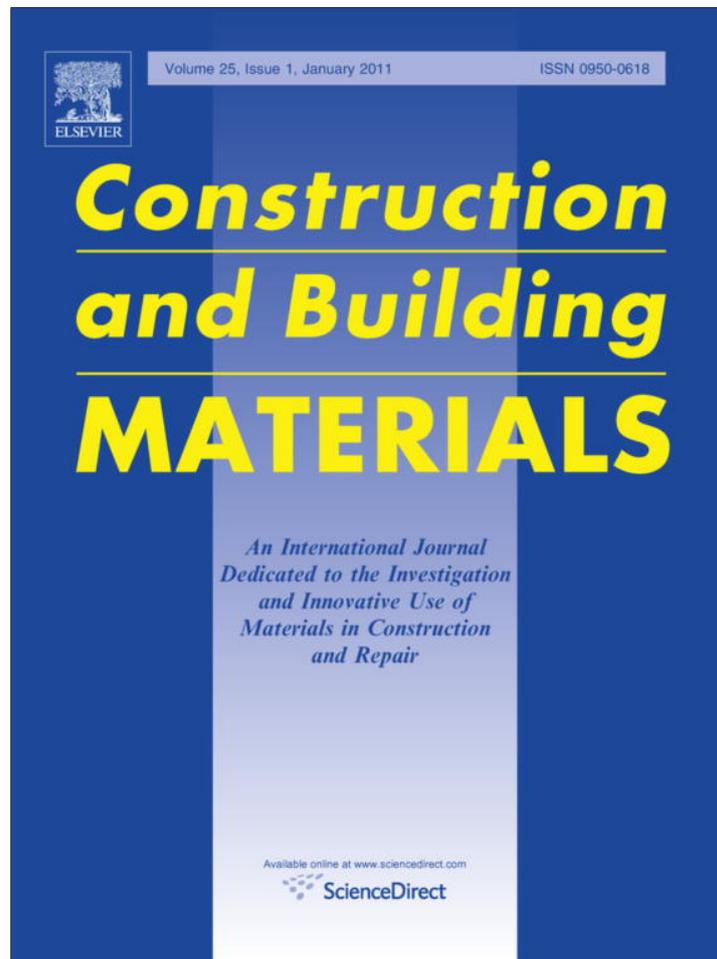


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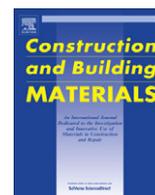
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# Construction and Building Materials

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## Strengthening of Korean residual soil with $\beta$ -1,3/1,6-glucan biopolymer

Ilhan Chang, Gye-Chun Cho\*

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, South Korea

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### ABSTRACT

Soil improvement and stabilization are important geotechnical issues when using soil as an engineering material. The most widely used material for soil treatment is cement, a trend that runs counter to environmentally friendly practice. In food and medical science, various biopolymers are commonly used as thickeners, stabilizers, binders, and so on. This study explores the feasibility of using environmentally friendly biopolymers for soil improvement. A commercial  $\beta$ -1,3/1,6-glucan polymer product was used to improve the strength of the Korean residual soil, *hwangtoh*. Liquid type  $\beta$ -1,3/1,6-glucan polymer solutions with different concentrations were mixed with *hwangtoh* and cured under different temperatures. The time-dependent compressive strength was measured in order to observe the strengthening mechanism of the  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh*. The particle surface adsorption and tensile strength of the  $\beta$ -1,3/1,6-glucan polymers significantly increased the compressive strength of the *hwangtoh*. The strength improvement was maximized under a curing temperature of 60 °C. Furthermore, a simple economic/environmental analysis revealed that the  $\beta$ -1,3/1,6-glucan polymer treatment had advantages not only in strengthening the *hwangtoh* but also in lowering its environmental impact while offering financial competitiveness over ordinary cement treatments.

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### 1. Introduction

Soil treatment (i.e. improvement and stabilization) has always been an important consideration throughout the history of human civilization. Various materials such as straw, bitumen, lime, salts, and pozzolans are conventional additions to soil, while cement, petrochemicals, and bacteria are currently being increasingly used in an effort to improve and stabilize soil from both mechanical and chemical aspects [1,2]. Among these, cement is the most widely used material for soil treatment in relation to soil strength improvement, ground water control, and hazardous contaminant fixes [3–6].

Ordinary cement production emits carbon dioxide, a significant greenhouse gas, during chemical calcination and fuel burning. It has been reported that 5% of the global carbon dioxide emissions are induced by the cement industries [7,8]. Meanwhile, the large amount of cement demolition waste (65 million tons/year in the United States [9]) also presents significant environmental problems. Both the disuse and recycling of cement-concrete waste are potentially hazardous to the environment due to the potential for pollutant leakage into the soil and groundwater [10,11]. Meanwhile, several alternatives such as geopolymers [12], alkali-activated cement [13], geocement [14], and inorganic polymer

concrete [15] have been developed in an attempt to reduce or replace cement use. However, the CO<sub>2</sub> reduction efficiency of these methods is insufficient due to their dependency on ordinary cement and heavy industry by-products (e.g. blast furnace slag, fly ash, etc.). Therefore, demand for the development of environmentally friendly construction materials that are relatively harmless and easily reused without environmental impacts is increasing significantly in the 21st century.

