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Geotechnical engineering behavior of biopolymer-treated soft marine soil

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Abstract. Soft marine soil has high fine-grained soil content and in-situ water content. Thus, it has low shear strength and bearing capacity and is susceptible to a large settlement, which leads to difficulties with coastal infrastructure construction. Therefore, strength improvement and settlement control are essential considerations for construction on soft marine soil deposits. Biopolymers show their potential for improving soil stability, which can reduce the environmental drawbacks of conventional soil treatment. This study used two biopolymers, an anionic xanthan gum biopolymer and a cationic ε-polylysine biopolymer, as representatives to enhance the geotechnical engineering properties of soft marine soil. Effects of the biopolymers on marine soil were analyzed through a series of experiments considering the Atterberg limits, shear strength at a constant water content, compressive strength in a dry condition, laboratory consolidation, and sedimentation. Xanthan gum treatment affects the Atterberg limits, shear strength, and compressive strength by interparticle bonding and the formation of a viscous hydrogel. However, xanthan gum delays the consolidation procedure and increases the compressibility of soils. While ε-polylysine treatment does not affect compressive strength, it shows potential for coagulating soil particles in a suspension state. ε-Polylysine forms bridges between soil particles, showing an increase in settling velocity and final sediment density. The results of this study show various potential applications of biopolymers. Xanthan gum biopolymer was identified as a soil strengthening material, while ε-polylysine biopolymer can be applied as a soil-coagulating material.

Keywords: marine clay; biopolymers; xanthan gum; ε-polylysine; improvement

1. Introduction

Rising sea levels are causing the loss of developable drylands (Rijsberman 1991, Darwin and Tol 2001), therefore, geotechnical engineering is useful as it can play an important role in the construction and maintenance of coastal protection infrastructures. Marine soils generally have a low undrained shear strength (in the range of 5-30 kPa) and are susceptible to the consolidation caused by infrastructure-induced loads (e.g., harbors, airports, and energy plants) due to their high fine-grained soil content (silt and clay) and high in-situ water content (Phetchuay, Horpibulsuk *et al.* 2016). Therefore, ground improvement techniques to enhance the consolidation and drainage behavior (Bergado, Sasanakul *et al.* 2003, Horpibulsuk, Chinkulkijniwat *et al.* 2012, Chai, Horpibulsuk *et al.* 2014, Bo, Arulrajah *et al.* 2015), shear and compressive strength (Du, Wei *et al.* 2013, Wu, Shen *et al.* 2015), and flocculation sedimentation (Chang and Cho 2010, Voordouw 2013) are necessary to enable construction on marine areas.

Previously, geotechnical engineers have applied cement-based materials to stabilize soft marine soil (Yin and Fang 2006). Portland cement and lime have been widely used to increase shear strength and to reduce the compressibility of soil (Locat, Bérubé *et al.* 1990, Horpibulsuk, Miura *et al.* 2004). However, the use of cement accompanies various environmental problems such as carbon dioxide emission, groundwater contamination, ocean pollution, and ecosystem contamination (Doerr 1952, Chang and Cho 2012, Chang, Im *et al.* 2015, Chang, Im *et al.* 2016).

Therefore, many attempts have been made to identify an environment-friendly soil stabilization material. Biogenic methods using microorganisms such as microbes and enzymes have shown potential for soil stabilization. The microbial induced calcite precipitation (MICP) method enhances the strength and stiffness of the soil by injecting ureolytic bacteria, thus binding soil particles through precipitation of calcium carbonate crystals in soil void spaces (Mujah, Shahin *et al.* 2017, Wang, Zhang *et al.* 2017). However, the MICP technique is difficult to apply to fine-grained soils because the small pore size inhibits bacterial transportation and growth (Rong, Qian *et al.* 2011; Yasuhara, Neupane *et al.* 2012). From another perspective, the direct use of a biopolymer (organic polymer) in soil has benefits, including reducing the time for cultivation and excrement precipitation, and is applicable to clayey soils (Chang, Im *et al.* 2016).

Biopolymers are polymers produced by biological

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organisms (e.g., agricultural crops, exoskeletons, cell walls, and bacteria) (Chang, Im *et al.* 2016). Hence, they are carbon-neutral and renewable materials (Ayeldeen, Negm *et al.* 2016), and improve the physical properties of soil (Chang, Im *et al.* 2016). Thus, previous research has suggested that biopolymers are environmentally friendly soil reinforcements (Chang, Prasidhi *et al.* 2015, Im, Tran *et al.* 2017, Qureshi, Chang *et al.* 2017). Biopolymers interact with soil particles, mainly clay, via direct ionic bonding (e.g., hydrogen bonding), thereby the soil strength and stiffness can be improved (Chang and Cho 2014, Chang and Cho 2018).

Additionally, biopolymers, especially cationic biopolymers, have the potential for coagulating soil suspensions (Pan, Huang *et al.* 1999, Kwon, Im *et al.* 2017). Cationic biopolymers accelerate sedimentation processes by forming bridges between clay particles with high water content. However, the interparticle bonding induced by biopolymers increases the compressibility of soils which enlarges settlement by vertical load. Additionally, biopolymers delay consolidation because the formation of hydrogel reduces the soil hydraulic conductivity (Bouazza, Gates *et al.* 2009). Thus, a detailed investigation of soil strengthening and consolidation is required to assess the effects of a biopolymer on fine-grained soil.

This study aims to assess the geotechnical behavior of biopolymer treated soft marine soil, regarding strength, sedimentation, and consolidation characteristics. This study used xanthan gum and ε-polylysine biopolymers as representative marine soil stabilization or coagulation materials which have been approved as nontoxic food additives by the United States Food and Drug Administration (FDA) (Kennedy 1984, García-Ochoa, Santos *et al.* 2000, Chang, Lu *et al.* 2010). Changes in the Atterberg limits with xanthan gum treatment were observed. Fall cone tests and laboratory vane shear tests were conducted to analyze the effect of xanthan gum biopolymer on the shear strength of marine soils. Additionally, oedometric consolidation experiments are reported in which xanthan gum biopolymer was used to treat soft marine soil. These results were measured by elastic wave techniques. In addition, sedimentation experiments of soft marine soil treated with ε-polylysine were carried out. Unconfined compressive strength tests on treated soft marine soil with both xanthan gum and ε-polylysine biopolymers were carried out to compare the strengthening effect of both biopolymers. The results obtained through a series of experimental analyses and the associated discussions provide some insight into the impact of biopolymers on stabilization of marine soils and possible applications in construction fields.

