



Effects of Xanthan gum biopolymer on soil strengthening



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HIGHLIGHTS

- We investigated the interaction between Xanthan gum biopolymer and soils.
- Xanthan gum prefers fine particles which enhances strength via hydrogen bonding.
- Xanthan gum–fine soil matrix acts as a cementation binder between coarse particles.
- Soil composition is important for chemical bonding and mechanical friction.
- The most effective concentration of Xanthan gum is 1–1.5% to the soil mass.

ARTICLE INFO

Article history:

Received 14 January 2014

Received in revised form 16 July 2014

Accepted 14 October 2014

Keywords:

Soil strengthening

Xanthan gum

Compressive Strength

Soil composition

SEM (Scanning Electron Microscope) images

ABSTRACT

The general aim of soil treatment in construction engineering is to improve soil properties such as aggregate stability, strength, and erosion resistance. Conventional soil treatment materials have several shortcomings, especially from an environmental standpoint. As a result, a suitable eco-friendly replacement for conventional materials is required. Xanthan gum is a polysaccharide commonly used as a food additive and rheology modifier. It has been used as a soil improvement material in the present study and experimental tests were performed with different types of soils. The results show that the Xanthan gum fibers interact directly with the charged surfaces of clayey particles while forming Xanthan matrices that resemble a hard plastic between uncharged particles. Consequently, the strengthening effect of Xanthan gum was shown to have the greatest efficiency with well graded soils with fine particles. Through experiments with varying concentrations of Xanthan gum, it was found that the strengthening effect leveled off at higher concentrations. The strengthening effect was also shown to be greatly dependent on the hydration level of the soils. Overall, the strengthening effect of Xanthan gum is shown to be dependent on four factors: type of soil, hydration level (e.g., moisture content), Xanthan gum content, and mixing method.

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1. Introduction

The general aim of soil treatment is to improve soil properties such as aggregate stability, strength, and erosion resistance. Numerous soil treatment methods are already in practice; among these, cement is the most commonly used material for soil treatment. However, even with the many benefits that ordinary cement provides, it has several shortcomings, especially when viewed from an environmental perspective. The most critical of these problems

are CO₂ and NO_x (nitrogen oxides) emissions and particulate air suspensions.

Cement has been found to be one of the world's leading causes of CO₂ emissions. With the calcination of limestone (CaCO₃ → CaO + CO₂) and the heat energy (e.g., 1450 °C in a kiln) required in the production of cement, approximately one ton of CO₂ is produced for every ton of cement production. This means that cement alone is responsible for 5% of annual global CO₂ production [1]. Along with CO₂, another byproduct of cement production is NO_x. Most of these nitrogen oxides are produced in the cement kiln, with 2.3 kg/ton of clinker produced [2].

Particulate air emission in the form of cement dust is another environmental problem. Cement dust from concrete can be released into the air through such actions such as demolitions or earthquakes [3]. During the Great Hanshin Earthquake (1995;

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Hyogo, Japan), there was a total of $150 \mu\text{g}/\text{m}^3$ of suspended particulates, most of which was a direct result of suspended cement dust [4].

Owing to the low degradability of cement mixtures, cement used for soil treatment is left in place for extremely long periods of time. The presence of the cement within the soil may cause disturbances to the ecosystem (e.g., high pH) and increase the effects of desertification [2]. With the ultimate goal of reducing the environmental impact of cement, several studies have been performed for the purpose of soil improvement without cement [5,6]. In this vein, a Xanthan gum biopolymer was used in attempts at soil strengthening [7]. However, the inter-particle relations and the strengthening behavior of the biopolymer–soil matrices have not been extensively reported in the current literature.

The purpose of this study therefore is to verify the engineering performance and efficiency of Xanthan gum biopolymer-treated soil. Experimental tests were carried out to identify the strengthening characteristics of several soils treated with a Xanthan gum biopolymer. Compressive strength measurement and a SEM analysis were performed to investigate the macro- and micro-interactions of soil–biopolymer mixtures. Long time durability was evaluated to verify the usability and sustainability of Xanthan gum biopolymer-treated soil. Various effects such as different mixing methods, soil composition, and biopolymer proportions on the strengthening performance were also evaluated.

2. Materials and experimental procedure

2.1. Xanthan gum biopolymer

Xanthan gum is a polysaccharide commonly used as a food additive and rheology modifier; it is produced by fermentation of glucose or sucrose by the *Xanthomonas campestris* bacterium [8,9]. This anionic polysaccharide is composed of D-uronic acid, D-mannose, pyruvylated mannose, 6-O-acetyl D-mannose, and 1,4-linked glucan [10]. The basic chemical structure of Xanthan gum ($\text{C}_{35}\text{H}_{49}\text{O}_{29}$) is a linear linked β -D glucose backbone with a trisaccharide side chain on every other glucose. The trisaccharide side chain is aligned with the backbone, which provides stability and overall conformation through the use of hydrogen bonds.