Biopolymers are polymers produced by living organisms, and most biopolymer applications are in the field of medical engineering, such as drug delivery systems, wound healing, and surgical implantations [16]. With the aim of environmentally friendly development, biopolymers such as welan gum and curdlan have been used as bio-admixtures in concrete or dry-mix mortar as water-retention agents or superplasticizers according to their pseudoplasticity properties [17]. In the fields of soil science, geotechnical engineering, and geoenvironmental engineering, biopolymers have been applied as soil stabilizers in order to control or reduce soil erosion [18,19] and are used for soil drilling mud and temporary excavation supports [20]. Aligning with this trend, theoretical and experimental verifications of the interactions between various types of biopolymers and soil media are required in the geotechnical and geoenvironmental fields.

*Hwangtoh* is a common residual soil in Korea and is considered to be an environmentally friendly material due to its high absorbency, self-purification, and far infrared ray radiation characteristics [21]. However, its strength and drying shrinkage

\* Corresponding author. Tel.: +82 42 350 3662/3622; fax: +82 42 350 7200.

E-mail addresses: [ilhanchang@kaist.ac.kr](mailto:ilhanchang@kaist.ac.kr) (I. Chang), [gyechun@kaist.edu](mailto:gyechun@kaist.edu) (G.-C. Cho).

problems have restricted its usage and development [22]. Thus, an environmentally friendly approach to strengthening *hwangtoh* is required in order to amplify its benefits and usage.

In this study, a commercial beta-1,3/1,6-glucan polymer solution (Polycan™) is introduced as a soil-treatment material. The inter-particle behavior of the  $\beta$ -1,3/1,6-glucan polymer and particulate material is defined. Also, the structural and engineering behavior of the  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh* is investigated through a series of laboratory experiments. Finally, the optimized conditions for the *hwangtoh* engineered using the  $\beta$ -1,3/1,6-glucan polymer are discussed in terms of efficiency and feasibility.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Beta-1,3/1,6-glucan biopolymer

Beta-1,3/1,6 glucan polymers are biopolymers of D-glucose monomers linked by glycosidic bonds [23]. Beta-glucan has various natural formations such as cellulose in plants, bran in cereal grains, and cell walls of yeast, fungi, mushrooms, and bacteria. The molecular weight of typical beta-glucan polymers has been reported to be 250–3000 kDa and electrostatically neutral [24,25]. In particular, yeast and mushroom-derived  $\beta$ -1,3/1,6-glucan polymer has a high biological activity and is used as immune system modulators in medical engineering [26]. With respect to engineering applications, beta-glucan has been used as an additive in superplasticizers and water reducing agents in concrete [27].

In this study, Polycan™ (Glucan Corp., Busan, Korea), a modified liquid  $\beta$ -1,3/1,6-glucan polymer solution produced via a UV-induced mutant of *Aureobasidium pullulans* SM-2001 and carboxymethylated by lactate ions ( $\text{CH}_3\text{CH}(\text{OH})\text{COO}^-$ ), is used [28]. The  $\beta$ -1,3/1,6-glucan polymer content of the pure Polycan™ product is 8.2 g/L, which is defined as  $c_0 = 1.0$ , while the other solutions are notated according to their dilution ratio ( $c_0 = 0$  represents distilled water). Although natural  $\beta$ -1,3/1,6-glucan is electrostatically neutral, the hydroxyl groups ( $\text{OH}^-$ ) and carboxymethylated modification make the  $\beta$ -1,3/1,6-glucan polymer used in this study be negatively charged. The specific details of the  $\beta$ -1,3/1,6-glucan polymer solutions are summarized in Table 1.

#### 2.1.2. Hwangtoh (Korean residual soil)

*Hwangtoh* is a primary residual soil in Korea and originate from granitic rocks. The main minerals consist of kaolinite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ) and halloysite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot 2\text{H}_2\text{O}$ ), both of which have a 1:1 layer structure of Si-tetrahedral sheets and Al-octahedral sheets [21]. The microstructure of *hwangtoh* shows a honeycomb structure which renders a high porosity of up to 50% [29]. The high porosity of *hwangtoh* induces several physiological characteristics such as high absorbency, self-purification, and deodorizing and sanitizing properties [30,31]. Moreover, *hwangtoh* emits far infrared rays [32], which are beneficial to the human body [33].

On the basis of its physiological and health promoting characteristics, *hwangtoh* has been traditionally used to make house bricks, cook food, dye clothes, and treat red tide problems in Korea [34]. In particular, interest in *hwangtoh* as an indoor finishing material has been increasing in recent times. However, disadvantages such as shrinkage-induced cracking and low strength have limited its use in engineering applications [22]. This study presents a new environmentally friendly approach to strengthening *hwangtoh* through a biopolymer treatment.

