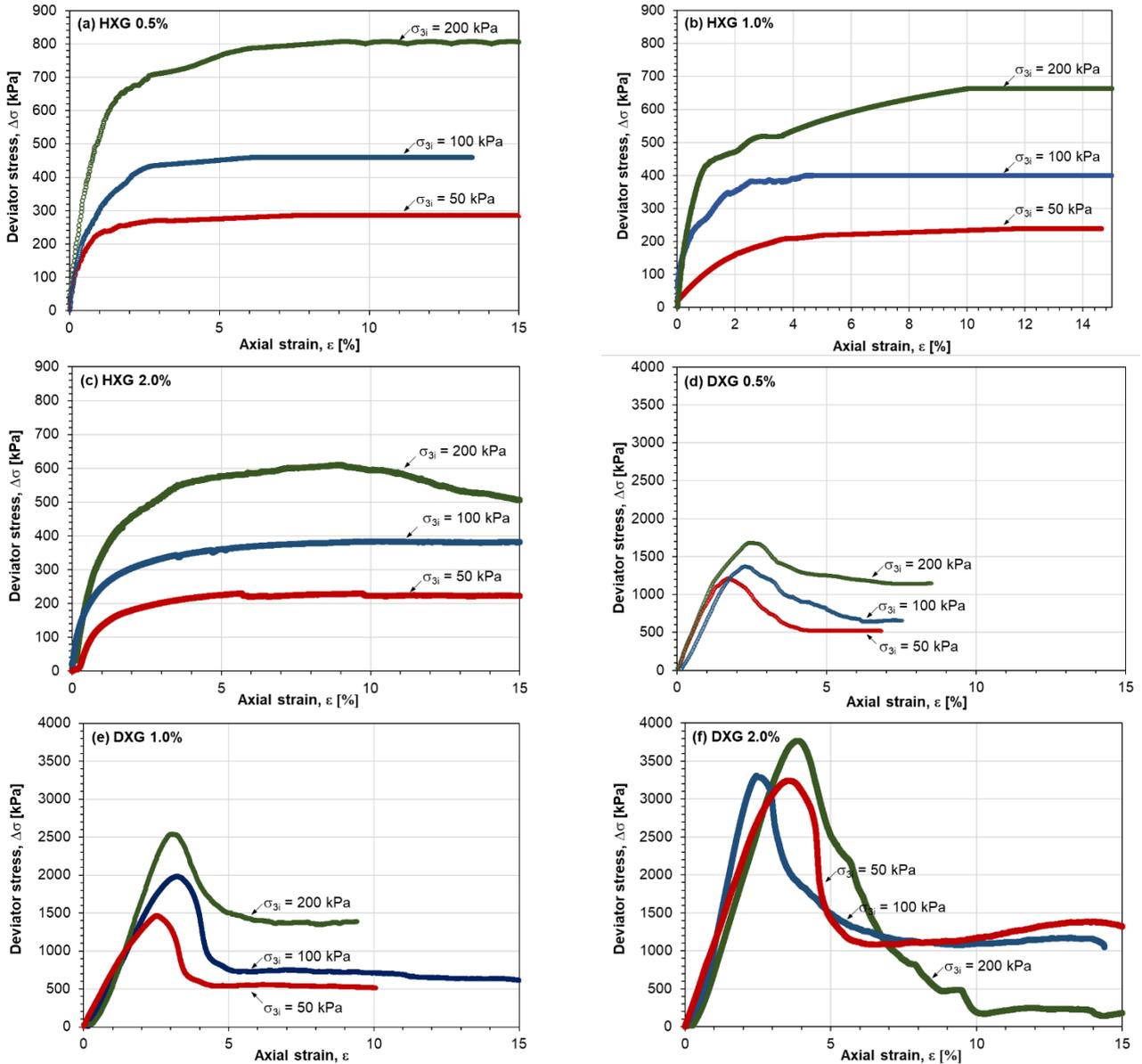


Fig. 6 Stress-strain relationship of biopolymer-treated soil varying treatment content and hydraulic condition. (a) $m_{bp}/m_s = 0.5\%$ at HXG condition, (b) $m_{bp}/m_s = 1.0\%$ at HXG condition, (c) $m_{bp}/m_s = 2.0\%$ at HXG condition, (d) $m_{bp}/m_s = 0.5\%$ at DXG condition, (e) $m_{bp}/m_s = 1.0\%$ at DXG condition and (f) $m_{bp}/m_s = 2.0\%$ at DXG condition