2. Materials and experimental method

2.1 Materials

2.1.1 Soil: Soft marine soil

Soft marine soil (SMS) is widespread in the west and south coasts of the Korean peninsula. Clay or silty SMS contains a low content of sand (usually approximately 20-30%) and a large amount of fine-grain particles (70-80%). The SMS used in this study was obtained from Yeosu, Korea. The particle size distribution of Yeosu SMS obtained by hydrometer analysis is shown in Fig. 1 (ASTM 2017). The SMS has a mean particle size (D_{50}) of 18 μm, a coefficient of uniformity (C_u) of 11.75, and a coefficient of curvature (C_c) of 1.31. The SMS has a specific gravity (GS) of 2.65 (ASTM 2014). Its liquid limit is 56%, and its plastic limit is 29%. Thus, SMS obtained from Yeosu, Korea is classified as clay with high plasticity (CH) based on the unified soils classification system (ASTM 2017).

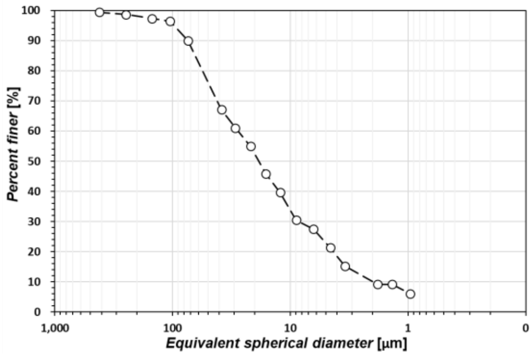


Fig. 1 Particle size distribution of soft marine soil

2.1.2 Biopolymers: Xanthan gum and ε-Polylysine

<u>*Anionic biopolymer: Xanthan gum*</u>

Xanthan gum (XG) is an anionic biopolymer that is produced by the metabolism of the *Xanthomonas campestris* bacterium. Due to its high viscosity when dissolved in water, XG solutions are widely used as thickeners in the food, farming, and oil industries (García-Ochoa, Santos *et al.* 2000).

Recent studies have attempted to apply XG in the geotechnical area as a soil strengthening material (Chang, Im *et al.* 2015, Latifi, Horpibulsuk *et al.* 2016, Lee, Chang *et al.* 2017). Studies have shown that XG interacts with clay particles forming a structured matrix between them, thus increasing the strength of the clay material and undrained shear strength (Chang, Im *et al.* 2015). Other researchers have focused on the decrease of soil permeability by forming impervious barriers (Martin, Yen *et al.* 1996), where XG reduced the hydraulic permeability of soil in orders of 10^2 or more.

Research grade xanthan gum (Sigma-Aldrich, CAS No. 11138-66-2) was used in this study to provide better standardization. It has a yellowish beige color appearance at powder form. The viscosity of 0.5% XG solution has been measured to as 10,020 – 11,170 cps using a laboratory viscometer (Brookfield DV 2TLV).

<u>*Cationic biopolymer: ε-Polylysine*</u>

ε-Polylysine ($C_{180}H_{362}N_{60}O_{31}$; EPL) is a cationic biopolymer fermented by the *Streptomyces albulus* bacterium. EPL is composed of lysine homopolymers containing bonds between the carboxyl and ε-amino groups.

Positively charged hydrophilic amino groups at the L-lysine can be used as coagulating materials of negatively charged colloids (Bolto and Gregory 2007, Kwon *et al.* 2017). EPL has been researched as a cell adhesion material

(Mazia *et al.* 1975), tissue or drug coating in biotechnology (Park *et al.* 2006) and food preservative in the food industry (Hiraki *et al.* 2003). EPL can be used as a surfactant (Furst *et al.* 1996) because it has both hydrophobic methylene groups and hydrophilic carboxyl and amino groups. Thus, surface coating with EPL can prevent the decomposition of food and avoid a proliferation of microorganisms such as yeast and bacteria (Geornaras, Yoon *et al.* 2007).

In this study, the effect of EPL on coagulating and flocculating SMS suspensions was assessed via a series of sedimentation experiments.

Commercially available EPL (BNF CO., LTD, CAS No. 28211-04-3) was used in this study. Its molecular weight is 3,200 – 4,500 g/mol, and it is effective over a wide range of pH values, from about 4-10.

2.2 Experimental programs

2.2.1 Soil-BP Mixture preparation

Biopolymer-treated SMS specimens were prepared through the following procedures. First, the SMS samples were dried at 110°C for at least 48 h to remove all moisture from the soil and to reduce the effects of organic material on the Atterberg limits (ASTM 2010, 2017). Then, the biopolymer and deionized water were mixed to make an aqueous biopolymer solution to activate the biopolymer. The biopolymer-treated SMS samples were prepared by mixing a dry SMS with a biopolymer solution and a target water content (Amezketa, Singer *et al.* 1996, Lado, Ben-Hur *et al.* 2004).

2.2.2 Soil consistency tests

The liquid limit (*LL*) and plastic limit (*PL*) of fine-grained soil are basic properties to determine various geotechnical characteristics, such as soil condition and strength. This study assessed the effect of the XG biopolymer on the Atterberg limits of the SMS.

The *PL*s of the soil samples were determined using a thread-rolling test according to ASTM D 4318 (ASTM 2017). The *LL*s were determined via the fall cone test (BSI 1990). A Standard cone (mass of 80 g, tip angle of 30°) penetrated soil specimens for 5 seconds, and *LL*s were determined as water content at a depth of penetration of 20 mm. The penetration depths were measured using a dial gauge with a resolution of less than 0.01 mm.

The *PL*s and *LL*s were obtained after at least three repeated tests.

2.2.3 Fall cone undrained shear strength

The fall cone undrained shear strength of the XG-treated SMS with various water contents was evaluated using the fall cone penetration tests. Fall cone undrained shear strength measurements have been conducted to assess the effect of XG on the shear strength at different water contents.