The *hwangtoh* used in this study was obtained from Ha-dong, Korea. Its mineral constitution (by mass) consists of quartz (8.4%), kaolinite (45.8%), halloysite (22.7%), illite (14.8), and goethite (8.3%). Meanwhile, the chemical composition of *hwangtoh* is distributed as:  $\text{SiO}_2$  (42.5%),  $\text{Al}_2\text{O}_3$  (36.3%),  $\text{Fe}_2\text{O}_3$  (4.05%), CaO (0.57%),  $\text{K}_2\text{O}$  (0.41%),  $\text{TiO}_2$  (0.23%),  $\text{Na}_2\text{O}$  (0.18%). The natural *hwangtoh* was oven dried at 110 °C [35], and was then grinded (grain size <75  $\mu\text{m}$ ) for the specimen preparation.

### 2.2. Experimental program

#### 2.2.1. Tensile strength test on the $\beta$ -1,3/1,6-glucan biopolymer

In order to investigate the physical properties (strength) of the  $\beta$ -1,3/1,6-glucan polymer, a solid state polymer film that is suitable for tensile strength testing was fabricated. The  $\beta$ -1,3/1,6-glucan polymer solution ( $c_0 = 1.0$ ) was dehydrated at 20 °C to prevent rapid moisture evaporation. The dehydrated  $\beta$ -1,3/1,6-glucan polymer

solution formed a yellowish thin film. The film was trimmed (10 mm in width, 0.34 mm in thickness) in order for it to be suitable for tensile testing. The tensile strength of the  $\beta$ -1,3/1,6-glucan polymer film was measured by using a universal testing machine (UTM) device (INSTRON 5583).

An alternative method was also used to evaluate the sample's surface adhesion with other materials. A simple  $\beta$ -1,3/1,6-glucan polymer – filter paper (Whatman® No. 4) composite was prepared via coating liquid state  $\beta$ -1,3/1,6-glucan polymer solution ( $c_0 = 1.0$ ) on both sides of the filter paper. After dehydration, the tensile strength of the  $\beta$ -1,3/1,6-glucan polymer – filter paper composite, as well as that of the pure filter paper, were measured using the UTM. Finally, the tensile strength of the  $\beta$ -1,3/1,6-glucan polymer induced by the surface adhesion was derived through comparisons of the strengths of the filter paper and  $\beta$ -1,3/1,6-glucan polymer – filter paper composite.

#### 2.2.2. Microscopic observation

Microscopic observation can be readily used to determine the  $\beta$ -1,3/1,6-glucan polymer behavior in a particulate (soil) matrix. Glass beads (uniform grain size; mean diameter = 1.5 mm) were used to identify how the  $\beta$ -1,3/1,6-glucan polymer interacts with the particulate materials. The pure  $\beta$ -1,3/1,6-glucan polymer solution was mixed with glass beads at a solution/solid weight ratio of 60%. After dehydration at 20 °C, scanning electron microscope (SEM; Philips XL30SFE) images were obtained in order to visualize the inter-particle structure between the glass bead particles and the  $\beta$ -1,3/1,6-glucan polymers.

#### 2.2.3. $\beta$ -1,3/1,6-Glucan biopolymer and soil mixture

The dried *hwangtoh* and  $\beta$ -1,3/1,6-glucan polymer solutions (Table 1) were mixed together using a laboratory automatic rotator. For the mixing, the initial moisture content (i.e. liquid/solid ratio in the mass) is an important criterion because it defines the initial density and workability of the biopolymer–soil mixture. Thus, the initial moisture content was set at 60% by considering the liquid limit (LL) of *hwangtoh* (LL: water content (%) when soil behavior transforms from plastic to liquid; LL of natural *hwangtoh* = 53.7%, LL of oven-dried *hwangtoh* = 50.6%). The mixing process was performed for a sufficiently long period in order to provide a uniform mixture. After mixing, the mixture was placed into cubic molds (40 mm in length). A vibration compacter was used to remove the air voids trapped inside the specimens and to level the surface. Finally, spatulas were used to smooth the top surface of the specimens; then, the mold was removed from the specimens. The molded specimens were cured at 20 °C, 60 °C, and 100 °C, respectively, in order to explore the effect of the curing temperature on the behavior of the  $\beta$ -1,3/1,6-glucan polymer – *hwangtoh* mixtures. For comparison, *hwangtoh* was also mixed with ordinary Portland cement (Lafarge Halla Cement, Korea) at a cement/soil mass ratio of 10% and an initial water/soil mass ratio of 60%, as commonly used in practice. Cubic specimens of the cement – *hwangtoh* mixture were also prepared and cured at 20 °C.