Fig. 6. There was no remarkable strengthening effect when the biopolymer remained in its hydrogel state (i.e., the HXG condition). More specifically, it seems that there was no difference between the untreated soil and the biopolymer-treated soil in the HXG condition with the lower confining pressure. Moreover, the deviatoric stress in the biopolymer-treated soil at the higher confining pressure was slightly decreased compared to that of the untreated soil. Meanwhile, the reinforcing effect was stronger when the biopolymer was sufficiently dried (i.e., the DXG condition).

In addition, the effect of the biopolymer content rendered a different tendency depending on the hydraulic conditions. Specifically, the deviatoric stress at the same confining pressure condition decreased as the biopolymer content increased when the biopolymer remained in its hydrogel state (i.e., the HXG condition), whereas the resisting force was enhanced as the biopolymer content rose

when the biopolymer was dried sufficiently (i.e., the DXG condition). For the HXG condition, there was no noticeable difference irrespective of the biopolymer content up to a confining pressure of 100 kPa, but the strengthening effect at a confining pressure of 200 kPa was decreased with higher amounts of biopolymer content.

On the other hand, the deviatoric stress rose substantially with a higher amount of biopolymer content in the DXG condition. The stress-strain curve of the biopolymer-treated soil in the HXG condition and the DXG condition with different amounts of biopolymer content is described in Fig. 6.

For the HXG condition, the biopolymer-treated soil exhibited an elastic-plastic behavior or a strain-hardening behavior, whereas the biopolymer-treated soil in the DXG condition displayed a strain-softening behavior, as did the untreated soil. It seems that there was no difference