Fall cone penetration depth represents the strength of the remolded cohesive soils (Hansbo 1957, Koumoto and Houlsby 2001). Hansbo (1957) derived the relationship between cone penetration depth and undrained shear strength of soil as

$$c_u = K\frac{W}{d^2} \tag{1}$$

where c_u is the undrained shear strength, W is the weight of the cone, d is the penetration depth of the cone (mm), and K is the cone factor.

The effect of the XG biopolymer on the fall cone undrained shear strength of the SMS with various water contents was calculated using Eq. (1). The cone factor mainly depends on the cone angle, while the cone roughness, the rate of shear, and the water content of the soil have a minor effect. A standard cone (mass of 80 g, tip angle of 30°) was used for this study. A cone factor of K = 0.867 was determined based on a c_u of 1.7 kPa at the *LL* (Sharma and Bora Padma 2003, Vardanega and Haigh 2014).

Additionally, based on the log-log relation between water content and penetration depth, Kuomoto and Houlsby (2001) suggested the correlation between undrained shear strength and water as (Koumoto and Houlsby 2001)

$$c_u = \left(\frac{a}{w}\right)^{1/b} \tag{2}$$

where w is the water content, and a and b are coefficients related to clay types. The parametric study of the obtained fall cone shear strengths of XG-treated SMS was conducted.

2.2.4 Laboratory vane shear test

Laboratory vane shear strength of the soft marine clay with in-situ water content (100%) was measured using the laboratory vane shear equipment (ASTM 2007). The objective of the laboratory vane shear test was to evaluate the applicability of XG for stabilization of soft marine clay with high in-situ water content.

Vane shear tests were performed to measure the undrained shear strength of cohesive fine soils at shallow depths (Brunori, Penzo *et al.* 1989). For this study, a rectangular vane blade with a length of 12.7 mm and a width of 12.7 mm was used. The vane was pushed 30 mm into the soil, and the undrained shear strength was measured by rotating the blade at a rate of 1 degree per second using a spring suitable for clay (k = 1.862 N·mm / degrees). The vane shear strength was determined vane blade ceased to resist the rotation force.

2.2.5 PZT Bender element sensor embedded consolidation test

Laboratory consolidation experiments were performed on the XG-treated soil specimens. During the consolidation procedure, the shear wave velocity was measured to evaluate variations in their shear stiffness.

An oedometric cell made of acrylic tubes (7.45 cm in diameter and 7.1 cm in height) with bender element sensors embedded is illustrated in Fig. 2. Bender element type piezoelectric transducer (PZT) sensors were set at both the bottom and top plates to measure the shear wave velocity of soil. The bottom sensors were connected to a signal generator (Agilent 33120 A), and a single-step square signal was generated with an amplitude of 5 volts at a frequency of 8 kHz. A digital oscilloscope (Keysight DSO 6104A) displayed the input and output signals.

The initial water content of the SMS samples was set to

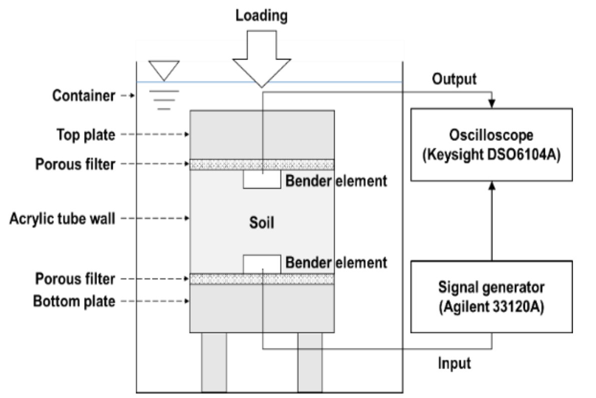


Fig. 2 Schematic diagram of the bender element sensor embedded consolidation test device (Chang and Cho 2010)

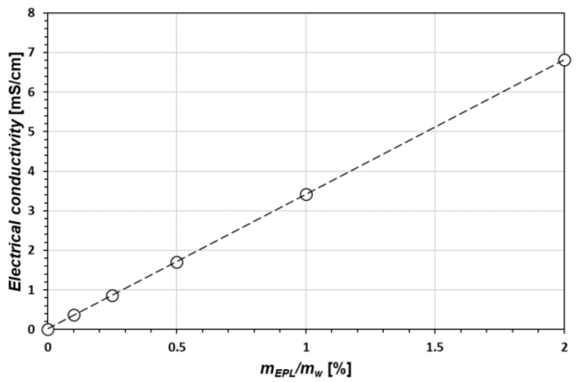


Fig. 3 The electrical conductivity of ε-polylysine solutions

56%, close to the *LL* of the SMS. Consolidation was measured at four vertical loading steps (10 kPa, 50 kPa, 100 kPa, 200 kPa, and 400 kPa) with both upward and downward drainage allowed. For every step, the specimen height was measured with a dial gauge until the settlement becomes less than 0.01 mm/day. After all loadings, unloading (400 kPa to 200 kPa) was performed to evaluate structural rebound. During the step-by-step loading processes, the travel time of the shear wave between the two bender elements was measured simultaneously.

2.2.6 Laboratory sedimentation test

Laboratory sedimentation tests of SMS suspensions were performed to assess the coagulation efficiency of a cationic EPL. EPL solutions were prepared by mixing the EPL with deionized water (DI). The DI used had an electrical conductivity of 5.2 μS/cm and a pH of 6.5 at room temperature. The cationic charge of the EPL increased the electrical conductivity of the pore fluid, as shown in Fig. 3. During the experiments, the temperature and relative humidity were controlled at 22°C and 30%, respectively. As the amount of soil, fluid mass, pH, and temperature of the suspension were controlled to be the same, it can be assumed that the EPL to water ratio in mass (m_{EPL}/m_w) dominantly affected the sedimentation behavior.

