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Geotechnical behavior of a beta-1,3/1,6-glucan biopolymer-treated residual soil

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Abstract. Biopolymers, polymers produced by living organisms, are used in various fields (e.g., medical, food, cosmetic, medicine) due to their beneficial properties. Recently, biopolymers have been used for control of soil erosion, stabilization of aggregate, and to enhance drilling. However, the inter-particle behavior of such polymers on soil behavior are poorly understood. In this study, an artificial biopolymer (β-1,3/1,6-glucan) was used as an engineered soil additive for Korean residual soil (i.e., *hwangtoh*). The geotechnical behavior of the Korean residual soil, after treatment with β-1,3/1,6-glucan, were measured through a series of laboratory approaches and then analyzed. As the biopolymer content in soil increased, so did its compactibility, Atterberg limits, plasticity index, swelling index, and shear modulus. However, the treatment had no effect on the compressional stiffness of the residual soil, and the polymer induced bio-clogging of the soil's pore spaces while resulting in a decrease in hydraulic conductivity.

Keywords: beta-1,3/1,6-glucan; biopolymer; Korean residual soil; geotechnical behavior; elastic wave

1. Introduction

Soil is a natural material consisting of multiple phases that differ from the morphological, physical, chemical, and mineralogical characteristics of their parent minerals. Moreover, soil is a mixture of inorganic minerals and organic constituents that exist in solid, aqueous, and gaseous states (Paul 2007). Geotechnical engineering focuses mainly on the physical and mechanical behaviors of soil, whereas geochemical and biological influences are considered as minor concerns. Nowadays, unusual geotechnical phenomena (e.g., quick clay, underground waste/pollutant remediation, bio-fouling) have raised the necessity for, and importance of, more holistic consideration of the chemical and biological factors affecting geotechnical engineering (Mitchell and Santamarina 2005, Soga and Jefferis 2008). Organic compounds in the soil has been reported to increase the inter-particle binding forces and incremental cohesion (DeJong *et al*. 2010, Piccolo and Mbagwu 1999) and the elastic modulus of soil (Nason 1987), according to the reinforcement by biological fibers (Soane 1990) and variation of electrical charge in pore fluids (Brown and

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Thomas 1987).

The aforementioned behavior of soils generally appears by a sequence of microscopic processes (i.e., (1) inoculation and attachment of microbes; (2) bacterial growth and accumulation of biomass; (3) biofilm formation on soil mineral surfaces; (4) synthesis of by-products such as biopolymers or excrement; and (5) interaction between soil particles and bio-products) (Baveye *et al*. 1992). However, the growth, multiplication, accumulation, and biopolymer synthesis processes of soil microbes are irregular (in time, quantity, and quality) and sensitive to environmental conditions (e.g., temperature, moisture content, nutrients, gaseous concentrations, pore sizes) (Mitchell and Santamarina 2005). Thus, direct application of biopolymers can become an alternative approach for consistent quality control and ensured reliability of soils, regardless of environmental conditions and time.

Biopolymers are hydrocarbon-polymers produced by a wide variety of living organisms, including plants and microorganisms that vary considerably in chemical composition, the majority of which have not been thoroughly characterized. The most common applications of biopolymers are for medical and food purposes (Van de Velde and Kiekens 2002). Meanwhile, in the field of civil construction, exopolysaccharides (e.g., welan gum and curdlan) have been used as water-retention agents or super-plasticizers in concrete or dry-mix mortar according to their water adsorption or pseudo-plasticity characteristic (Khayat and Yahia 1997).

For geotechnical engineering purposes, biopolymers have been used as soil-stabilizing additives to control or reduce the soil erosion of farmlands (Orts *et al*. 2007). Generally, the presence of biopolymers affects the adsorption behavior between pore fluids and solids in soil (Sposito 1989). However, detailed understanding of the interactions between soils and biopolymers is still far from clear. Thus, in this study, geotechnical behaviors of a commercially refined biopolymer (i.e., beta-1,3/1,6-glucan) treated residual soil are explored through various laboratory approaches.

Beta-glucans are biopolymers of D-glucose ($C_6H_{12}O_6$) monomers linked by β-glycosidic bonds and have various structural formations (Bacic *et al*. 2009). In particular, β-1,3/1,6-glucan shows ramiform and helical forms that induce high levels of binding with external ions or molecules via hydrogen bonding (Ooi and Liu 2000).

In geotechnical applications, beta-glucans are applied as superplasticizers and water reducing agents in concrete mixing (Nagai *et al*. 1999). Regarding geotechnical activities, beta-glucans are promising as engineered soil agents, due to their high tensile strength (i.e., 20-80 MPa) and helix adsorption characteristics (Park *et al*. 1993, Skendi *et al*. 2003). Moreover, beta-glucans are food grade and harmless biopolymers endorsed by the US FDA (GRAS notice 000309). However, to date, no detailed understanding of this biopolymer exists in the field of geotechnical engineering.

2. Materials

2.1 Korean residual soil (*KRS*)

Korean residual soil (i.e., hwangtoh, KRS) is a common soil material in Korea. On the Korean peninsula, the surface residual soil (in most cases KRS) consists of granite-originated minerals such as kaolinite ($Al_2Si_2O_5(OH)_4$) and halloysite ($Al_2Si_2O_5(OH)_4 \cdot 2H_2O$), both of which have a 1:1 layer structure of Si-tetrahedral sheet and Al-octahedral sheet (Yang *et al*. 2007).