The most well-known characteristic of Xanthan gum is its pseudo-plasticity (i.e., viscosity degradation depending on the shear rate) [11]. In static conditions, a small amount of Xanthan gum (in most foods, 0.5%) induces a large increase in the viscosity of a liquid. Moreover, unlike other gums, Xanthan gum shows high stability under a wide range of temperatures and pH [12,13]. In addition, its anionic and hydrophilic surface characteristics facilitate interactions with cations [14,15] and other polysaccharides, such as glucose, mannose ($\text{C}_6\text{H}_{12}\text{O}_6$), potassium gluconate ($\text{C}_6\text{H}_{11}\text{KO}_7$), acetate (CH_3CO_2^-), and pyruvate ($\text{CH}_3\text{COCO}_2^-$), inducing stronger gelation [16].

In the field, Xanthan gum has been used in the oil industry as a drilling mud thickener, because it provides consistent rheology through the drilling hole [17]. It is also applied as an additive in concrete to increase viscosity and prevent wash-outs [18].

2.2. Soils tested

2.2.1. Sand

Jumunjin sand is a standard sand in Korea (USCS = SP); its mean grain size is $D_{50} = 0.52 \text{ mm}$ ($C_u = 1.35$, $C_c = 1.14$). Its specific gravity (G_s) is 2.65 and its structural composition is between $e_{\min} = 0.644$ and $e_{\max} = 0.892$.

2.2.2. Natural soil

Natural soil was sampled from an embankment construction site in Cheonan, Korea. The in-situ soil is composed mostly of sand mixed with a few fine soils; its mean grain size is $D_{50} = 0.32 \text{ mm}$ ($C_u = 3.02$, $C_c = 0.92$). Its specific gravity (i.e., $G_s = 2.65$) and particle size distribution data (Fig. 1) lead to classification of this natural soil as poorly graded sand with silt (SP-SM).

2.2.3. Red Yellow soil

Red Yellow soil (*hwangtoh* in Korean) is a common residual soil in Korea originating from weathered granite, which distinguishes it from yellow loess in China. Red Yellow soil is composed mostly of kaolinite, halloysite, illite, vermiculite, and chlorite. The primary chemical components of this soil are SiO_2 , Al_2O_3 , Fe, Mg, Na, and K. It has a hive structure with a large surface area in which most of the voids are composed of a double layer structure. Red Yellow soil has a specific gravity

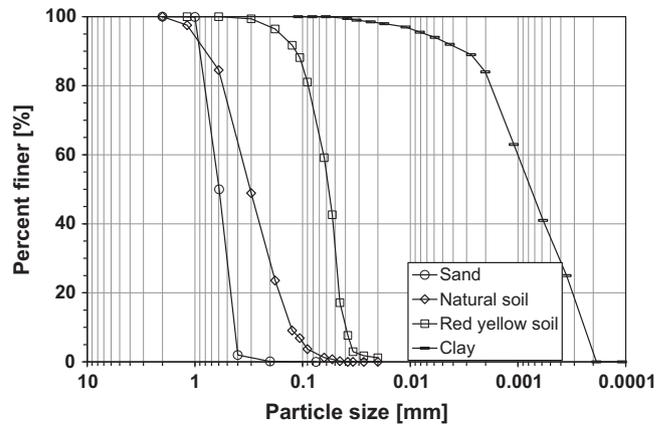


Fig. 1. Particle size distribution curves of sand, Natural soil, Red Yellow soil, and clay.

$G_s = 2.70$ and can be classified as sandy lean clay (CL) on the basis of the particle size distribution (i.e., $D_{50} = 0.058 \text{ mm}$, $R_{200} = 27$) and Atterberg limits (i.e., $LL = 44$, $PI = 18$). Details are listed in Table 1.

2.2.4. Clay

Kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) is a single silica-tetrahedral sheet with a distorted gibbsite sheet. Each layer of kaolinite easily bonds to another through hydrogen bonds [19]. Due to inter-particle hydrogen bonding, pure kaolinite particles are not easily broken down or separated. Furthermore, any sorption (e.g., hydrogen bonding) occurring along the edges and surfaces of the kaolinite leads to a strong structural composition [20]. Kaolinite is thus expected to show appropriate interaction with Xanthan gum. Bintang kaolin (Belitung Island, Indonesia) is used to represent clay in this study. The basic properties of kaolin are also summarized in Table 1.