ε-Polylysine concentrations were determined as m_{EPL}/m_w = 0, 0.1, 0.25, 0.5, 1, and 2% to ensure that the amount of EPL in the unit volume was consistent with other experiments. A cylinder was capped with a paraffin film. 4 g of the SMS was mixed with 20 mL of the EPL solutions by a magnetic stirrer. Then, 80 mL of the EPL solutions were added to the cylinder corresponding to the initial void ratio of 68.56. High water content (2500%) is required to form uniform clay colloidal suspension (Kolaian and Low 2013) and to evaluate the effect of the Coulombic attraction force between the clay and the EPL, rather than gravimetric forces (Imai 1980). An acrylic cylinder with an inner diameter of 2.65 cm was selected to avoid the settling due to the wall effect (Michaels and Bolger 1962).

Soft marine soil samples were thoroughly mixed with the EPL solutions until a uniform appearance was observed, they were then allowed to hydrate for 24 h (Palomino and Santamarina 2005). The hydrated SMS solutions were remixed by inverting the cylinder upside down at least 20 times (Dollimore and Horridge 1973, Kwon, Im *et al.* 2017). After the last inversion, acrylic cylinders were placed on the level surface; this instant was considered as time zero. The sediment height was recorded until the sediment height remains constant.

2.2.7 Unconfined compression test

Unconfined compressive strengths were measured to compare the strengthening effect of both XG and EPL treatment. Cubic (40 × 40 × 40 mm^3) specimens (initial water content = 60%) were prepared with untreated, 1% XG-treated, and 1% EPL-treated SMS. The mixtures were set into a mold and dried in an oven at 30 °C for 48 h and 168 h. Unconfined uniaxial compression tests were performed in a dry condition using a master loader (Humboldt Mgf. Co., HM-5030.3F) device. The axial strain rate was controlled at 0.5 mm/min (i.e., 1% strain / min). The maximum strength and the stress-strain behaviors were obtained by averaging three different measurements for a single condition. Experiments were conducted at room temperature (22°C) and at a relative humidity of 30%.

3. Results and observations

3.1 Atterberg limits of XG-treated soft marine soils

The results for the fall cone test, thread rolling experiment, and classification results of the xanthan-treated SMS samples are summarized in Table 1. *LL* and *PI* tend to increase with the XG-to-soil mass content.

The *LL* increased steadily according to the XG content, and the maximum *LL* was observed with 2% of the XG content (75.3%). *LL* and m_{XG}/m_s (XG to soil content in mass) can be correlated as Eq. (3)

$$LL_{XG} = 10.7 \cdot m_{XG} / m_s + LL_s \quad (3)$$

where LL_{XG} is the liquid limit of XG-treated SMS, and LL_s is the liquid limit of a natural SMS.

A linear increase of the liquid limit with XG content is mainly due to the formation of the viscous hydrogel in the soil pore space (Chang and Cho 2014) and the direct electrical interaction between XG and clay particles (Nugent, Zhang *et al.* 2009). *PL* shows a slight decrease with low XG content (smaller *PL* of 0.1% XG-treated SMS

Table 1 Properties of xanthan gum treated soft marine soil

m_{XG}/m_s [%]	LL [%]	PL [%]	PI [%]	USCS
0.0	56.0	29.4	26.6	CH
0.5	62.7	27.3	35.4	CH
1.0	70.0	30.4	39.7	CH
2.0	75.3	33.0	42.3	CH

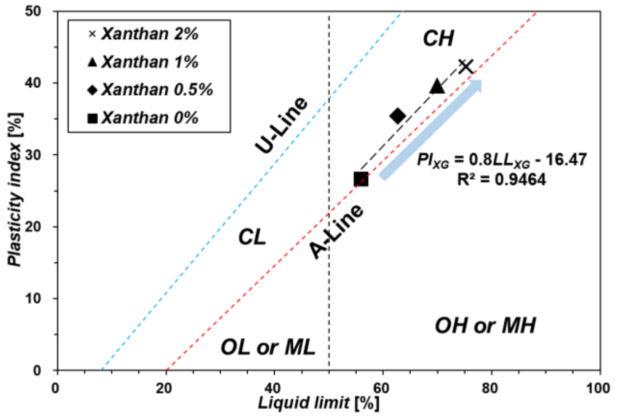


Fig. 4 Plasticity chart of xanthan gum treated soft marine soil

than untreated marine soil) and increases with higher XG content. However, the effect of XG on PL (increase up to 4%) is less than that on the liquid limit (increase up to 19%). Because the effect of XG on LL is dominant, PI also steadily increased with XG content.

Based on the obtained LL and PI, classification of the XG-treated SMS based on the unified soils classification system (USCS) was performed (Fig. 4). The linear relationship between PI and LL of XG-treated soils is expressed as

$$PI_{XG} = 0.8 \cdot LL_{XG} - 16.5 \quad (4)$$

where PI_{XG} is the plasticity index, and LL_{XG} is the liquid limit of XG-treated SMS.

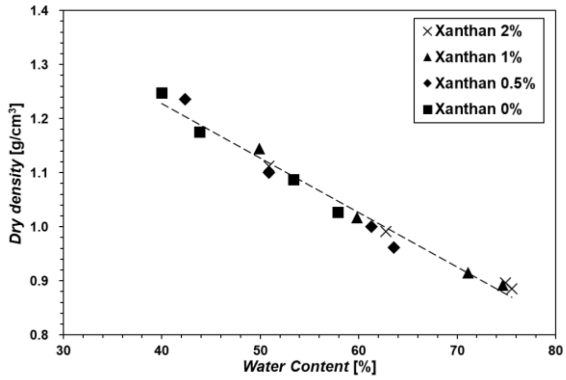
Additionally, the correlation between XG content and PI can be derived by substituting Eqs. (3)-(4) in Eq. (5) as

$$PI_{XG} = 8.56 \cdot m_{XG} / m_s + 28.3 \quad (5)$$

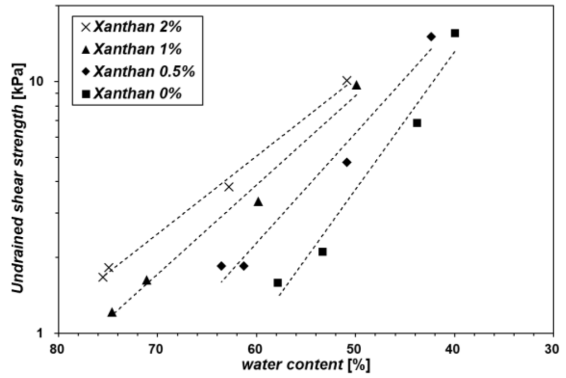
3.2 Fall cone undrained shear strength

The results for dry density and undrained shear strength of the XG-treated SMSs with various water contents are shown in Fig. 5. The dry density of the tested samples showed similar trends regardless of the XG content (Fig. 5(a)). The fall cone undrained shear strength increased with a decrease in the water content (Fig. 5(b)). Although the effect of XG on the dry density of soil was not significant below a content of 2%, the XG treatment showed an increase in the fall cone shear strength of the soil with the same water content.