The KRS used in this study is from Ha-dong, Korea, which is well known producer of commercialized KRS. The mineral composition by mass, as determined by XRD (X-Ray

Table 1 Geotechnical index of Korean residual soil

Specific gravity [G_s]	Atterberg limits [%]			Friction angle [°]	Particle size distribution [μm]		Specific surface [m^2/g]	USCS*
	LL	*PL*	*PI*		D_{60}	D_{10}		
2.60	53.7	37.4	16.3	25~30	70	5	6.81	MH

* Unified Soil Classification System

Diffraction) analysis, is quartz (8.4%), kaolinite (45.8%), halloysite (22.7%), illite (14.8%), and goethite (8.3%). The natural KRS examined in this study was air-dried at room prior to testing. Basic geotechnical properties of KRS are summarized in Table 1.

2.2 Biopolymer: Beta-1,3/1,6-glucan (BG)

To provide better standardization and practical application, Polycan^{TM} (Glucan Corp., Korea) was used in this study. Polycan^{TM} is a modified (i.e., carboxymethylated by a lactate ion ($CH_3CH(OH)COO^-$)) BG compound produced by a UV-induced mutant of *Aureobasidium pullulans* SM 2001 (Shin *et al*. 2004, 2007). The hydroxyl (OH^-) and carboxyl (COO^-) group on the edges render surface polarization which enhances hydrogen bonding characteristic of β-1,3/1,6-glucan (BG). The Polycan^{TM} product used in this study has a BG content of 8.2 g/L. The BG content of diluted reagents is defined separately according to their dilution ratio using distilled water (e.g., 1:2 = 4.10 g/L,…, 1:100 = 0.08 g/L).

Under the existence of water, the BG as tested has a high capacity for water adsorption via hydrogen bonding and with swelling which renders pore filling and soil volumetric expansion. Besides, the loose of free (i.e., unbounded) and bound water through dehydration increases the inter-particle interaction between soil particles and biopolymers. In this stage, the soil-biopolymer mixture becomes denser due to closer particle attachment and reinforcement.

3. Experimental program

3.1 Compaction test

Soil density is an important parameter controlling the strength and bearing capacity of soil. Dry density represents particle arrangement and plays a significant role in soil strength. Thus, it is necessary to identify the variations in soil density induced by the presence of BG biopolymers.

KRS was mixed thoroughly with different BG solutions (i.e., 0, 4.10, and 8.20 g/L). Following a standardized procedure (British Standards 1990a), five compaction tests were performed each BG solution with different solution quantities, to evaluate the maximum dry density, and optimum water content for each cases. After compaction, each specimen was weighed and oven dried to obtain its density and moisture content.

3.2 Atterberg limit test

Beta-1,3/1,6-glucan is known to be a hydrophilic biopolymer (Lee *et al*. 2003). Thus, KRS treated with BG was expected to have higher liquid limits and plasticity indices, as the biopolymer content in the soil increased. However, the conventional method (ASTM D4318) using a brass cup shows insufficient liquid limit evaluation due to the pseudoplasticity behavior (i.e., shear thinning; immediate closure of the groove due to the dynamic impact of cup dropping) of BG treated soil. Thus, a fall cone method (BS 1377) is accepted to evaluate the liquid and plastic limits of BG treated KRS in this study.

KRS was mixed with different BG solutions having different biopolymer concentrations (i.e., 0.08, 0.33, 0.82, 1.64, 4.10, and 8.20 g/L). For each concentration of BG, the amount of biopolymer solution was controlled to make soil mixtures of varying water content. Samples were taken from the soil mixtures by a ring-shaped sampler to minimize soil disturbance. Then, a cone penetrometer test (British Standards 1990a) was performed to estimate the liquid limit and plastic limit of each BG treated KRS (Feng 2000).

3.3 Piezoelectric sensor embedded consolidation test

Laboratory consolidation tests were performed on the treated soil specimens for three purposes: to characterize their one dimensional stress-strain behavior, to identify their compressibility and swelling behavior, and to evaluate variations in their stiffness.

An oedometeric cell made of acrylic (diameter 7.4 cm, height 7 cm) is illustrated in Fig. 1. The top cap, and bottom plate, host piezoelectric transducer (PZT) sensors. Two different PZT types were applied: plate-type sensors for compressive (*P*-) wave measurement, and bender-element-type sensors for shear (*S*-) wave measurement. In addition, the top cap also enables measurement of vertical loading and strain. Detailed methods for sensor soldering and the housing can be found in (Chang and Cho 2010).