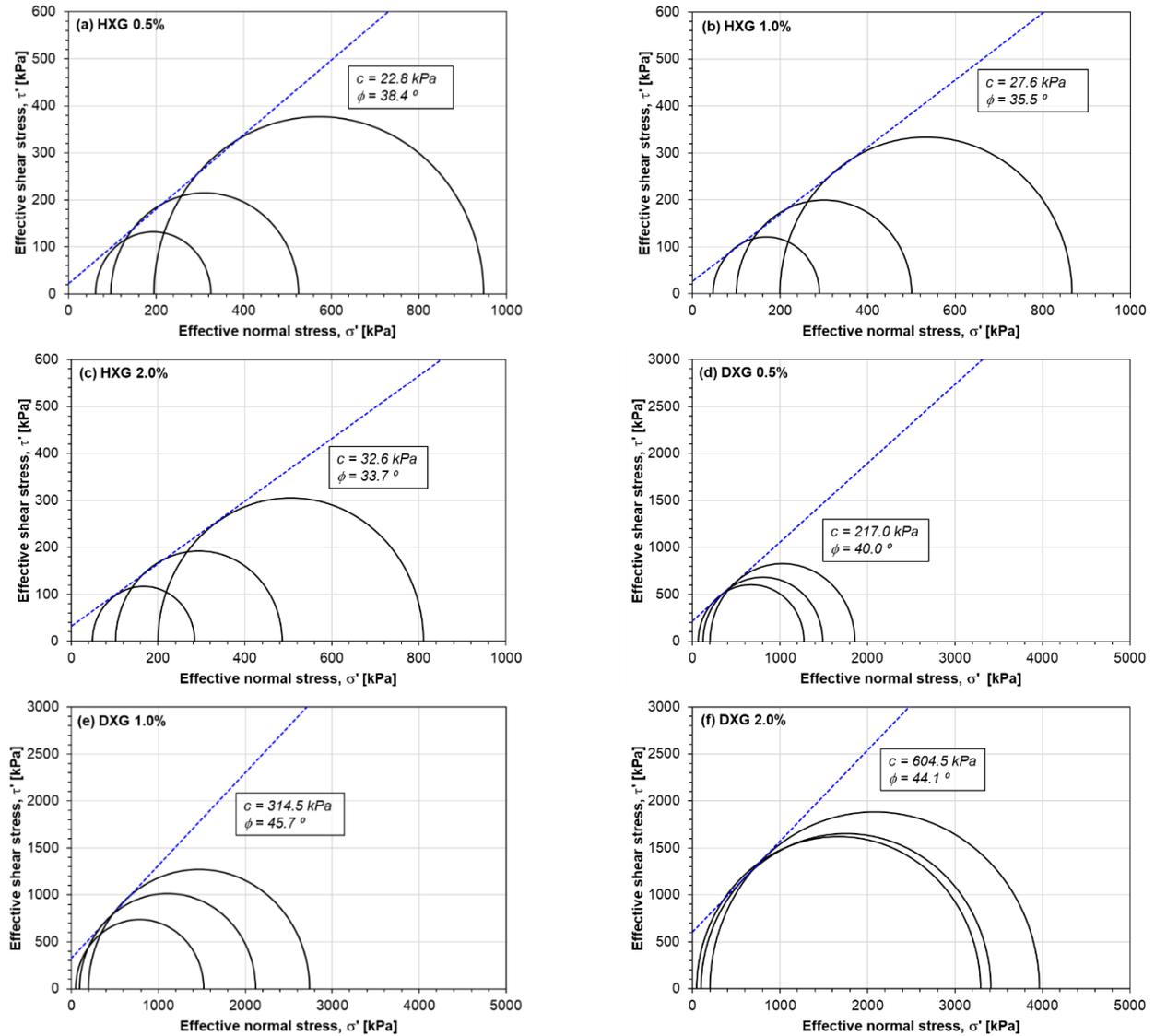


Fig. 7 Mohr-coulomb failure envelope of biopolymer-treated soils varying treatment content. (a) $m_{bp}/m_s = 0.5\%$ at HXG condition, (b) $m_{bp}/m_s = 1.0\%$ at HXG condition, (c) $m_{bp}/m_s = 2.0\%$ at HXG condition, (d) $m_{bp}/m_s = 0.5\%$ at DXG condition, (e) $m_{bp}/m_s = 1.0\%$ at DXG condition and (f) $m_{bp}/m_s = 2.0\%$ at DXG condition

Table 2 Triaxial shear parameters of testing

	Untreated		HXG			DXG		
Biopolymer content ¹⁾	-	0.5%	1.0%	2.0%	0.5%	1.0%	2.0%	
Friction angle, ϕ' [°]	38.3	38.4	35.5	33.7	40.0	45.7	44.1	
Cohesion, c' [kPa]	4.1	22.8	27.6	32.6	217.0	314.5	604.5	
Dilatancy, ψ [°]	11.0	8.4	5.5	3.7	10.0	15.7	14.1	
Friction angle, ϕ [°] ²⁾	27.9	31.5	31.8	32.5	32.1	34.6	38.4	
Cohesion, c [kPa] ²⁾	13.0	34.3	50.2	92.6	160.6	182.7	218.4	

¹⁾ Biopolymer to sand ratio in mass (i.e. m_{bp}/m_s)

²⁾ Previous experimental study results by direct shear testing (Lee *et al.* 2017)

between the peak strength and the residual strength up to a confining pressure of 100 kPa regardless of the biopolymer

content at the HXG condition. However, the residual strength at a confining pressure of 200 kPa showed a different trend. The residual strength increased up to a biopolymer content of 1.0%, but it decreased when the biopolymer content was 2.0%. Meanwhile, the higher the biopolymer content, the higher the residual strength was when the biopolymer remained in the DXG condition, with the exception of the 2.0% biopolymer content condition. There was no residual strength tendency when the biopolymer content was 2.0% in the DXG condition.

The friction angle and cohesion of the biopolymer-treated soil were derived by plotting the Mohr–Coulomb diagram, as shown in Fig. 7. In the HXG condition, the friction angle decreased slightly with a higher biopolymer content, whereas the cohesion increased somewhat. Conversely, both the friction angle and the cohesion were enhanced when the biopolymer was dried. The dilatancy angle was calculated using the estimation method (Chu *et al.* 2003), and the results are shown in Table 2.

Following the trend of the friction angle change, the biopolymer-treated soil in the HXG condition showed a tendency to decrease whereas the dilatancy angle of the biopolymer-treated soil increased for the DXG condition.