2.3. Specimen preparation

The soils were mixed with the biopolymer at a 1% weight ratio of Xanthan gum to soil (i.e., $w/w = 1\%$). Different water contents were separately applied for the soils (i.e., sand = 30%, natural soil = 30%, Red Yellow soil = 60%, and clay = 60%) due to the different soil–water characteristics (e.g., liquid limit). For proper mixing, purified Xanthan gum (Sigma–Aldrich®, CAS number 11138-66-2) was dissolved in distilled water. To increase the solubility, the solvent (i.e., distilled water) was heated to 80°C , and a magnet stirrer was used for uniform dissolution. The Xanthan gum solution (with concentrations of 3.33% for sand and natural soil, and 1.67% for Red Yellow soil and clay) was thoroughly mixed with soil. For the sand, natural soil, and Red Yellow soil, samples with $w/w = 0.5\%$ and 1.5% conditions were additionally prepared to investigate the strengthening mechanism of soil composites consisting of coarse and fine particles together, where the Xanthan gum–fine soil matrix is expected to behave as a cementation binder between coarse particles. Dry mixing was performed for the Red Yellow soil to compare the performance variation induced by different mixing methods. For dry mixing, purified Xanthan gum ($w/w = 1\%$) was thoroughly mixed with dried Red Yellow soil before adding water (i.e., 60%) for mixing, while wet mixing was performed under the same temperature conditions (i.e., at room without heating).

The Xanthan gum–soil mixture was placed into a cubical ($40 \text{ mm} \times 40 \text{ mm} \times 40 \text{ mm}$) mold. Even though cubic specimens show different failure patterns and levels of failure strength compared to cylindrical samples ($\sigma_{\text{cube}} = \sigma_{\text{cylinder}}/0.85$), they were chosen for this study because they are easier to test in numerous mixing cases in terms of specimen preparation and test performance [21]. The cubic specimens were air dried at room temperature (20°C), forming a firm Xanthan gum–soil mixture.

In addition, 10% ordinary Portland cement (Lafarge Halla®) mixed Red Yellow soil samples were prepared to compare the strengthening efficiency of Xanthan gum treatment with that of typical soil–cement methods [22,23].

2.4. Test procedure

The unconfined compressive strength of cubic specimens was measured using a standard UTM (Universal Testing Machine) device (INSTRON 5583, strain: 1%/min). All geometric dimensions were measured, as was specimen mass, while the top and bottom surfaces were slightly trimmed to avoid an uneven stress distribution during the testing. Additionally, in order to prevent stress localization, filter paper was placed above and below the samples during testing. Samples were loaded until failure and the residual compressive strength was observed. Three measures for each case were averaged and all data points deviated less than 5% from the average.

Table 1
Basic properties of Korean Red Yellow soil and clay.

Soil	Specific gravity G_s	Liquid limit LL (%)	Plastic limit PL (%)	pH	D_{50} (mm)	USCS
Red Yellow soil	2.33	44	26	6.2	0.058	CL
Clay (kaolinite)	2.65	56	24	6.6	0.044	CH
Sand	2.65	–	–	7	0.52	S
Natural soil	2.65	–	–	7	0.32	SP–SM

The elastic modulus (*i.e.* secant modulus) was estimated by measuring the slope of a straight line (in most cases, between 1–2% strain) of the stress–strain curve during compression.

SEM (Scanning Electron Microscope) images were also taken using a Nova 230 device. Samples were dried and coated with gold (Emitech K550X) in order to avoid electron scattering on the specimen surfaces. Images of the Xanthan gum interactions with the different types of soil were then taken.

3. Strengthening parameters of Xanthan gum treated soils

3.1. Microscopic behavior

SEM images of Xanthan gum treated sand, clay, and Red Yellow soil are shown in Fig. 2. Xanthan treatment for coarse sand (Fig. 2a)

coated the grain surfaces and increased the contact area among the soil particles, while also creating connection bridges between particles that are not directly in contact. This shows that the strength values of Xanthan treated coarse grained soils greatly depend on the strength of the Xanthan gum fiber matrices (in the form of threads or fabrics) existing in the pore space.

Due to the electrically charged clay particles, direct interaction (*e.g.*, hydrogen bonding) between fine particles and Xanthan gum strands occurs (Fig. 2b). Along with these direct interactions, Xanthan gum bridges form between distant particles; this enhances particle alignment and is in line with strength improvement (Fig. 2c). This demonstrates that the strengthening mechanism of Xanthan gum treated fine soil can be explained as a combination