#### 2.2.4. Uniaxial compressive test on $\beta$ -1,3/1,6-glucan biopolymer treated soil

Uniaxial (i.e. unconfined) compressive tests were performed using a UTM device (ASTM D1633). The compressive strength of the specimens cured at different temperatures was measured consistently every 7 days. For each set of conditions (amount of  $\beta$ -1,3/1,6-glucan polymer and curing temperature), three specimens were applied and the average value was selected in order to represent the mechanical behavior of the biopolymer-treated *hwangtoh*. The compressive strength of the cement-treated (10%) specimens was also measured for comparison. Fig. 1 shows the typical stress–strain behavior from the unconfined compression test result of the  $\beta$ -1,3/1,6-glucan treated *hwangtoh* (0.05 g/kg, 20 °C cured) with time. At the end of the curing (i.e. 28 days), SEM (Philips XL30SFE) images were obtained in order to confirm the interaction between the  $\beta$ -1,3/1,6-glucan polymer chains and *hwangtoh* particles.

## 3. Results and discussion

### 3.1. Tensile strength of $\beta$ -1,3/1,6-glucan biopolymer

Previous studies have proved that the tensile strength of oat  $\beta$ -glucan polymer typically ranges from 20 to 80 MPa, which varies with the moisture content due to a plasticizing phenomenon [36]. The direct tensile strength of the pure  $\beta$ -1,3/1,6-glucan polymer was measured to be 48 MPa, while the tensile strength of the filter paper-attached  $\beta$ -1,3/1,6-glucan polymer was measured to be

**Table 1**  
Description of  $\beta$ -1,3/1,6-glucan polymer solution.

$\beta$ -1,3/1,6-Glucan polymer solution	$c_0 = 1.0$	$c_0 = 0.5$	$c_0 = 0.1$	$c_0 = 0.05$	$c_0 = 0.01$
$\beta$ -1,3/1,6-Glucan concentration (g/L: solid mass/solution volume)	8.2	4.1	0.82	0.41	0.08
$\beta$ -1,3/1,6-Glucan/soil ratio (g of $\beta$ -1,3/1,6-glucan/kg of soil)	4.92	2.46	0.49	0.25	0.05

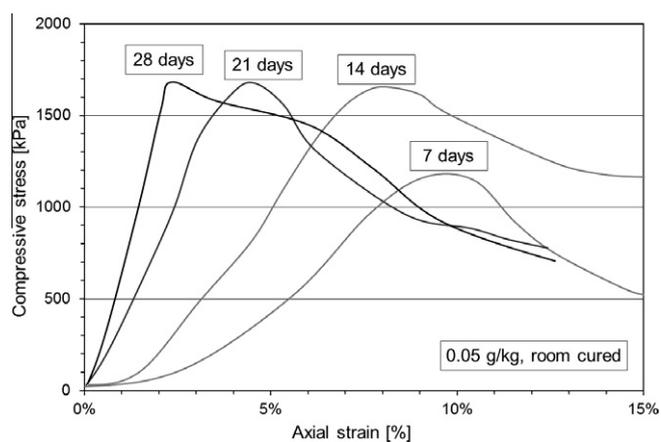


Fig. 1. Unconfined compressive test result of  $\beta$ -1,3/1,6-glucon treated *hwangtoh* (0.05 g/kg, cured at 20 °C) with time.

36.3 MPa. The lower tensile strength (36.3 MPa) relative to the pure  $\beta$ -1,3/1,6-glucon polymer (48 MPa) appears to be attributable to the adhesion with other materials (i.e. filter paper). Thus, the reduced tensile strength value becomes the relevant tensile behavior of the  $\beta$ -1,3/1,6-glucon polymer interacting with other materials.

### 3.2. Inter-particle behavior between the $\beta$ -1,3/1,6-glucon biopolymer and glass bead particles

The adsorption of the  $\beta$ -1,3/1,6-glucon polymers on particles during the dehydration process can be explained as biopolymeric cementation. The behavior of the cemented particulate materials is affected by the cementation material content, confining stress, and strain level [37]. The SEM image in Fig. 2a shows that a biopolymer coating forms on the glass bead surfaces and enlarged contact area between the spherical contacts governs the inter-particle behavior of the  $\beta$ -1,3/1,6-glucon polymer. Meanwhile, for non-contacted particles, the  $\beta$ -1,3/1,6-glucon polymer forms bridges between the detached particles (Fig. 2b). In this case, the adsorption strength and tensile strength govern the inter-particle behavior of the  $\beta$ -1,3/1,6-glucon polymer.

### 3.3. Strengthening of the $\beta$ -1,3/1,6-glucon biopolymer-treated *hwangtoh*

The adsorption and cementation of polymers on clay particle surfaces, which are entropy driven processes, increase as the size and molecular weight of the polymers increase [38]. The polymer surface conformation can be classified into three modes: directly attached “trains”, three-dimensional “loops”, and two freely suspended “tails” [39]. The fraction of the train segments ( $p$ ;  $p = 0.3$ – $0.5$  for uncharged polymers) governs the interaction between the polymers and soil particles. The modified (e.g. carboxymethylated)  $\beta$ -1,3/1,6-glucon polymer is a negatively charged polymer, and its adsorption leads to greater contact with the particle surface ( $p > 0.7$ ) [40]. Thus, the electrical interactions between the polymer, the natural cations (i.e.  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) in soil, and the surface charge characteristic of soil particles govern the inter-particle behavior of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* in this study.