Xanthan gum absorbs pore water and forms a viscous hydrogel (García, Alfaro *et al.* 2011). XG hydrogel in pore spaces increases the shearing resistance (Lee, Chang *et al.*



(a) Dry density of test samples



(b) Undrained shear strength

Fig. 5 Fall cone results of xanthan gum treated soft marine soils

Table 2 Coefficients for Eq. (2)

m_{XG}/m_s [%]	a [%]	b	R^2
0.0	61.05	0.16	0.983
0.5	69.56	0.186	0.988
1.0	77.44	0.197	0.994
2.0	85.05	0.223	0.999

2017). Additionally, direct interaction (e.g., hydrogen bonding) between XG and electrically charged soil particles can enhance the shear strength of soils (Chang, Im *et al.* 2015). Through these mechanisms, undrained shear strength increases with the increase in XG content.

Table 2 presents the increase in coefficients a and b by XG treatment. Coefficients a and b depend on the net inter-particle force (Dolinar and Trauner 2007), and the amount of the adsorbed water on soil surfaces (Trauner, Dolinar *et al.* 2005). Thus, it can be concluded that XG treatment enhances the inter-particle attraction force by forming direct bonding and increases the number of water molecules that can be adsorbed on XG-soil surfaces.

3.3 Laboratory vane shear strength at an in-situ water content

The change in the undrained shear strength of the SMS with a water content of 100% (in-situ water content) is summarized in Fig. 6. The undrained shear strength results under 2% XG content were too low to measure with the

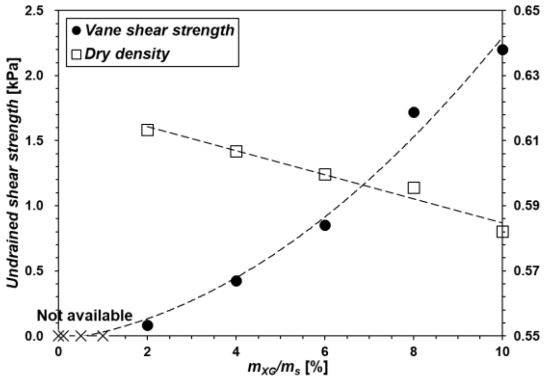
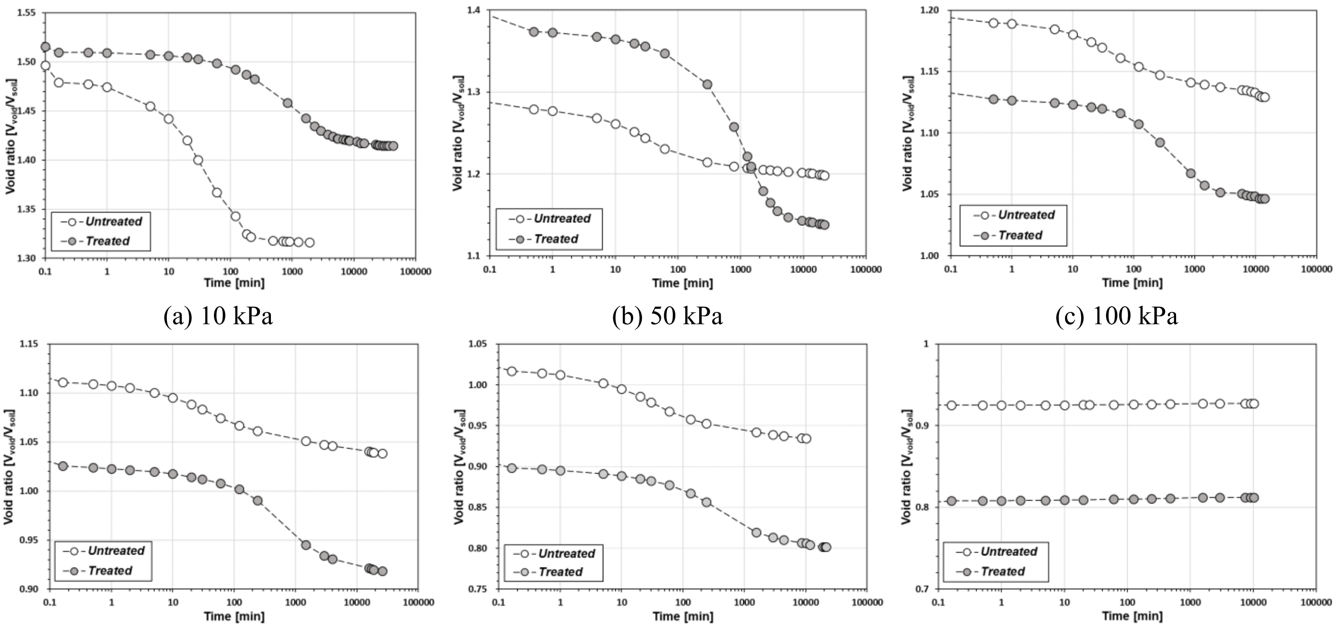


Fig. 6 Effect of xanthan gum on laboratory vane shear strength of soft marine soils



(a) 10 kPa (b) 50 kPa (c) 100 kPa

(d) 200 kPa (e) 400 kPa (f) 200 kPa (Unloading)

Fig. 7 Consolidation behaviors of untreated and 0.5% xanthan gum treated soft marine soil under different vertical confinements

vane blade used. Over 2% of XG, vane shear strength increased with the increase of XG content. Untreated in-situ SMS (water content of 100%) was in liquid state (water content higher than *LL*). Therefore, soils without XG treatment have almost no resistance to blade rotation, and vane shear strength was not measured. With the XG treatment, XG absorbs free pore water in void spaces and increases pore fluid viscosity. Thus, the soil state changes to a plastic state (water content under *LL*). Previous research also mentioned that undrained shear strength at the liquid limit (limit water content of plastic and liquid soil state) were in the range of 0.8 to 2.4 kPa (Norman 1958, Youssef 1965, Skempton and Northey 2008). Thus, it can be said that XG hydrogel transforms soil from a liquid to a plastic state over 8% XG content.