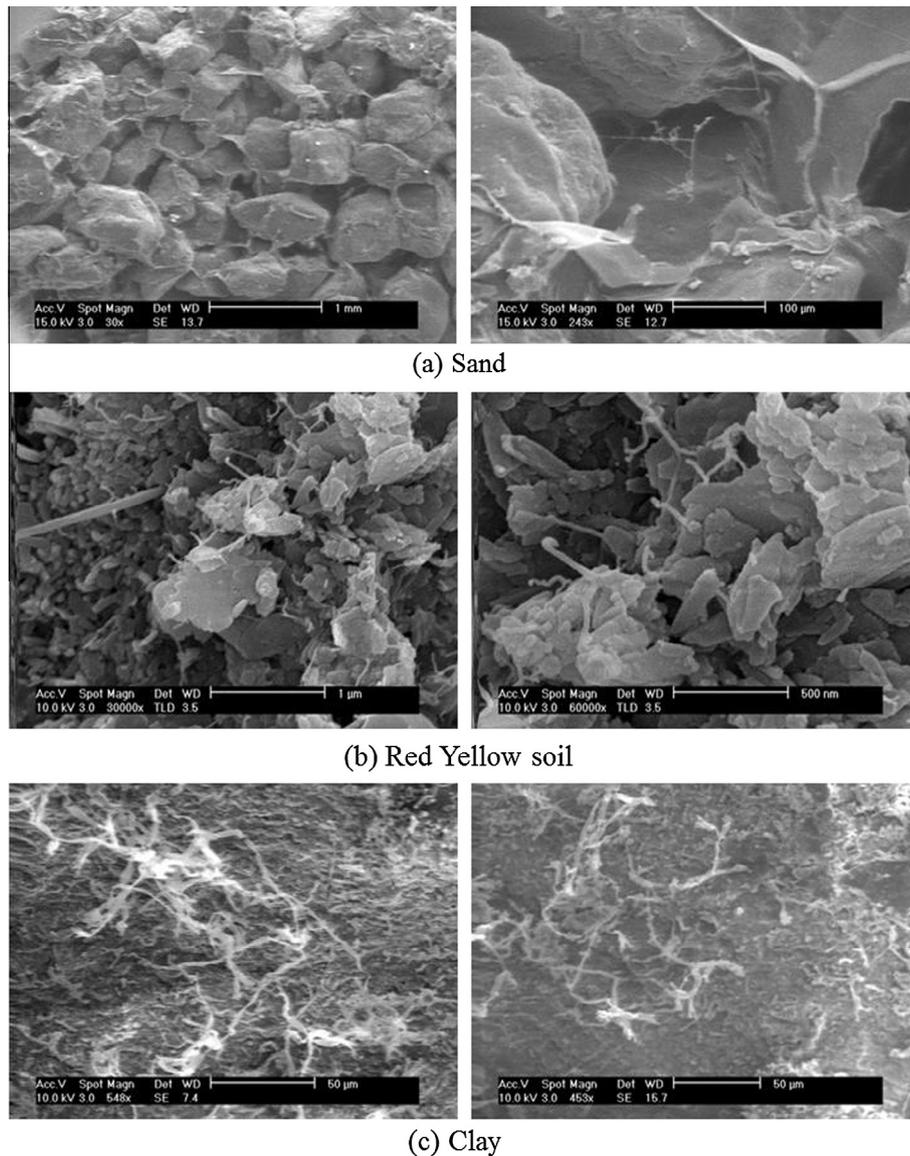


Fig. 2. The SEM images of Xanthan gum biopolymer treated soils.

of the Xanthan gum matrix (e.g., threads or textiles) strength and the hydrogen or electro-static bonding characteristics between the Xanthan gum and fine soil particles: these two factors lead to firm Xanthan gum–fine soil matrices.

3.2. Soil type effect

The compressive strength values of various soils at 28 days are shown in Fig. 3. All specimens show moisture content lower than 2%, and thus the effect of moisture on soil can be avoided in strengthening explanations.

In general, the Xanthan gum treated soils shown in Fig. 3 exhibited significant increases in compressive strength and elastic modulus. Even though the strength of the sand was unmeasurable, Xanthan treated sand shows a viable compressive strength, indicating that Xanthan treatment adds a cohesive property along with an increase of the elastic modulus in cohesionless sand. Moreover, Xanthan gum enhances the inter-particle bonding of fine soil (i.e., clay), showing six-fold compressive strength improvement.

From the viewpoint of stiffness, Xanthan treatment increases the stiffness in all cases; furthermore, it can be seen that the stiffness difference between Xanthan treated clay and sand is not as great as the difference between the compressive strengths of the two.

Xanthan gum treatment renders a higher compressive strength for clayey soils (2540 kPa) than it does for sandy soil (880 kPa). It is expected that, for further strengthening, Xanthan monomers can

be directly bonded to clayey particles via cation bridging and hydrogen bonding between the carboxylic acid (–COOH) and hydroxyl (–OH) groups of Xanthan and electrically charged fine particle surfaces [24]; on the other hand, electro-static and hydrogen bonding phenomena cannot be expected for sand, because sand particles carry no electrical charges.