The bottom PZT sensors were connected to a waveform generator (Agilent 33120A) to generate single step signals (*P* wave with 5 Hz frequency and 10 volts amplitude; *S* wave with 5 kHz frequency and 5 volts amplitude). The acquired signals were passed through a multi-channel analog filter (Krohn-Hite 3944) to remove unwanted noise (i.e., band-pass filtering: a high pass

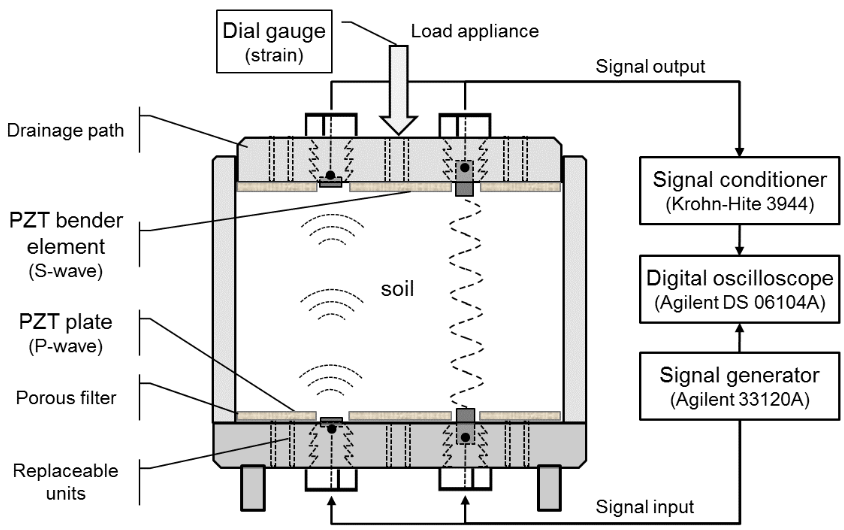


Fig. 1 Schematic diagram of instrumented consolidation testing device

Table 2 Initial conditions for consolidation tests

Solution used [g/L]	Water content [%]	β-1,3/1,6-glucan / soil weight ratio [w/w, %]	Initial volume [m^3]	Initial total weight [g]	Initial total density	Initial void ratio
0	60	0	2.97×10^{-4}	468.7	1.58	1.48
0.82	60	0.05	2.97×10^{-4}	476.9	1.61	1.46
4.10	60	0.25	2.97×10^{-4}	406.1	1.37	1.52

filter of 100 Hz and a low pass filter of 50 kHz). Both input and output signals were displayed on a digital oscilloscope (Agilent DS 06104A); then saved as data for further processing.

KRS was mixed with different solutions of BG (i.e., 0, 0.82, and 4.10 g/L). 500 g of dried soil was thoroughly mixed with 300 g of BG solution using a spatula. The initial moisture content of all mixtures was set as 60% to observe the stress-strain behavior of BG treated KRS in a wide void ratio range. The prepared mixture was then placed into the oedometric cell. All specimens were lightly compacted using a vibrator (600 rpm) during 30 seconds to remove unwanted air bubbles. Each specimen was then saturated with the same BG solution used for specimen preparation to prevent chemical osmosis.

Initial test conditions are summarized in Table 2. It is interesting that the initial mass density of each specimen showed different values. This seems to be a result of the micro-scale interaction between the BG polymer and soil particles.

For the consolidation test, vertical loading was applied step-by-step. As the oedometric mold has an odd geometry (i.e., diameter of 74 mm and height of 70 mm) compared to the ASTM D-2435 recommendation (i.e., diameter to height ratio of 2.5), loading for each new step was applied long enough (i.e., more than 3 days) to observe the convergence of the elastic wave velocity increment, and volumetric strain decrement, induced by the corresponding load. After several loading steps, an unloading process was performed to measure structural rebound. Thereafter, reloading and further loading were performed to recover swelling and to extend virginal compression. Elastic wave velocity and volumetric strain (i.e., height) were also measured throughout the consolidation test.

3.4 SEM images

After completion of the consolidation tests, soil samples were taken from the cell, trimmed (1 cm × 1 cm × 1 cm cubic) and dried in the laboratory. Specimens were coated with gold (20 nm) using a sputter coater (Emitech K550X) to avoid electron scattering, and then observed in a scanning electron microscope (SEM; Philips XL30SFEG).

4. Results and analyses

4.1 Micro-scale characteristics

A typical SEM image of KRS treated with BG (w_b / w_s = 0.05%), is shown in Fig. 2. The fibers of the biopolymer can be observed among the soil particles forming connections, or accumulated in voids to form small bundles or knots of polymer (Fig. 2(a)). Soil particles attached to biopolymer fibers seemed to behave as friction strands, which increased inter-particle friction in the soil

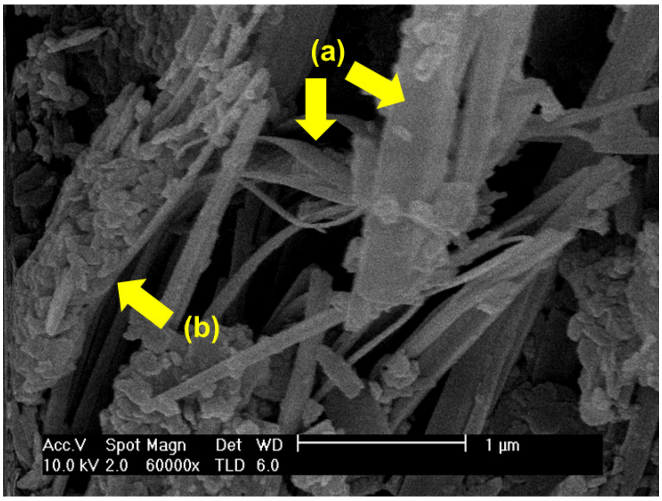


Fig. 2 SEM image of β-1,3/1,6-glucan (BG) treated Korean residual soil (w/w = 0.05%): (a) BG fibers with sparse soil particles attached; (b) Matrix of Korean residual soil particles and BG fibers