4. Discussion

4.1 Effect of the hydraulic condition

The experimental laboratory results showed that the biopolymer treatment was effective under certain confining pressures.

Assuming that the application of the confining pressures in our study was representative of in situ underground confining pressure conditions, it can be concluded that the biopolymer treatment is effective at shallow depths. However, it can be asserted that the biopolymer is susceptible to hydraulic conditions because the biopolymer-treated soil exhibited different shear behaviors in this study.

When the biopolymers remained in a hydrogel state (i.e., HXG condition), the deviatoric stress decreased under the same amount of confining pressure as the biopolymer content increased. This was because of the independent shear behavior of the biopolymer hydrogel and sand particles. In other words, an interrelationship between the biopolymer hydrogel and the sand particles was not established in the HXG condition. Since xanthan gum is a highly viscous material when it becomes a hydrogel, cohesion was enhanced with the increasing biopolymer content; however, the friction angle was diminished due to the decline in surface dilatancy of the sand particles, which interrupted the biopolymer hydrogel (Table 2). Nevertheless, once the biopolymer film matrix was formed between the sand particles following sufficient drying, the strengthening effect improved. It can therefore be deduced that the strengthening effect was impacted by the friction angle.

Due to the elastic properties of biopolymer film, the biopolymer-treated soil in the DXG condition resulted in higher ductility than the corresponding untreated soil. In addition, the higher residual strength can be explained by the elasticity of the biopolymer film fragments that appeared following failure.

Overall, the strengthening effect in the HXG condition was negative, but it improved substantially when the biopolymer was sufficiently dried and an interrelationship between the biopolymer film and sand particles was established. Notwithstanding, further research should be done to determine whether the biopolymer treatment will continue to be effective when the biopolymer film is exposed to water (i.e., re-submerged) because this study has established that the biopolymer is susceptible to water.

4.2 Comparison with previous studies

Using a triaxial consolidated drained test, a previous study determined the critical state line in the p' - q plane of very loose sand as $M_{CS} = 1.35$ for a friction angle of 33.4° (Chu *et al.* 2003). The test results for the untreated soil in this study are plotted in Fig. 8(a). The slope of the failure

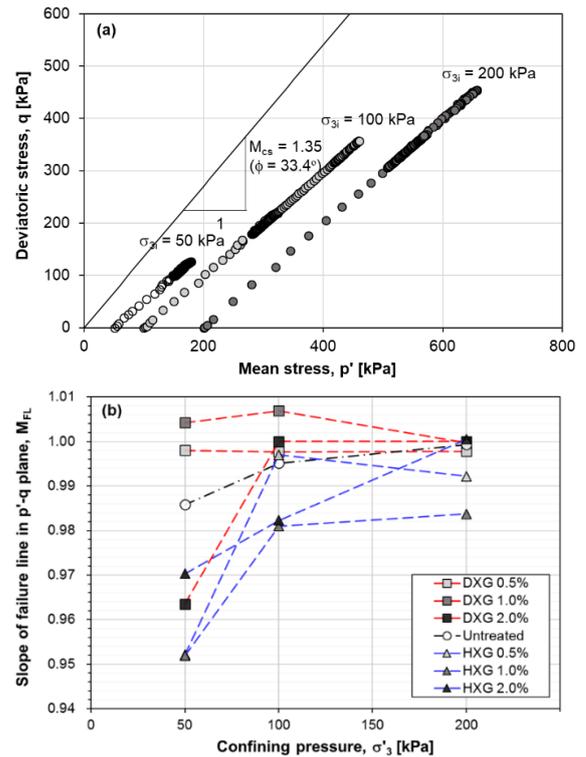


Fig. 8 Failure line in p' - q diagram. (a) comparison of slope on the graph using previous data (Chu *et al.* 2003) and experimental data (untreated soil) and (b) trend of failure slope on the diagram according to biopolymer status *Note: $p' = (\sigma'_1 - \sigma'_3/2)$, $q = (\sigma_1 - \sigma_3/2)$