3.4 Consolidation behavior

The variation of sediment void ratio with consolidation time for untreated soil and 0.5% XG-treated soil are presented in Fig. 7 and the corresponding consolidation parameters obtained based on the ASTM standard are summarized in Table 3 (ASTM 2011).

Table 3 Consolidation parameters of soft marine soil

Soil	Load [kPa]	t_{50} [min]	t_{90} [min]	H_{dr} [mm]	m_v [Pa^{-1}]	C_v [mm^2/min]		k [10^{-6}cm/sec]	
						Log t	√t	Log t	√t
Untreated	10	27	106	30.35	0.38	6.61	7.39	2.94	3.29
	50	28	90.25	28.35	0.40	5.60	7.55	2.61	3.51
	100	33	110	27.36	0.42	4.41	5.78	2.12	2.78
	200	28	93	26.32	0.43	4.82	6.33	2.42	3.18
	400	20	84	25.06	0.46	6.05	6.35	3.22	3.37
Treated (0.5%)	10	667	3233	30.35	0.55	0.27	0.24	0.17	0.15
	50	700	3243	27.88	0.62	0.22	0.20	0.16	0.14
	100	370	1790	25.80	0.65	0.35	0.32	0.26	0.24
	200	280	1809	24.51	0.69	0.42	0.28	0.34	0.22
	400	350	1296	22.81	0.73	0.29	0.34	0.25	0.29

Soft marine soil with low vertical stress (shallow depth),

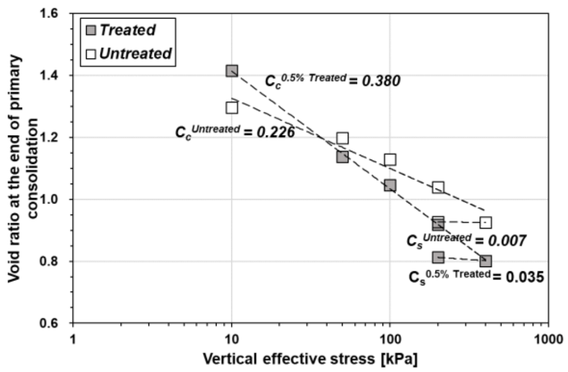
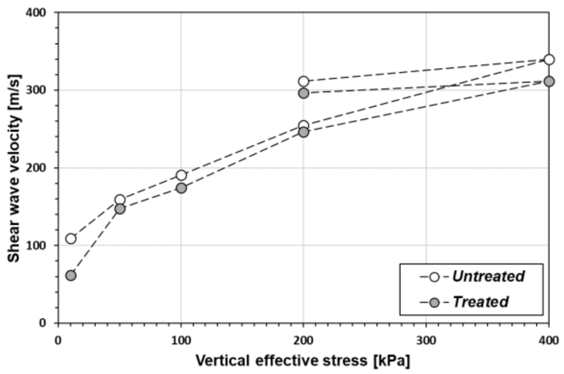
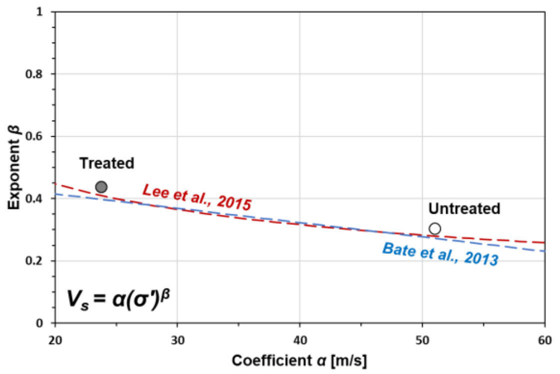


Fig. 8 Void ratio variation with vertical effect stress



(a) Shear wave velocity



(b) Shear wave parameters

Fig. 9 Shear wave velocity and parameters of soft marine soils

XG-treated SMS had less reduction in void ratio than that of untreated soil. However, with vertical stress increase, XG-treated specimens showed a more significant decrease in void ratio than untreated soil.

For all vertical loading conditions, XG delayed the consolidation behavior. The actual time corresponding to the degree of consolidation (t_{50}, t_{90}) increased with XG treatment. Thus, XG treatment significantly reduced the coefficient of consolidation (C_v) and the permeability coefficient ($k = c_v \cdot m_v \cdot \gamma_w$), regardless of the confining pressure (Table 3). This result implies that XG treatment has a potential for permeability control of soils (Chang and Cho 2014).

Final void ratio variation with vertical stress is displayed in Fig. 8. The XG treatment increased the compressibility (C_c) of marine clay from 0.226 (untreated soil) to 0.38 (0.5% XG content in soil mass). The void ratio of the XG-treated SMS (from 0.802 to 0.812) was five times larger than that of the untreated SMS (from 0.925 to 0.927) when the vertical loading decreased from 200 kPa to 100 kPa. Previous research also pointed out that the addition of organic material in soil increases soil compressibility and swelling index (Angers 1990, Cabalar, Wiszniewski *et al.* 2017, Cabalar, Awraheem *et al.* 2018).

Final shear wave velocity with vertical stress is plotted in Fig. 9(a). XG treatment slightly decreased the shear wave velocity compared to the untreated SMS with a similar vertical effective stress, which is possibly due to wave propagation through the hydrogel media or air bubbles retained in the XG solution (Greenwood and Bamberger 2002). Previous research (Santamarina, Klein *et al.* 2001, Chang and Cho 2010) mentioned that shear wave velocity and vertical effective stress could be correlated with a power function as in Eq. (10)

$$V_s = \alpha \left(\frac{\sigma'}{1\,\text{kPa}} \right)^{\beta} \tag{10}$$

where α (m/s) is the shear wave velocity at the effective stress of 1 kPa, and β is the sensitivity of the skeletal shear stiffness to the applied stress.