(Fig. 2(b)). Such biopolymer bundles and friction strands have been previously shown to improve the unconfined compressive strength more than 300%, compared to that of untreated natural KRS even though biopolymer treated soil shows lower dry densities (Chang and Cho 2012). Based on results from this and previous studies, the effect of the test biopolymer on the geotechnical behavior of the soil can be explained by a sequential process: (1) adsorption and attachment: hydrogen bonding of BG polymers to KRS particles (or vice versa), increasing the zeta-potential of the particle surfaces; and (2) strengthening: interaction of the BG strands with the soil to create reinforcement or connection bridges that induce higher shear resistance.

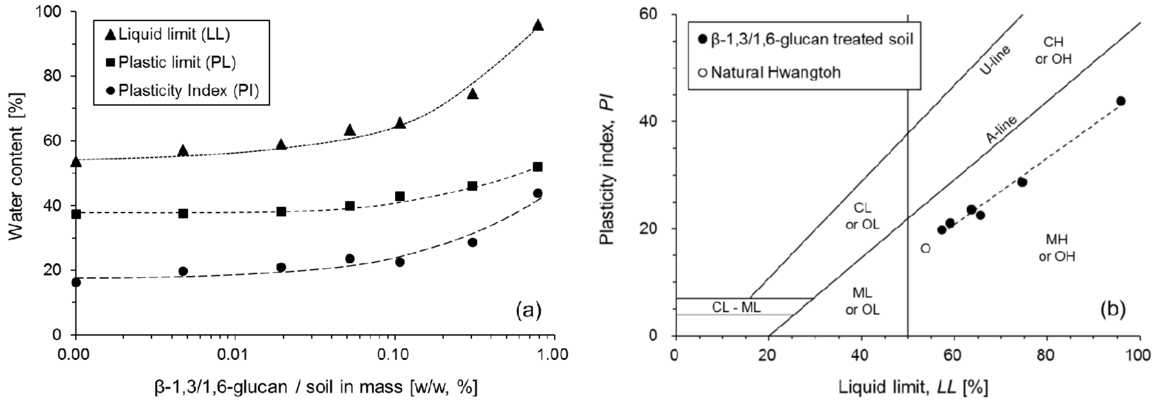
4.2 Maximum dry density and optimal water content

The optimum water content increased slightly from 25% (untreated KRS) to 28.5% (compacted by 8.2 g/L BG solution; w_b / w_s = 0.23%). The increment of optimum water content is expected to be a result of the hydrophilic property of the BG polymer used in this study. The maximum dry density of KRS treated with BG increased from 13.6 to 14.1 kN/m^3 with a parallel increase in BG content (w_b / w_s = from 0 to 0.11% and 0.23%), which is attributed to the enhanced inter-particle attraction (e.g., hydrogen bonding) induced by biopolymer existence with low water content.

4.3 Atterberg limits: LL, PL, and PI

The results for the liquid and plastic limits of the treated soil are shown in Fig. 3(a). Because the Atterberg limits are defined as the mass ratio between pore fluid (w_f) and solid particles (w_s), the BG solution concentration (g/L: w_b / w_f) was also expressed as the weight ratio of BG to soil (w_b / w_s). The liquid limit of natural KRS used in this study is 53.7%. The results indicate that higher glucan content in the soil raises the liquid limit (up to 100% for w_b / w_s = 0.8%). The plastic limit increases slightly from 37.4% to 52% in the same manner.

The liquid limit of KRS treated with BG (LL_β) can be approximated as



(a) (b)

Fig. 3 Atterberg limits of β-1,3/1,6-glucan (BG) treated Korean residual soil: (a) *LL*, *PL*, and *PI*; (b) Plasticity chart

$$LL_{\beta} = LL_{soil} + 49 \cdot C_{\beta} \tag{1}$$

where LL_{soil} is the liquid limit of natural KRS and C_{β} is the BG content in the soil (w_b / w_s [%]). The linear increment of the liquid limit after BG treatment is expected to be a result of the high water adsorption of BG polymers remaining in the soil voids.

KRS that has been treated with BG, is classified as high-plastic silty soil (MH) as shown in Fig. 3(b). The linear trend provides an approximate calculation to determine *PI* of BG treated KRS as

$$PI_{\beta} = 0.62 LL_{\beta} - 17 \tag{2}$$

4.4 Coefficient of consolidation

For each single load, the void ratio of treated KRS mixtures (w_b/w_s = 0.25% and 0.05%) and natural KRS (w_b / w_s = 0%) decreased significantly during the first 100-200 minutes, and converged to a certain value, while the elastic wave velocity values increased continuously at first, but converged after 2000 minutes. The discrepancy between the convergences of the void ratio and wave velocity may indicate the existence of remaining excess pore pressure or particle and/or polymer rearrangement even though the apparent strain deformation appears to be completed. The converged final elastic wave velocity and void ratio values (e.g., final measurements for each load step) are summarized in Table 3.