Meanwhile, Xanthan gum treated natural soil and Red Yellow soil both exhibited higher compressive strengths (3680 kPa and 4940 kPa, respectively) and elastic moduli (220 MPa and 195 MPa) than did either Xanthan gum treated sand or clay. Generally, polysaccharides are known to have strong sorption and strong microstructural interaction with clay [25]. The higher strength revealed by Xanthan gum treatment on natural soil and Red Yellow soil indicates that Xanthan gum can be more effectively used with well graded soils than with poorly graded soils. Specifically, the strengthening behavior of sandy lean clay (i.e., Red Yellow soil) and poorly graded silty sand (i.e., natural soil) implies that fine particles in well graded soils form firm Xanthan gum–fine soil matrices via electrostatic and hydrogen bonding, while the friction component of coarse soil particles synergizes the strengthening of soil. The relatively higher stiffness of Xanthan treated natural soil and Red Yellow soil is in accordance with the elastic wave velocity characteristics of sand–clay mixtures.

From an elastic wave velocity perspective, a sand:clay ratio of 60:40 shows a maximum *P*-wave velocity, at which clay disperses in the pore space of the load bearing sand [26]. Thus, well graded soils are expected to show high strength due to a combination of Xanthan gum–fine soil matrix formation and enhanced inter-particle characteristics (e.g., contacts, force) induced by the cementation of Xanthan gum–fine soil matrices in the pore space of the load bearing coarse particles.

Furthermore, 1% Xanthan gum treatment results in much higher compressive strength than 10% cement treatment, even though Xanthan gum treatment renders better ductility (i.e., lower stiffness). Therefore, Xanthan gum has strong potential for use related to environmentally-friendly purposes in place of conventional construction and building materials.

3.3. Long term durability assessment

The decomposition problem is an important concern for polymers (e.g., polyethylene, starch, polyester) used in geotechnical engineering [27,28]. Although Xanthan gum is known as a thermo-stable biopolymer [29], it shows decomposition by bacteria or aerobic microorganisms [30]. The long term durability against bio-decomposition of Xanthan gum treated soil thus must be verified to allow recommendation of the usage of Xanthan gum in geotechnical engineering fields.

Fig. 4 shows the stress–strain behavior of Xanthan gum treated clay and sand on the 21st and 63rd days. In all cases, the compressive strength of both sand and clay slightly increased. The stiffness of Xanthan gum treated clay meanwhile remained nearly constant while that of sand showed a notable increase with time regardless of the Xanthan gum content.

The compressive strength increase of both soils is ascribed to continuous Xanthan gum gel hardening due to the dehydration of residual moisture in Xanthan gels. The stiffness behavior of Xanthan gum treated sand indicates that the micro-interactions between load bearing sand particles and cementitious Xanthan gum gels improve the particle contact characteristics. The stiffness increase of Xanthan gum treated sand (40 MPa at 21st day → 80 MPa at 28th day → 100 MPa at 63rd day; Figs. 3 and 4) regardless of biopolymer content (i.e., 1.0% and 1.5%) indicates that 1.0% Xanthan gum is sufficient to provide cementation at particle-to-particle contacts of sand. Further, there was no evidence of material decomposition (e.g., strength or stiffness loss) during 3 months.

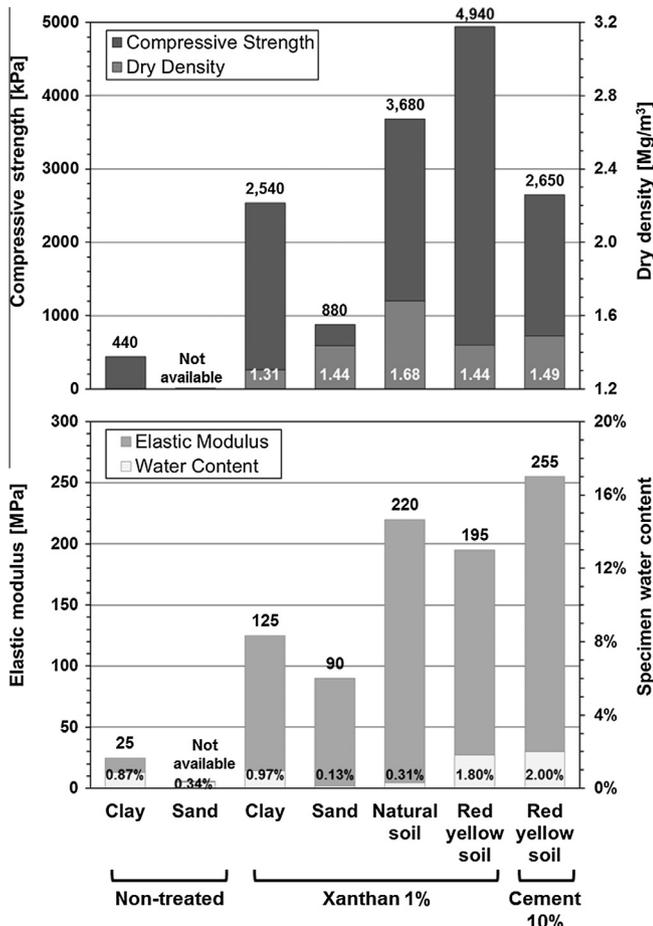


Fig. 3. Compressive strength, elastic modulus, dry density, and water content of 1% Xanthan gum treated soil specimens 28 days after mixing. Non-treated pure clay, sand, and 10% cement treated Red Yellow soil are plotted together for comparison.