Fig. 2c shows a SEM image of natural *hwangtoh*, while Fig. 2d shows the result of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* (4.92 g/kg, cured at 20 °C for 28 days). It can be seen that platy *hwangtoh* particles are attached to the  $\beta$ -1,3/1,6-glucon polymer bundles, not vice versa. The molecular weight ( $M_w$ ) of the  $\beta$ -glucon polymer has been reported to be 250–3000 kDa [24,25]. As the

length of a single glucose molecule ( $M_w = 180$  Da) is approximately 1 nm, the length of a single  $\beta$ -glucon polymer can be estimated to be 1.4–16.7  $\mu\text{m}$ . Thus, a single  $\beta$ -1,3/1,6-glucon polymer is generally larger than a single *hwangtoh* particle ( $d < 1 \mu\text{m}$ ). Therefore, the adsorption phenomenon between the  $\beta$ -1,3/1,6-glucon polymers and *hwangtoh* particles can be explained as the *hwangtoh* particles accumulating around the  $\beta$ -1,3/1,6-glucon polymer bundles (Fig. 2d). As both the modified  $\beta$ -1,3/1,6-glucon polymers and *hwangtoh* particles are negatively charged, the existence of natural cations (i.e.  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  from the soil;  $\text{H}^+$  ions from the aqueous solution) enhance the ionic bonding between the  $\beta$ -1,3/1,6-glucon polymer chains and *hwangtoh* particles; this is different from the inter-particle behavior of the  $\beta$ -1,3/1,6-glucon polymer with large spherical particles (Fig. 2a). Fig. 3 shows a schematic summary of the particle-polymer interaction (e.g. ionic bonding phenomena) between the  $\beta$ -1,3/1,6-glucon polymer chains and *hwangtoh* particles.

### 3.4. Compressive strength of $\beta$ -1,3/1,6-glucon biopolymer-treated *hwangtoh*

The compressive strength of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* was investigated in terms of curing time, curing temperature, and biopolymer content. Fig. 4 shows the strengthening tendency on the compressive strength of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* cured at 20 °C. Initially (i.e. after 7 days), specimens with different  $\beta$ -1,3/1,6-glucon polymer contents demonstrated a narrow variation around a strength value of 1000 kPa, which corresponds to the maximum compressive strength of the untreated natural *hwangtoh* (i.e. 1050 kPa). The compressive strength values increased significantly during 7 to 14 days of curing (e.g. water content decrease), and finally converged after 14 days. In the same manner, the water content of all specimens converged to 2–3% after 14 days. Thus, the results demonstrate that the strength variation of cured specimens is induced by the different amounts of  $\beta$ -1,3/1,6-glucon treatment rather than a change in water content or dry density.

The global trend of the  $\beta$ -1,3/1,6-glucon polymer treatment renders greater compressive strength compared with untreated *hwangtoh*. In particular, the 2.46 g/kg  $\beta$ -1,3/1,6-glucon polymer specimens showed more than 100% improvement in compressive strength (1050 kPa  $\rightarrow$  2280 kPa), while the 4.92 g/kg  $\beta$ -1,3/1,6-glucon polymer specimens showed a 200% strength increase (1050 kPa  $\rightarrow$  3225 kPa).

The effect of the curing temperature (i.e. 20 °C, 60 °C, and 100 °C) on the compressive strength of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* (28 days) is shown in Fig. 5. Regardless of the curing temperature, the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* showed minimum compressive strength at 0.25 g/kg  $\beta$ -1,3/1,6-glucon polymer content (also shown in Fig. 4), where the *hwangtoh* particles appear to be fully attached to the  $\beta$ -1,3/1,6-glucon polymers. For lower  $\beta$ -1,3/1,6-glucon polymer conditions (<0.25 g/kg), the strengthening mechanism can be explained as a combination of the tensile strength of the  $\beta$ -1,3/1,6-glucon polymers and the friction between the  $\beta$ -1,3/1,6-glucon polymer adsorbed particles and free *hwangtoh* particles. At the minimum point (0.25 g/kg), it is presumed that most *hwangtoh* particles are adsorbed by the  $\beta$ -1,3/1,6-glucon polymers, which induces minimum inter-particle friction between the *hwangtoh* particles. Meanwhile, at higher  $\beta$ -1,3/1,6-glucon polymer conditions (>0.25 g/kg), additional  $\beta$ -1,3/1,6-glucon polymer treatment induces surplus  $\beta$ -1,3/1,6-glucon polymers, which globally reinforces the soil.