The measurement of the void ratio over time provides information about t_{50} (time at 50% primary consolidation) and average specimen height ($2H_{dr}$, due to top and bottom drainage) values for each specimen and each loading step. Thus, the coefficient of consolidation (c_v) during each single load can be obtained by

$$c_v = \frac{T_{50} H_{dr}^2}{t_{50}} = \frac{0.197 H_{dr}^2}{t_{50}} \tag{3}$$

Under one-dimensional consolidation, the coefficient of consolidation depends on the initial

Table 3 Consolidation test results of β-1,3/1,6-glucan (BG) treated Korean residual soil

w_b/w_s [%]	Experimental properties		Step of loading/unloading 1st	2nd	3rd	4th	5th	6th	7th
0	Final load [kPa]		0.50	2.49	9.47	18.72	9.47	18.72	41.86
	Elastic wave velocity [m/s]	V_p	123.2	287.0	337.3	463.1	464.3	470.5	519.8
		V_s	59.4	112.9	168.2	215.0	221.2	214.9	267.4
	Void ratio		1.46	1.32	1.15	1.06	1.07	1.06	0.94
0.05	Final load [kPa]		0.49	2.48	9.50	18.93	9.50	18.93	42.06
	Elastic wave velocity [m/s]	V_p	120.0	232.3	320.4	420.5	410.2	425.0	504.5
		V_s	62.6	120.5	192.0	242.3	249.1	255.0	330.0
	Void ratio		1.47	1.34	1.18	1.08	1.09	1.08	0.95
0.25	Final load [kPa]		1.00	9.58	32.80	55.95	32.80	55.95	79.09
	Elastic wave velocity [m/s]	V_p	195.4	399.8	420.3	525.4	518.1	534.4	629.0
		V_s	97.7	217.4	334.5	414.8	415.8	409.5	460.0
	Void ratio		1.41	1.16	1.01	0.92	0.93	0.92	0.87

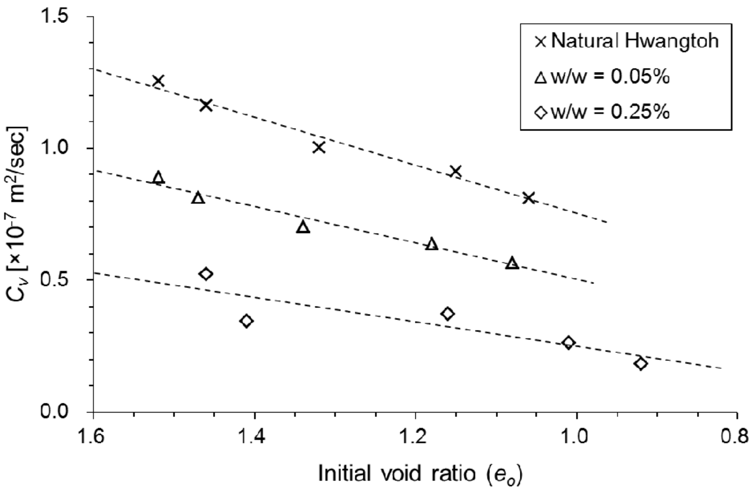


Fig. 4 Coefficient of consolidation (C_v) of beta-1,3/1,6-glucan treated Korean residual soil

void ratio (e_o) before loading. The final void ratio for each load in Table 3 represents the initial void ratio for the next loading step.

The evaluated c_v values are presented with the e_o values in Fig. 4. For a single specimen, c_v decreases as the initial void ratio decreases. Meanwhile, for a same-soil density condition, the c_v diminishes as the BG content increases. Assuming the approximation of c_v to be 0 (i.e., x-intercept by linear expansion) indicates the minimum void ratio ($e_{\min}$), the $e_{\min}$ of natural KRS is estimated to be 0.52, while 0.05% BG treatment increases to 0.57 and 0.25% treatment expands to 0.63. This result implies that BG treatment reduces the hydraulic conductivity of soil by filling the void (pore) fraction in the soil. In other words, BG treatment shows potential for allowing control of soil hydraulic conductivity (e.g., $k = c_v \cdot m_v \cdot \gamma_w$) in relation to geotechnical engineering aspects such as bio-barriers or bio-clogging.

4.5 Compressibility and swelling indices

The final void ratio values of each load step are reconstituted in Fig. 5. The vertical effective stress corresponds to the applied total axial stress at the end of each loading (i.e., after excess pore pressure was dissipated). The compressibility of KRS shows no to low correlation with biogenic materials (e.g., β-1,3/1,6-glucan). Each soil specimen shows a similar compressibility index regardless of the amount of BG ($C_c \approx 0.27$). Thus, the compressibility of soil was not altered by treatment with BG.

The unloading curves in Fig. 5 also show a higher swelling index (C_s) with greater BG content. The swelling became almost twice as high when the BG content increased from 0% to 0.25% (mass ratio).