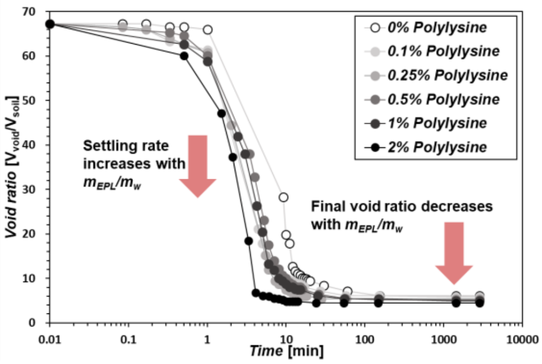
The α and β values obtained are shown in Fig. 9(b) with the previously suggested correlation between α and β (Bate, Choo *et al.* 2013, Lee, Seo *et al.* 2015, Ku, Subramanian *et al.* 2017). Presence of XG biopolymer shows a decrease in the α factor and increase in the β exponent, according to the plasticity (Fig. 4) and compressibility (Fig. 8) increments of SMS with XG treatment (Santamarina, Klein *et al.* 2001, Cha, Santamarina *et al.* 2014).

3.5 Sedimentation effect of ε-polylysine

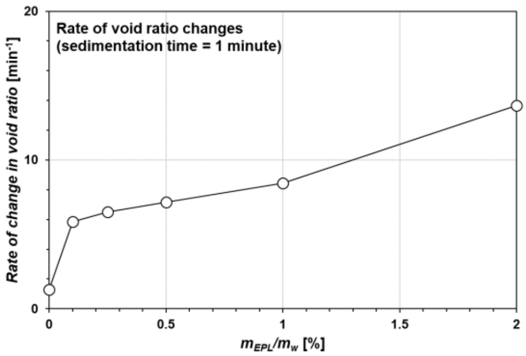
Sedimentation trends of EPL-treated SMSs are plotted in Fig. 10(a). EPL treatment accelerated the sedimentation process. Sediment void ratio became constant after 24 minutes in case of the 2% EPL-treated soil, while it took 1440 minutes for untreated soil.

Variation of void ratio during the initial 1 minute of sedimentation is shown in Fig. 10(b). The rate of void ratio change is defined as the amount of void ratio reduction during the initial state (1 minute) of the settlement curve. It indicates the time required for the soil particles to interact with each other and how suspension structures are ordered (Palomino and Santamarina 2005). Additionally, floc size affects settling velocity (Wang and Siu 2006). Therefore, an increase in the rate of the void ratio at an initial stage indicates that EPL accelerates the interaction between the soil particles and aids the formation of larger flocs. The final void ratio was observed after 48 h (Fig. 10(c)). Final sediment void ratio tends to decrease with EPL concentration (m_{EPL}/m_w). It indicates that EPL treatment changed the arrangement of soil particles more densely.

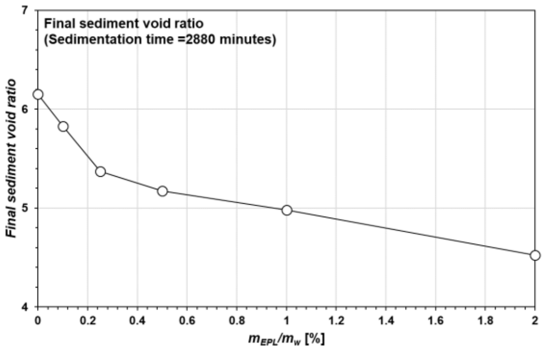
ε-Polylysine flocculates SMS particles, which enlarges the floc size (Voordouw 2013, Kwon, Im *et al.* 2017). The positively charged hydrophilic amino groups of EPL directly interact with charged soil particles, enabling



(a) Sedimentation curves by time



(b) Initial settling rate



(c) Final sediment void ratio

Fig. 10 Sedimentation behaviors of ε-polylysine treated soft marine soil suspensions

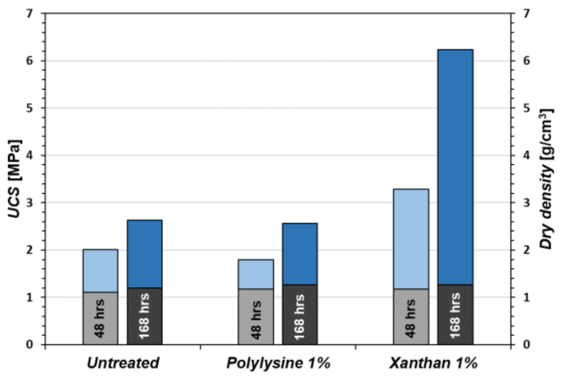


Fig. 11 Unconfined uniaxial compression strength variation by curing time and biopolymer types

bridges between the particles to be built, which increases the sedimentation velocity (Petzold, Mende *et al.* 2003). The flocculation induced by EPL results in a dense final sediment (Fig. 10(c)) because EPL prevents soil segregation and fills the pores between coarse-grained flocs with fine-grained flocs (He, Chu *et al.* 2017).

3.6 Unconfined compressive strength of XG and EPL treated SMS

The effect of XG and EPL on uniaxial compression strength for SMS is shown in Fig. 11. The compressive strength after 7 days of drying was larger than that after 48 h of drying, regardless of the biopolymer type, because of the remaining moisture. The water contents after 48 hours of drying were measured to be 4.7%, 13.42%, and 9.89% for the untreated, XG-treated, and EPL-treated SMS samples, while those after 7 days of drying were 0.7%, 2.58%, 2.74%, respectively. XG-treated soils exhibited significant increase in compressive strength. XG-treated marine clay showed 1.6 times (48 hours) and 2.4 times (7 days) higher compressive strengths than that of the untreated SMS. XG enhanced the compressive strength of soils by direct interparticle bonding between charged soil particles (Nugent, Zhang *et al.* 2009, Chang, Kwon *et al.* 2018) and by soil surface coating (Chang, Im *et al.* 2015). Meanwhile, EPL treatment slightly decreased the compressive strength of soils. Thus, it can be concluded that XG treatment is suitable for soil strengthening (undrained shear strength, and compressive strength in dry condition), while the EPL is suitable for settling soil suspensions. Previous studies also support that the application of cationic polymers stimulates sedimentation (Ibanez, Chassagne *et al.* 2015, He, Chu *et al.* 2017, Kwon, Im *et al.* 2017).