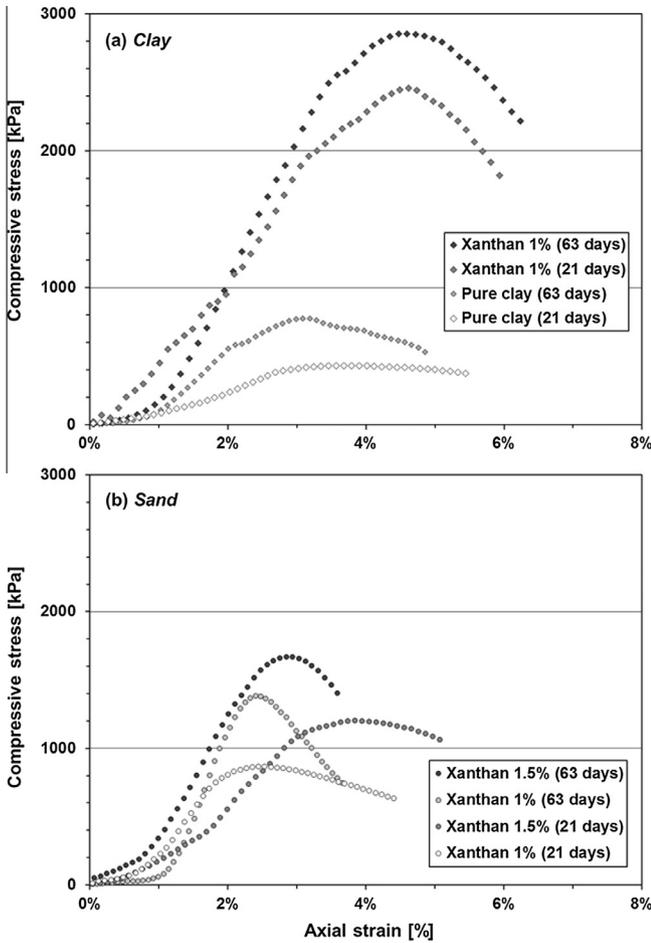


Fig. 4. Stress–strain behavior of Xanthan treated clay (a) and sand (b) at 21 and 63 days of curing. In all cases, the compressive strength slightly increases. In the aim of stiffness, Xanthan treated clay remains almost constant, while Xanthan treated sand specimens show increments which are not negligible.

Therefore, the usage of Xanthan gum for soil treatment can be recommended, especially under low moisture conditions.

In addition, because biopolymers are organic matter, there are concerns about the durability of Xanthan treated soils. In terms of durability against decomposition, a comparison between Xanthan gum treated Red Yellow soil cured for 28 days and 750 days without wetting or drying (Fig. 5) shows that the stability of Xanthan gum treated Red Yellow soil did not degrade but actually remained constant or increased slightly. The compressive strength and elastic modulus appeared to increase slightly; this increase may perhaps also be attributed to possible long term variations such as hardening or aging.

In fact, Xanthan gum is a stable compound against thermo-decomposition below 250 °C [12]. It is also a stable polysaccharide against oxidation, and is widely used as an anti-oxidation additive in oil and protein products [13]. Moreover, its stability under extreme conditions including acidic and alkaline environments and high salt concentrations provides high potential for use in various industrial purposes [31]. However, the stability under cyclic wetting and drying should be verified in further studies.

3.4. Xanthan gum content

The compressive strength values of Xanthan gum treated sand, natural soil, and Red Yellow soil with different Xanthan content (i.e., 0.5%, 1.0%, and 1.5%) on the 28th day of curing are shown in Fig. 6. The compressive strength values of the Xanthan gum treated

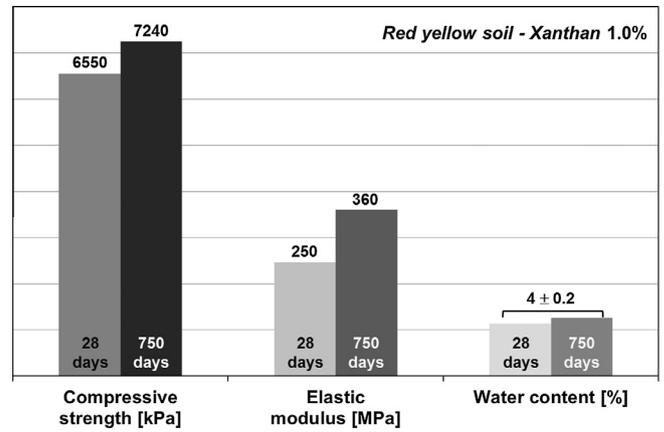


Fig. 5. The mechanical properties measured after 28 days and 2 years for long-time verification. The results show excellent durability performance which ease concerns of functional degradation.