4.6 Elastic wave velocities

The final shear-wave velocity values of each specimen are plotted versus their corresponding vertical effective stress values, and shown in Fig. 6(a). Shear-wave velocity increased with increases in vertical effective stress for all specimens. Typically, shear-wave velocity can be expressed as a power function of the vertical effective stress (i.e., $V_s = \alpha(\sigma'_v / 1\text{ kPa})^{\beta}$), where α factor depends on soil porosity, coordination number, contact behavior, and fabric. A higher β exponent is generally associated with higher plasticity (Santamarina *et al.* 2001). The curve fitting

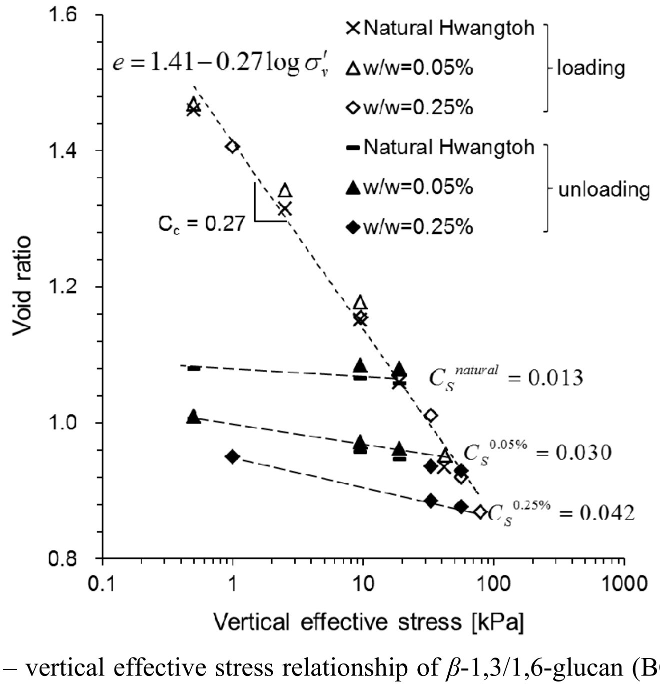
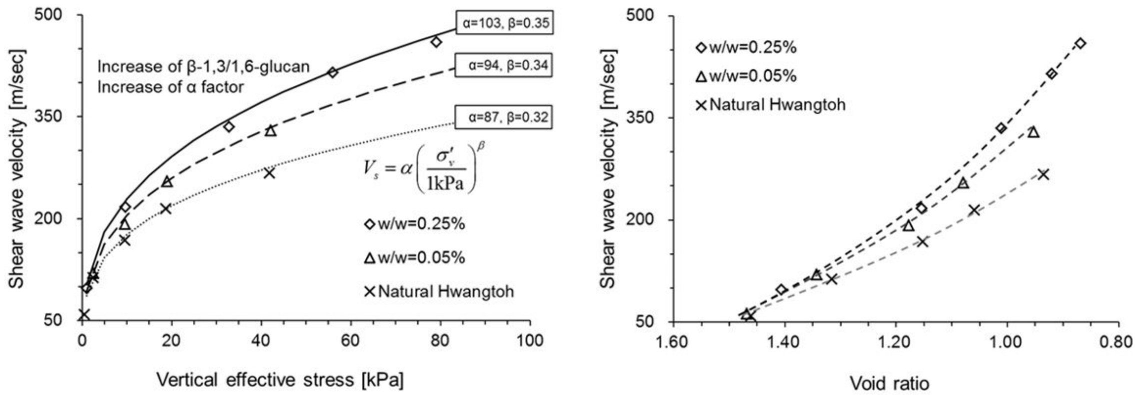


Fig. 5 Void ratio – vertical effective stress relationship of β-1,3/1,6-glucan (BG) treated Korean residual soil

results are also shown in Fig. 6(a). The α factor increased with increases in the BG content. Thus, it can be concluded that the increase of BG content in soil improves the soil fabric and inter-particle contact behavior, as well as the shear modulus. This is in line with previous studies (Hartge and Stewart 1995, Zhang 1994) which reported that the increase of organic matter in soil increases internal particle friction and cohesion.

The shear-wave velocity values are plotted versus void ratio values in Fig. 6(b). Given similar conditions in the void ratio (or density), the shear-wave velocity increased as the BG content in soil increased, and this phenomenon was maximized under high density conditions. Thus, for a unique soil particle composition, the presence of BG biopolymers strengthens soil structure which renders shear modulus (G) increment (e.g., $G = \rho V_s^2$). For practical applications, therefore, biopolymer treatment appears a suitable quick soil treatment for situations such as landslides, deep excavation, and slurry wall problems in the field.



(a) (b)

Fig. 6 Shear wave velocity of β-1,3/1,6-glucan (BG) content treated Korean residual soil: (a) with vertical effective stress; and (b) with void ratio

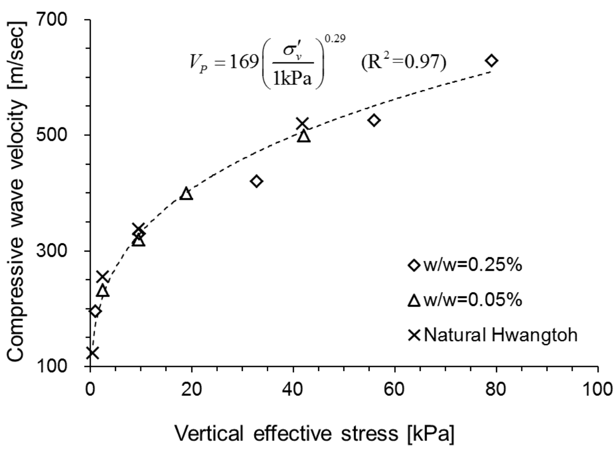


Fig. 7 Compressive wave velocity of β-1,3/1,6-glucan (BG) content treated Korean residual soil with vertical effective stress

