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

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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$_2$ 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.

$Hwagnoth$ 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
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 polymers 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 (CH3CH(OH)COO-) was 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 c0 = 1.0, while the other solutions are noted according to their dilution ratio (c0 = 0 represents distilled water). Although natural beta-1,3/1,6-glucan is electrostatically neutral, the hydroxyl groups (OH-) and carboxymethylated modification make the beta-1,3/1,6-glucan polymer used in this study 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 (Al2Si2O5(OH)4) and halloysite (Al2Si4O10(OH)4·2H2O), 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 has been found to interact with particulate materials. The pure 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, specimens were used to smooth the top surface of the specimens: then, the mold was removed from the specimens. The moulded specimens were cured at 20°C, 60%RH, 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 prepared and cured at 20°C.

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 (c0 = 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 (c0 = 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 XL30SEF) 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, specimens were used to smooth the top surface of the specimens: then, the mold was removed from the specimens. The moulded specimens were cured at 20°C, 60%RH, 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 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 prepared 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 XL30SEF) 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 3.1 Chang, G.-C. Cho / Construction and Building Materials 30 (2012) 30–35 31
36.3 MPa. The lower tensile strength (36.3 MPa) relative to the pure β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer interacting with other materials.

3.2. Inter-particle behavior between the β-1,3/1,6-glucan biopolymer and glass bead particles

The adsorption of the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer. Meanwhile, for non-contacted particles, the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer.

3.3. Strengthening of the β-1,3/1,6-glucan 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 “chains”, 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) β-1,3/1,6-glucan 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. Na⁺, K⁺, Ca²⁺, Mg²⁺) in soil, and the surface charge characteristic of soil particles govern the inter-particle behavior of the β-1,3/1,6-glucan polymer-treated hwangtoh in this study.

Fig. 2c shows a SEM image of natural hwangtoh, while Fig. 2d shows the result of the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer bundles, not vice versa. The molecular weight (Mw) of the β-glucan polymer has been reported to be 250–3000 kDa [24,25]. As the length of a single glucose molecule (Mw = 180 Da) is approximately 1 nm, the length of a single β-glucan polymer can be estimated to be 1.4–16.7 μm. Thus, a single β-1,3/1,6-glucan polymer is generally larger than a single hwangtoh particle (d < 1 μm). Therefore, the adsorption phenomenon between the β-1,3/1,6-glucan polymers and hwangtoh particles can be explained as the hwangtoh particles accumulating around the β-1,3/1,6-glucan polymer bundles (Fig. 2d). As both the modified β-1,3/1,6-glucan polymers and hwangtoh particles are negatively charged, the existence of natural cations (i.e. Na⁺, Mg²⁺, and Ca²⁺ from the soil; H⁺ ions from the aqueous solution) enhance the ionic bonding between the β-1,3/1,6-glucan polymer chains and hwangtoh particles; this is different from the inter-particle behavior of the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer chains and hwangtoh particles.

3.4. Compressive strength of β-1,3/1,6-glucan biopolymer-treated hwangtoh

The compressive strength of the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer-treated hwangtoh cured at 20 °C. Initially (i.e. after 7 days), specimens with different β-1,3/1,6-glucan 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 β-1,3/1,6-glucan treatment rather than a change in water content or dry density.

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

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

The compressive strength of the β-1,3/1,6-glucan 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 β-1,3/1,6-glucan polymer. At β-1,3/1,6-glucan polymer content
lower than 2.46 g/kg, the curing temperature had little effect on strength improvement, whereas above 2.46 g/kg a distinct effect was observed. Notably, the specimens cured at 60 °C demonstrated better improvement. In relation to this, the β-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 thermosetting induced by the heat adsorption during the β-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 β-1,3/1,6-glucan polymers. Notably, the β-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 β-1,3/1,6-glucan polymers.
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 \(^\circ\)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 \(^\circ\)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\(^-\)) 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\(_2\) emission in kg) induced by 1 ton soil treatment is 129,180 kg CO\(_2\) for the cement treatment and 66.72 kg CO\(_2\) 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\(_2\) emission trade is $22/ton CO\(_2\) [45,46]. The total economical price (direct material cost + indirect CO\(_2\) 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**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ordinary Portland cement</th>
<th>Beta-1,3/1,6-glucan</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market price</td>
<td>60 USD/ton(^a)</td>
<td>320 USD/kg(^b)</td>
<td></td>
</tr>
<tr>
<td>Required amount for 1 ton soil treatment</td>
<td>0.1 ton (c/s = 10%)</td>
<td>4.92 kg (c/s = 0.49%)</td>
<td></td>
</tr>
<tr>
<td>Material price for 1 ton soil treatment (USD)</td>
<td>6</td>
<td>1574</td>
<td></td>
</tr>
<tr>
<td>CO(_2) emission per 1 kg material production (kg CO(_2)/kg)</td>
<td>1291.8g(\times)49</td>
<td>13.50(\times)51</td>
<td>$\beta-1,3/1,6$-Glucan262 times expensive</td>
</tr>
<tr>
<td>Total CO(_2) emission for 1 ton soil treatment (kg CO(_2))</td>
<td>129,180</td>
<td>66.72</td>
<td>$\beta-1,3/1,6$-Glucan626 times expensive</td>
</tr>
<tr>
<td>Total CO(_2) emission cost (USD)</td>
<td>2842</td>
<td>1.5</td>
<td>OPC emits CO(_2)194 times more</td>
</tr>
<tr>
<td>Total cost (direct/indirect) for 1 ton soil treatment (USD)</td>
<td>2848</td>
<td>1576</td>
<td>$\beta-1,3/1,6$-Glucan900 times inexpensive</td>
</tr>
</tbody>
</table>

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

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

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

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Fig. 6. Comparison of compressive strength of \( \beta-1,3/1,6 \)-glucan polymer-treated hwangtoh (cured at 60 \(^\circ\)C) to that of natural and 10\% cement-treated hwangtoh (after 28 days).
negatively charged platy particles (e.g., clay), the ionic bondings between the β-1,3/1,6-glucan polymers, soil particles, and cations improve the strength of the β-1,3/1,6-glucan biopolymer–soil biosystem.

In practice, the β-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 β-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 bioproduts 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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