The compressive strength of the  $\beta$ -1,3/1,6-glucon polymer-treated *hwangtoh* cured at 20 °C and 60 °C is significantly improved when the polymer content is increased above 0.49 g/kg content of a  $\beta$ -1,3/1,6-glucon polymer. At  $\beta$ -1,3/1,6-glucon polymer content

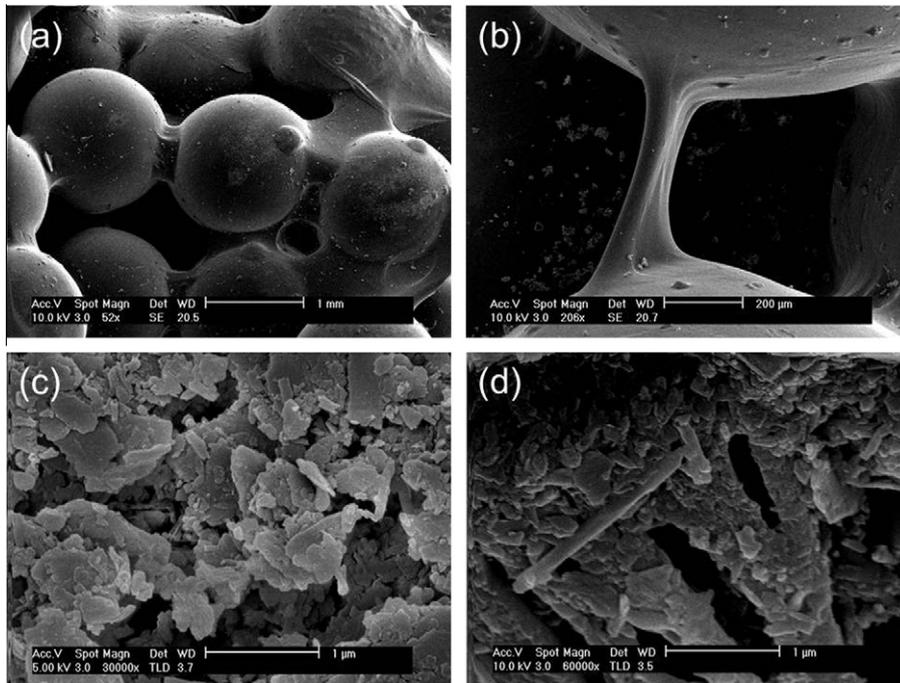


Fig. 2. SEM images. Glass bead and  $\beta$ -1,3/1,6-glucan mixture (a and b). Natural *hwangtoh* (oven dried at 110 °C) (c). 4.92 g/kg  $\beta$ -1,3/1,6-Glucan polymer-treated *hwangtoh* (cured at 20 °C; 28 days) (d).

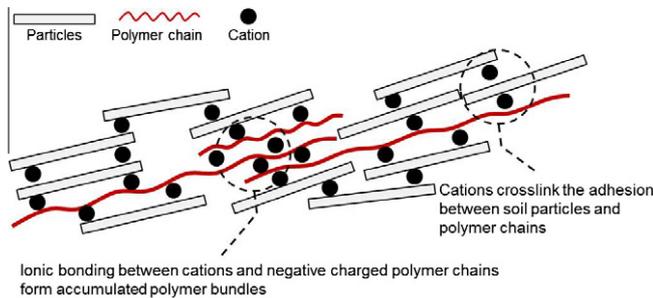


Fig. 3. Schematic view of the particle-polymer interaction of  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh*. Long-length  $\beta$ -1,3/1,6-glucan polymer bundles adsorb *hwangtoh* particles with the aid of intermediate cations.

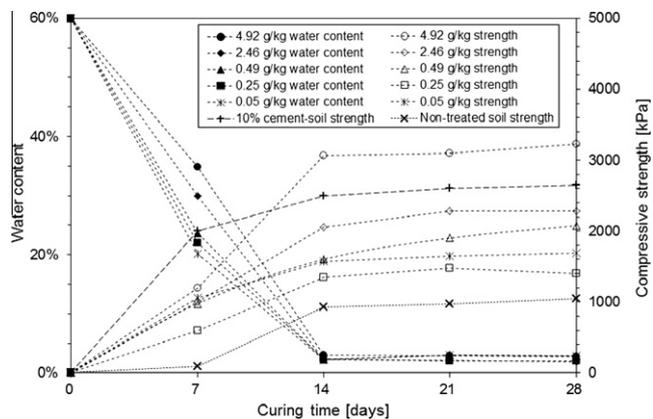


Fig. 4. Strengthening and water content decrement tendency on the compressive strength behavior of  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh* (cured at 20 °C) compared with non-treated and 10% cement treated conditions.

lower than 2.46 g/kg, the curing temperature had little effect on strength improvement, whereas above 2.46 g/kg a distinct effect

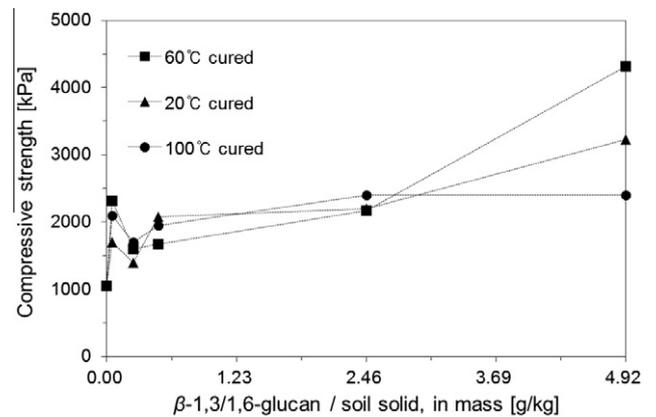


Fig. 5. Effect of curing temperature on compressive strength of  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh* (after 28 days).

was observed. Notably, the specimens cured at 60 °C demonstrated better improvement. In relation to this, the  $\beta$ -1,3-glucan polymer (i.e. curdlan) forms a gel via an endothermic reaction at 60 °C, thereby inducing swelling [41]. Thus, the better performance of the specimens cured at 60 °C is thought to result from the thermo-setting induced by the heat adsorption during the  $\beta$ -1,3/1,6-glucan polymer gel formation at the initial stage of curing under the optimum temperature.