In Fig. 7, the compressive wave velocity is plotted with vertical effective stress. It is surprising to observe that the results are unique regardless of the content of the biopolymer. That is, the presence of the experimental biopolymer had no effect on the compressive wave velocity. For example, the compressive strength (~10 kPa) and stiffness (~20 kPa) of BG polymer (Lazaridou *et al*. 2003) are extremely small compared to its tensile properties (~40 MPa in strength and ~2GPa in stiffness) (Park *et al*. 1993, Skendi *et al*. 2003). Thus, as BG fibers in soil scarcely form rigid matrixes such as those found in C-S-H gels (i.e., cement crystals), the existence of BG fibers improve soil shear resistance by acting as reinforcement, while they have minor or no effect on the axial deformation constraint (i.e., $M = \rho V_p^2$).

5. Discussions: Geotechnical behavior of β-1,3/1,6-glucan biopolymer treated KRS

Under wet conditions, the presence of BG biopolymers, which tend to adsorb water, in soil increases the optimum water content and compactibility, and Atterberg limits (Fig. 3) of soil, while decreasing the coefficient of consolidation (i.e., hydraulic conductivity; Fig. 4) due to a clogging effect induced by BG biopolymers. Regarding physical aspects, treatment with BG is less relevant to soil compressibility (Fig. 5) and axial constraint modulus (e.g., compressive wave velocity; Fig. 7). However, treatment with the biopolymer shows great influence on the swelling (Fig. 5) and shear resistance (Fig. 6).

When the ratio of biopolymer weight (w_b) to soil weight (w_s) was low ($w_b / w_s < 0.25\%$), biopolymer strands interacted directly with soil particles by hydrogen bonding, inducing a slight increase of the macro-scale soil density. Meanwhile, when the content is higher ($w_b / w_s > 0.25\%$), some of the biopolymer fiber formed helices of gels in the soil voids. In these voids, the biopolymer helix was able to adsorb numerous water molecules (i.e., bound water) rendering pore volume expansion. This explanation corresponds to the swelling behavior of organic clays (Nugent *et al*. 2009). Organic soils with high organic matter content (e.g., 10-80% in organic matter/soil mass) are generally known to be associated with a decreased soil dry density (Coutinho and Lacerda 1987, Soane 1990). However, small quantities of bio-materials fully interact with soil particles, creating an interconnected network involving the soil particles (Nugent *et al*. 2009).

The Atterberg limits of soil depend strongly on the specific surface conditions of soil particles. The hydrogen bonds, ion exchange, and van der Waals force between organic matter and soil particles affect the double-layer, rendering different responses on the liquid limit behavior. Thus, biopolymers are generally known to increase the plasticity of soil (Nugent *et al*. 2009).

Higher liquid limits and plasticity indices of soil generally indicate higher undrained shear strength and lower hydraulic conductivity (Sharma and Bora 2003). Thus, beta-glucan treatment is expected to increase the strength and stability of soils. Under certain conditions of water content, increased BG content in soil may induce higher shear strength, which increases the geotechnical stability of soil. Moreover, as BG fibers interact quickly with soil particles, treatment with BG is recommended for application to critical geotechnical problems (e.g., quick conditioners, water reducing admixtures, or temporary stabilizers. In addition, soil with higher liquid and plastic limits (i.e., MH or OH soil, according to the Unified Soil Classification System) is expected to have higher resistance to liquefaction (Boulanger and Idriss 2006). Thus, BG treatment can be useful for artificially improving resistance to liquefaction.

Meanwhile, the understanding of the effects of organic matter on soil compressibility remains uncertain. Several studies show that the compression index (C_c) increases with an increase in organic content (Angers 1990), while opposite views also exist, i.e., that organic matter has no significant effect on soil compressibility (O'Sullivan 1992, Zhang 1994). The swelling (or wettability) behavior of organic soil strongly depends on the hydrophilic or hydrophobic characteristics of the organic matter (Chenu *et al*. 2000, Sullivan 1990). Therefore, the swelling behavior is expected to be affected by the hydrophilic property of the BG biopolymer. The swelling and shrinking of soil (volumetric expansion and contraction) induces geotechnical problems such as ground disturbance (Bjerrum *et al*. 1961), and damage to structures with foundations on or in the soil.

Under axial compression, the skeletal structure of soil particles governs the response of soil, and BG polymers played no important role. Not only soil particles, but also the BG polymer, resist lateral shearing, due to their high tensile strength and adsorption forces on particle surfaces. Therefore, the major strengthening functions of treated KRS are schematically explained in Fig. 8 as reinforcement induced by biopolymer fibers interacting with soil particles by hydrogen bonding.