soils tend to increase with an increase in the Xanthan gum content. It is expected that higher Xanthan gum content leads to a larger and thicker Xanthan matrix in coarse soils (e.g., sand) and more soil–Xanthan gum interactions in fine soils. The compressive strength, however, increases non-linearly, and is expected that it would level off with a large increase of Xanthan gum content (Fig. 6b). The most effective amount of Xanthan gum content appears to be approximately in a range of 1–1.5%. Larger amounts

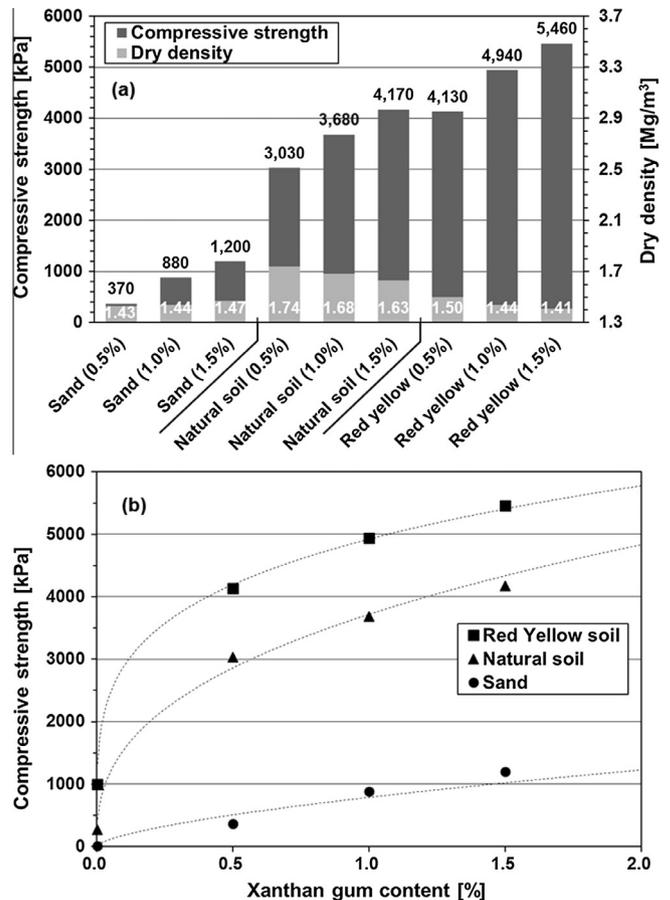


Fig. 6. The strength variation with different soil types and Xanthan gum contents. Higher biopolymer content renders higher strength. (a) The approximated trends show that Red Yellow soil is the most effective soil type among others. (b) The global trend indicates that higher fine content in soil renders higher strengthening induced by soil–biopolymer interaction.

of Xanthan gum lead to lower workability because the viscosity of the soil–Xanthan gum–water mixture increases significantly above 1.5% Xanthan content in fine soils.

Another factor that varies with Xanthan gum content is the dry density of the Xanthan gum treated soils (Fig. 6a). Due to the bonding and rheology characteristics of Xanthan gum, the variation in the dry density of the treated soils appears to depend on the type of soil with which the Xanthan gum is mixed. In the case of coarse grained soils, Xanthan gum creates gel matrices and indirectly interacts with sand particles on surfaces (e.g., coating), between particle-to-particle contacts (e.g., cementation), and within void spaces (e.g., pore filling). The dry density of Xanthan gum treated sand thus increases slightly with higher Xanthan gum content, because the void volume decreases due to contraction of Xanthan gum gels via dehydration [32]. Meanwhile, for fine grained soils, Xanthan gum undergoes direct interaction with fine particles and water. As Xanthan gum content increases, surplus Xanthan monomers adsorb water and form a highly viscous suspension [33], which fills the spaces between the soil particles. With this arrangement, larger Xanthan gum content will increase the spaces between the clay particles and will thereby increase the global volume of void spaces within the treated soils. Consequently, larger Xanthan gum content effectively decreases the dry density of the treated soils.

Natural soil, which contains silty particles but is primarily composed of sandy particles, shows high dry density in the initial phase, while this density decreases with an increase of the Xanthan gum–fine soil matrix concentration. Moreover, Red Yellow soil shows the lowest dry density values due to its fine particle content (more than 60%), which is higher than that of natural soil (approximately 20%); high fine particle content leads to enhanced Xanthan gum–soil–water interaction.

3.5. Mixing method

For the sample preparation, two different mixing methods were used: dry mixing in which the Xanthan gum powder was directly mixed with the soil before adding water, and wet mixing in which the Xanthan gum was first mixed with water to form a hydro-solution before mixing in the soil. Both mixing methods were implemented at room temperature. Compressive strength test results on the 28th day show that dry mixing is more effective than wet mixing when the aim is to strengthen the material (Fig. 7).