4. Discussions: Geotechnical behavior of biopolymer treated soft marine soil

4.1 Effect of biopolymers on geotechnical properties of marine soil

Xanthan gum biopolymer affects the geotechnical properties of soil by transforming the pore fluid into a viscous hydrogel (Barrére, Barber *et al.* 1986, Lee, Chang *et al.* 2017) and by electrical interaction with charged soil particles (e.g., hydrogen bonding) (Chang, Im *et al.* 2015). Through these properties, XG increases the double layer thickness (the amount of water that soil media can absorb), which is related to the Atterberg limits of soil. Thus, the presence of the XG biopolymer increases the *LL* and *PI*, with an exception for the dip at 0.5% of the m_{XG}/m_s (Table 1). Results also match with previous research (Nugent, Zhang *et al.* 2009).

Electrical interaction and hydrogel formation effect of XG also increases fall cone shear strength with various water contents (Fig. 5) and vane shear strength with in-situ high water content (Fig. 6). At low water content (less than *LL*) and low XG content (under 2% XG content), XG seems to form bridges between soil particles via hydrogen bonding mainly, thus fall cone shear strength increases with XG content without significant density variation (Fig. 5). However, with high water content (100% water content for this study) and high XG content (over 2% XG content), XG enhances the viscosity of the SMS by forming a hydrogel, which increases the undrained shear strength (Locat and Demers 1988). In this case, XG binds water molecules and expands pore spaces. Thus, dry density of soils used for laboratory vane shear strength tends to decrease with XG content. This finding corresponds to previous research (Chang and Cho 2014). Additionally, XG treatment shows an increase in the compressive strength of marine clay in a dry condition (Fig. 11). Because soil skeletal structure governs the compressive strength of soil, the increase of compressive strength indicates that XG transforms soil structure, thereby increasing its resistance to vertical stress.

However, xanthan gum treatment has limitations regarding consolidation reduction in SMS. XG treatment (0.5% XG content in this study) decreases the coefficient of consolidation (C_v) related to hydraulic conductivity (Fig. 7 and Table 3) because the XG hydrogel occupies pore spaces. Additionally, XG biopolymer increases compressibility (C_c) (Fig. 8). Increase in C_c seems to be caused by the hydrophilic characteristics of the XG biopolymer (Angers 1990, Chang and Cho 2014). The XG hydrogel reduces the shear wave velocity at a constant effective stress, which accompanies a decrease in the shear wave velocity parameter α and an increase in β (Fig. 9). A lower α and higher β are also characteristics of more-compressible soil (i.e., higher plasticity, lower coordination number) (Chang and Cho 2010, Cha, Santamarina *et al.* 2014).

ε-Polylysine has the potential to become a coagulation material for marine clay suspension. Cationic charges of the EPL interact with the negatively charged clay surface. EPL chains connect clay particles and enlarge aggregate size (Petzold, Mende *et al.* 2003). Therefore, EPL has a potential for sedimentation purposes (Fig. 10). However, EPL seemingly does not affect compressive strength of SMS (Fig. 11).

4.2 Possible implementations of XG and EPL in geotechnical engineering practices

This study assessed the geotechnical engineering behavior of SMS treated with the microbial biopolymers, XG and EPL. The experimental results indicate that the XG biopolymer has excellent potential for strengthening purposes (compressive strength in a dry condition, and undrained shear strength in a wet condition), while it increases the compressibility and delays the consolidation process. Therefore, deep consideration about target depth and main reinforcement purpose is necessary to apply XG in the real field. XG application is recommended for shallow depth stabilization (e.g., slope surface, soil pavement, and surface erosion control). Meanwhile, additional drainage techniques (e.g., sand drain, pack drain, plastic board drain) should be considered to apply XG to the strengthening of soils at great depths (effective stress > 10 kPa for this study). Besides, XG can be utilized as a hydraulic barrier to control migration of contaminants in landfills.

ε-Polylysine biopolymer has potential to coagulate clay particles in remarkably higher water content (e.g., soil suspension). Therefore, EPL can be applied to soil washing, wastewater treatment, land reclamation, and tailings management. However, EPL has little effect on strength, thereby requiring the use of additional additives such as XG.

5. Conclusions

This study aims to explore the impact of xanthan gum, an anionic biopolymer, and ε-polylysine, a cationic biopolymer, on the geotechnical behavior of the Korean marine soils. Xanthan gum shows its potential as a soil-strengthening material. It affects the geotechnical properties of soft marine soil by enhancing the viscosity (García-Ochoa, Santos *et al.* 2000) and by bonding the soil particles (Nugent, Zhang *et al.* 2009, Chang, Im *et al.* 2015). Due to xanthan gum behaviors, the xanthan gum-treated marine soil showed an increase in the Atterberg limits (*LL* and *PI*), shear strength at constant water content (fall cone shear strength, and laboratory vane shear strength), and unconfined compressive strength in a dry state. However, the results of the consolidation experiment and *LL* measurement show that xanthan gum treatment increases the compressibility (C_c) and decreases the shear wave velocity and coefficient of consolidation (C_v), attributed to the decrease of soil hydraulic conductivity. Therefore, the application of the xanthan gum biopolymer is most effective at shallow depths, while additional drainage methods are required for deep depth applications to reduce the xanthan gum-induced delay of consolidation. The ε-polylysine biopolymer shows its potential as a soil-coagulating material. ε-Polylysine mainly affects the settling behavior of marine soil suspensions. Due to its cationic properties, ε-polylysine coagulates soil particles by forming bridges between them. Thus, it increases floc size and accelerates settling velocity, aligning soil in a dense structure.

The experimental results show that biopolymers can improve the geotechnical properties of soft marine soils, such as their undrained shear strength, compressive strength (in a dry state), and settling behavior. However, consideration of the consolidation behavior is necessary because biopolymers delay consolidation and increase compressibility.

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