The experimental results indicate that BG biopolymer has great potential and feasibility as a new soil treatment material in various geotechnical engineering fields. Some limitations have to be overcome for future expansion and application in engineering practice. The durability of biopolymers becomes an important issue, because they are biodegradable. Thus, the long-term behavior of mixtures of soil and biopolymers has to be verified to define its serviceability. Meanwhile, BG and other hydrophilic biopolymers adsorb great amounts of water which induce volumetric expansion (i.e., swelling) in soil and makes the soil structure softer. Conversely, the soil swelling has advantages in horizontal earth-pressure supports such as slurry walls. In practice, guar gum biopolymer slurry has been tried as a replacement for bentonite slurry for deep slurry

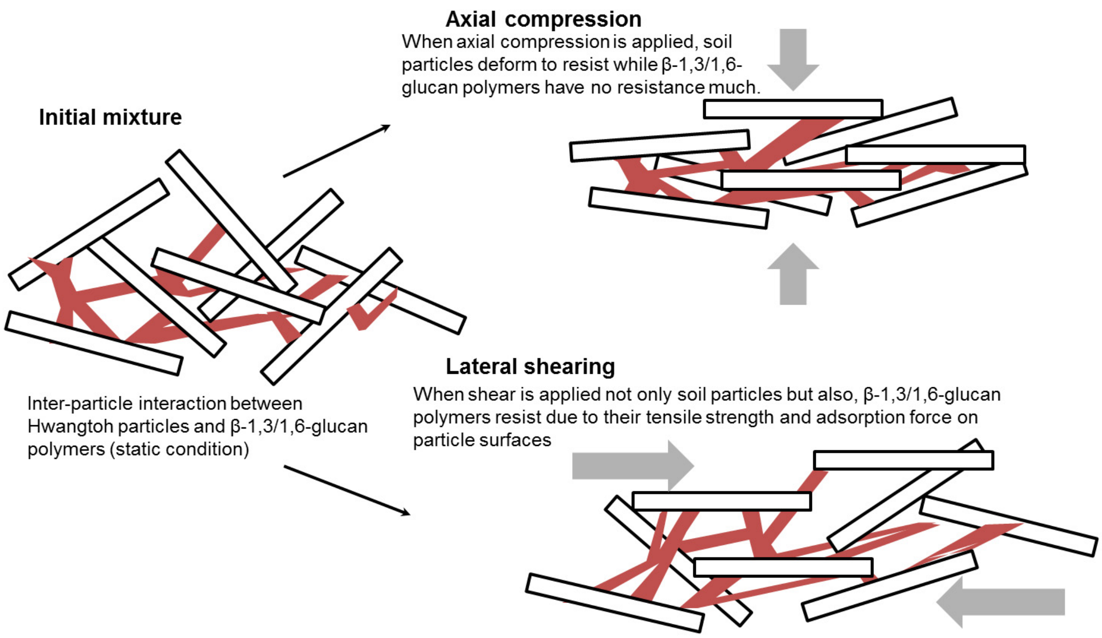


Fig. 8 Schematic model of the inter-particle behavior of β-1,3/1,6-glucan (BG) treated Korean residual soil

wall structures in the US (Day *et al*. 1999). Thus, treatment with BG also has potential for similar purposes in geotechnical engineering practice.

Compared to other current soil improvement materials (e.g., cement, lime), the present high cost of BG, and other biopolymers, is restricting their use in geotechnical engineering. However, biopolymer treatment has special merits regarding its strengthening performance, low environmental impact, and quickness of function. Moreover, the economic efficiency of biopolymers is increasing rapidly due to new manufacturing methods (i.e., bio-refineries) and environmental regulations (e.g., CO_2 emission).

At present, we suggest that biopolymers can be applied as temporary additives for soil strengthening and stabilization of environmentally sensitive areas (e.g., slopes, riversides and lakesides, soil pavement, dust and erosion control). Moreover, biopolymers are reported to improve the germination and growth of vegetation (Nierop *et al*. 2001). Thus, biopolymers can be effectively used to improve stabilization of vegetation on slopes, coasts, and extreme environments (e.g., arid and semi-arid regions). However, the high viscosity of biopolymers impedes its infiltration into soil. Thus, thorough mixing is recommended for effective site application.

6. Conclusions

We explored experimentally the effect of biopolymer on soil behavior, and identified the geotechnical behavior of KRS (Korean residual soil) after treatment with beta-1,3/1,6-glucan biopolymer. As the biopolymer content increased, the treated soil showed an increase in compactibility (maximum dry density and optimal water content), Atterberg limits (PL and LL) and plasticity index (PI), swelling index (C_s), and shear wave velocity (V_s or shear modulus), but a decrease in the coefficient of consolidation (c_v). However, the presence of biopolymer in soil had no effect on axial compression behaviors such as compressibility (C_c) and compressional wave velocity (V_p or constraint modulus).

Each finding demonstrates interactions between the BG polymer and KRS soil particles: (1) BG polymers are hydrophilic and have negatively charged surfaces; and (2) soil cohesion and inter-particle friction are improved by soil particles attached to the BG fibers.

Based on these limited test results, BG treatment shows substantial potential to provide solutions to some geotechnical engineering problems in the forms of quick conditioners, water reducing admixtures, temporary stabilizers, and slurry wall mixtures. Furthermore, soil treatment with biopolymer (i.e., under 1.0% of soil mass) appears to be a useful application for embankments, backfills, and pavements to improve the compaction performance of soil. Vibration compaction, in particular, should be very effective because of the pseudo-plasticity of beta-glucan biopolymers.

For all these reasons, biopolymer-based soil treatment is expected to become a bright new tool in the field of geotechnical engineering.

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