However, the specimens subjected to long-term (i.e. more than 21 days) curing at 100 °C demonstrated less strengthening over time. Thus, high temperature or excessive thermal curing decreases and disturbs the strength evolution of the  $\beta$ -1,3/1,6-glucan polymers. Notably, the  $\beta$ -1,3-glucan polymer fibers heated at 120 °C show a loose structure and separated fibrils [42]. Thus, it is expected that excessive thermal treatment (both heating temperature and duration) interrupts the strengthening function of the  $\beta$ -1,3/1,6-glucan polymers.

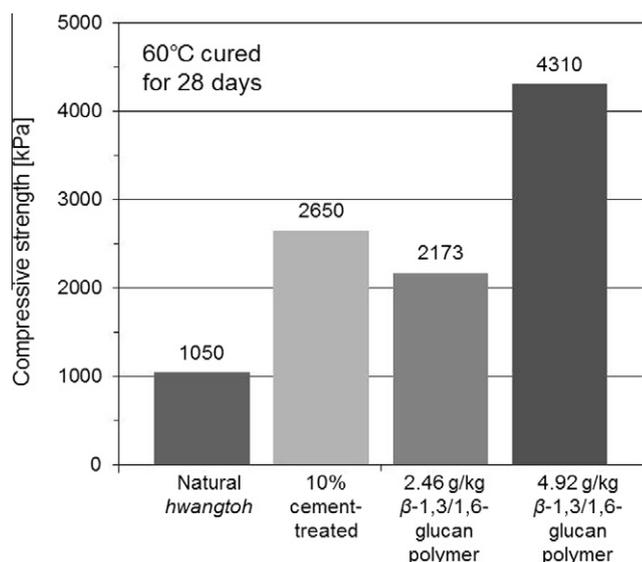


Fig. 6. Comparison of compressive strength of  $\beta$ -1,3/1,6-glucan polymer-treated hwangtoh (cured at 60 °C) to that of natural and 10% cement-treated hwangtoh (after 28 days).

For practical applications, the strengthening of the  $\beta$ -1,3/1,6-glucan polymer-treated hwangtoh is maximized at higher  $\beta$ -1,3/1,6-glucan polymer content and curing at temperatures below 60 °C. In order to verify the strengthening efficiency of the  $\beta$ -1,3/1,6-glucan polymer, the 28 day compressive strength values of 2.46 and 4.92 g/kg  $\beta$ -1,3/1,6-glucan polymer-treated hwangtoh, natural hwangtoh, and 10% cement-treated hwangtoh (cured at 20 °C) are compared in Fig. 6. The biopolymer treatment using the  $\beta$ -1,3/1,6-glucan polymer yields a significant improvement in the strength of hwangtoh. The effect of the organic matter on soil strength depends significantly on whether the organic matter is decomposed or present as fibers. When the organic matter is decomposed, soil properties such as strength, stiffness, and modulus are expected to be reduced due to the high water content in the soil adsorbed by the organic matter, whereas when the organic matter is present as fibers, the fibers act as reinforcement, thereby increasing the strength of the soil [20]. Thus, the primary role of the  $\beta$ -1,3/1,6-glucan polymers in strengthening soil appears to be as reinforcement fibers.

As shown in Figs. 4 and 6, the 4.92 g/kg  $\beta$ -1,3/1,6-glucan polymer treatment yields much higher compressive strength values than the 10% cement treatment. This implies that the minimum requirement for reliable improvement using the  $\beta$ -1,3/1,6-glucan polymer to replace cement mixing should be at least 0.5% soil in terms of mass. The soil-cement reaction produces primary C–S–H (calcium silicate hydrates) and C–A–H (calcium aluminate

hydrates) gels which are induced by the hydration reaction of the cement, and secondary C–S–H or C–A–H gels which are formed by the pozzolanic reaction between the hydroxides (OH<sup>-</sup>) and clay minerals [43]. The C–S–H and C–A–H gels in soil form reticulated contact, thereby increasing the physical strength between particles [44]. Therefore, the stronger compressive strength of the hwangtoh containing 0.49%  $\beta$ -1,3/1,6-glucan polymer implies the strengthening effect of  $\beta$ -1,3/1,6-glucan polymer fibers is greater than that of the C–S–H and C–A–H gels induced by 10% cement mixing.