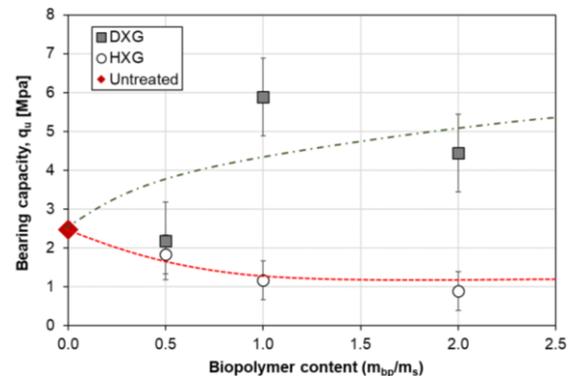


Fig. 9 Bearing capacity of xanthan gum treated sand

line (M_{FL}) was obtained from each p' - q plane and summarized in Fig. 8(b). With increasing amounts of biopolymer content in the HXG condition, the slope of the failure line rose as the confining pressure increased even though it showed a lower value than the corresponding untreated soil. However, the slope of the failure line increased overall when the biopolymer was sufficiently dried.

Nonetheless, there was no trend for the biopolymer content and confining pressure. It can therefore be concluded that the biopolymer treatment was effective in the DXG biopolymer treatment condition. In other words, the biopolymer treatment was considerably affected by the hydraulic condition.

To understand the effectiveness of the biopolymer

treatment, the bearing capacity (q_{ult}) was calculated using the values for cohesion and the friction angle obtained from this study. These were assumed to be $1 \text{ m} \times 1 \text{ m}$ square foot at a depth of 1 m (the unit weight of the soil was assumed to be 18 kN/m^3 for the surcharge calculation) and calculated using Terzaghi's bearing capacity equation (Terzaghi 1943; Kumbhojkar 1993). As the biopolymer content increased when the biopolymer was sufficiently dried, the bearing capacity of the treated soil was substantially enhanced (Fig. 9).

Conversely, there were no remarkable differences in biopolymer content when the biopolymer remained as a hydrogel. It is therefore recommended that the biopolymer be dried sufficiently to induce a high strengthening effect in terms of bearing capacity and shear resistance.

The values for cohesion and the friction angle obtained from this study were higher than the values from the laboratory direct shear testing (Table 2). This was due to the differences in the soil properties. In terms of shear resistance, it was obvious that the biopolymer treatment was highly effective in both surface construction and shallow depth construction conditions. This has been verified in previous laboratory direct shear testing and triaxial testing (Khatami and O'Kelly 2012, Lee *et al.* 2017).

5. Conclusions

In this study, the effectiveness of biopolymer treatment on soil stability under confined conditions was investigated via laboratory triaxial testing. It was determined that the strength of biopolymer-treated soil was enhanced with the application of increasing confining pressure following fundamental geotechnical engineering.

However, the effect of the biopolymer content varied according to the water content. When the biopolymer remained in a hydrogel state in the HXG condition, the strength reduced as the biopolymer dosage increased under the same confining pressure conditions. This occurred because there was no relationship between the biopolymer and the sand particles. The friction angle therefore reduced as the biopolymer content increased due to its independent shear behavior, even though cohesion increased because of its viscous characteristics. However, the strengthening effect was enhanced substantially once the biopolymer film matrix developed between the sand particles after a sufficient period of drying. The resultant increases in both cohesion and the friction angle enhanced the shear resistance in the biopolymer-treated soil.

Accordingly, it can be concluded that, with respect to its strengthening effects and sustainability, the biopolymer treatment described in this study has promising potential for soil stabilization at shallow construction depths where confining pressure is applied to the surrounding soils. In geotechnical engineering, the biopolymer can be used to prevent piping in earthen structures and the alternation of conventional backfill materials in tunnels, as well as to mitigate hydraulic erosion, wind erosion, and desertification. However, it has been confirmed that the biopolymer used in this study is susceptible to water conditions. Specifically, strengthening only becomes

effective once the biopolymer film matrix is developed within the soil. In other words, the biopolymer-treated soil has to be sufficiently dried for effective strengthening to occur. Otherwise, the hydrogel biopolymer will induce a lower strengthening effect under higher confining pressure conditions. Additionally, since the biopolymer is susceptible to water, further studies should be conducted to determine whether its strengthening effect can be maintained after re-submerging the biopolymer film.

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