### 3.5. Economic efficiency of the $\beta$ -1,3/1,6-glucan biopolymer compared with cement

Compared with cement, the compressive strength results of the  $\beta$ -1,3/1,6-glucan polymer-treated hwangtoh are superior when the  $\beta$ -1,3/1,6-glucan polymer content is 0.49% in terms of mass (i.e. 4.92 g/kg soil). From the perspective of engineered soil, the economic efficiency analysis between 10% cement-mixed hwangtoh and 0.49%  $\beta$ -1,3/1,6-glucan polymer-treated hwangtoh is summarized in Table 2. Generally, biopolymers are considerably more expensive than cement. In Table 2, for a unit amount (1 ton) of soil treatment, the biopolymer is insufficient to replace the role of ordinary cement treatment in terms of the pure material price.

Consideration of the environmentally friendly aspects and carbon emission trading, however, leads to an interesting result. According to the literature, the total indirect environmental impact (CO<sub>2</sub> emission in kg) induced by 1 ton soil treatment is 129,180 kg CO<sub>2</sub> for the cement treatment and 66.72 kg CO<sub>2</sub> for the  $\beta$ -1,3/1,6-glucan polymer treatment. In order to meet the requirements of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (1997), the EU nations impose a carbon tax on high carbon emitting industries. The recent rate for CO<sub>2</sub> emission trade is \$22/ton CO<sub>2</sub> [45,46]. The total economical price (direct material cost + indirect CO<sub>2</sub> emission expense) for 1 ton of soil improvement then becomes \$2848 for 10% cement mixture and \$1576 for 0.49%  $\beta$ -1,3/1,6-glucan polymer treatment. Therefore, from a holistic viewpoint, the biopolymer treatment has advantages in engineering performance, environmental impact, and economics.

## 4. Conclusions

The primary purpose of this study is to investigate the biosystem behavior of  $\beta$ -1,3/1,6-glucan biopolymer treated Korean residual soil from an engineering viewpoint. The inter-particle behavior of the  $\beta$ -1,3/1,6-glucan biopolymer has two cases according to the particle condition. For non-charged spherical particles (e.g. sand), the biopolymer adsorption on the particle surfaces and the enlarged particle contact areas govern the inter-particle behavior of the attached particles, while the  $\beta$ -1,3/1,6-glucan biopolymer extends as a bridge between the detached particles. Whereas, for

Table 2  
Economic and environmental analysis of OPC and  $\beta$ -1,3/1,6-glucan.

Material	Ordinary Portland cement	Beta-1,3/1,6-glucan	Note
Market price	60 USD/ton <sup>a</sup>	320 USD/kg <sup>b</sup>	
Required amount for 1 ton soil treatment	0.1 ton ( $c/s = 10\%$ )	4.92 kg ( $\beta/s = 0.49\%$ )	
Material price for 1 ton soil treatment (USD)	6	1574	$\beta$ -1,3/1,6-Glucan 262 times expensive
CO <sub>2</sub> emission per 1 kg material production (kg CO <sub>2</sub> /kg)	1291.8 <sup>48, 49</sup>	13.56 <sup>50, 51</sup>	Chemical reaction, electricity, fuel burn
Total CO <sub>2</sub> emission for 1 ton soil treatment (kg CO <sub>2</sub> )	129,180	66.72	OPC emits CO <sub>2</sub> 194 times more
Total CO <sub>2</sub> emission cost (USD)	2842	1.5	$\beta$ -1,3/1,6-Glucan 1,900 times inexpensive
Total cost (direct/indirect) for 1 ton soil treatment (USD)	2848	1576	

Notation:  $c$  = mass of cement,  $s$  = mass of soil,  $\beta$  = mass of  $\beta$ -1,3/1,6-glucan.

<sup>a</sup> Depicts the price of cement (market prize of Lafarge Halla Cement: <www.lafarge-gypsum.co.kr>).

<sup>b</sup> Depicts the price of  $\beta$ -1,3/1,6-glucan (market prize: <www.sigmaldrich.com>) at May 2010.

negatively charged platy particles (e.g. clay), the ionic bondings between the  $\beta$ -1,3/1,6-glucan polymers, soil particles, and cations improve the strength of the  $\beta$ -1,3/1,6-glucan biopolymer–soil biosystem.

In practice, the  $\beta$ -1,3/1,6-glucan biopolymer enhances the compressive strength of soil more than 200% for the 4.92 g/kg treatment. Moreover, it is shown that the strengthening function was maximized in a 60 °C curing environment. For economic efficiency, the  $\beta$ -1,3/1,6-glucan biopolymer treatment becomes a competitive option to replace the use of less environmentally friendly cement in terms of engineering performance, environmental impact, and cost effectiveness.

Soil treatment using bioproducts is a new but uncertain and unfamiliar field in geotechnical engineering. However, as shown in this study, biopolymer treatment has great potential to replace ordinary methods (i.e. cement, chemical agents, etc.) in the aim of environmentally friendly development of soil treatment. Therefore, further studies on various conditions (i.e. different biopolymer type, soil type, curing environment, ionic concentration) are recommended in order to pioneer this new field of soil treatment using bioprocesses and biosystems.

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