This effect is attributed to the solubility and viscosity of Xanthan gum in water. Solubility tests on Xanthan gum carried out in this study showed that, at room temperature, 1.4% Xanthan gum content relative to water is the solubility point of Xanthan gum for thorough dissolution. Achieving higher Xanthan gum content above 1.5% in water is extremely difficult due to the increased viscosity of the Xanthan gum solution.

A value of 1% Xanthan gum relative to the quantity of soil leads to a value of approximately 1.7% of Xanthan gum to water (i.e., water content = 60% for Red Yellow soil); this value is well above the solubility point of 1.4%. Therefore, thorough mixing of Xanthan gum into the water may not have been possible for these mixing conditions, and an even distribution of Xanthan in the soil is unlikely. Meanwhile, dry mixing provides a well-distributed Xanthan matrix in soil. As a result, the compressive strength of the material prepared using wet mixing will not be the same as that prepared by dry mixing.

However, dry mixing is more effective only when the ratio of Xanthan gum to water is above the solubility point. Generally, the solubility of Xanthan gum increases with an increase of temperature [34]. For this reason, except for the mixing method comparison tests, the solvent (i.e., distilled water) temperature was increased to 80 °C for the preparation of other specimens. This

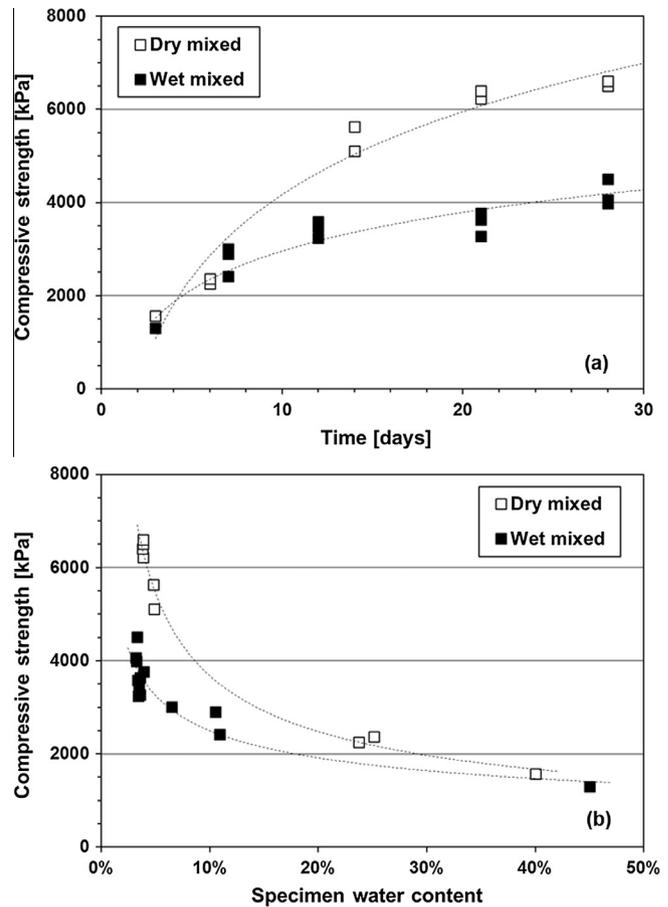


Fig. 7. The strengthening behavior of Xanthan gum treated (1%) Red Yellow soil with different mixing methods. Dry mixing shows higher strength which indicates that the dry mixing (i.e., mixing dried soil and Xanthan powder thoroughly and then mixing with water) performs a more uniform and sufficient biopolymer–soil mixture.

implies that dry mixing would be more appropriate for practical applications in the field, where thermal treatment is inconvenient.

4. Implications and discussion

4.1. Strengthening dominating factors

Results of experimental tests show that the strength values of the Xanthan gum treated soils mainly depend on four factors: (1) type of soil, (2) dehydration (e.g., moisture content), (3) Xanthan gum content, and (4) mixing method. The strength increases with an increase in the Xanthan gum content, but the strengthening effect tends to decrease or level off at higher Xanthan concentrations. As for the type of soil, it was shown that fine soils have a better strengthening effect than coarse grained soils; however, the most effective soil type was a mixture of the two with a well-graded size distribution. Also, for longer curing times, the water content within the soil decreased and, as a result, the compressive strength of the soils increased. Finally, the dry mixing method was shown to yield a more even distribution of Xanthan gum within the soil, thereby maximizing the strengthening effect on the soil.

4.2. Strengthening model of Xanthan gum treated soil

In the case of coarse grained soil (i.e., sand), the low and gradual strengthening behavior induced by Xanthan gum treatment (Fig. 6b) verifies that coarse particles do not have significant interaction with Xanthan gum, and this is ascribed to their electrically

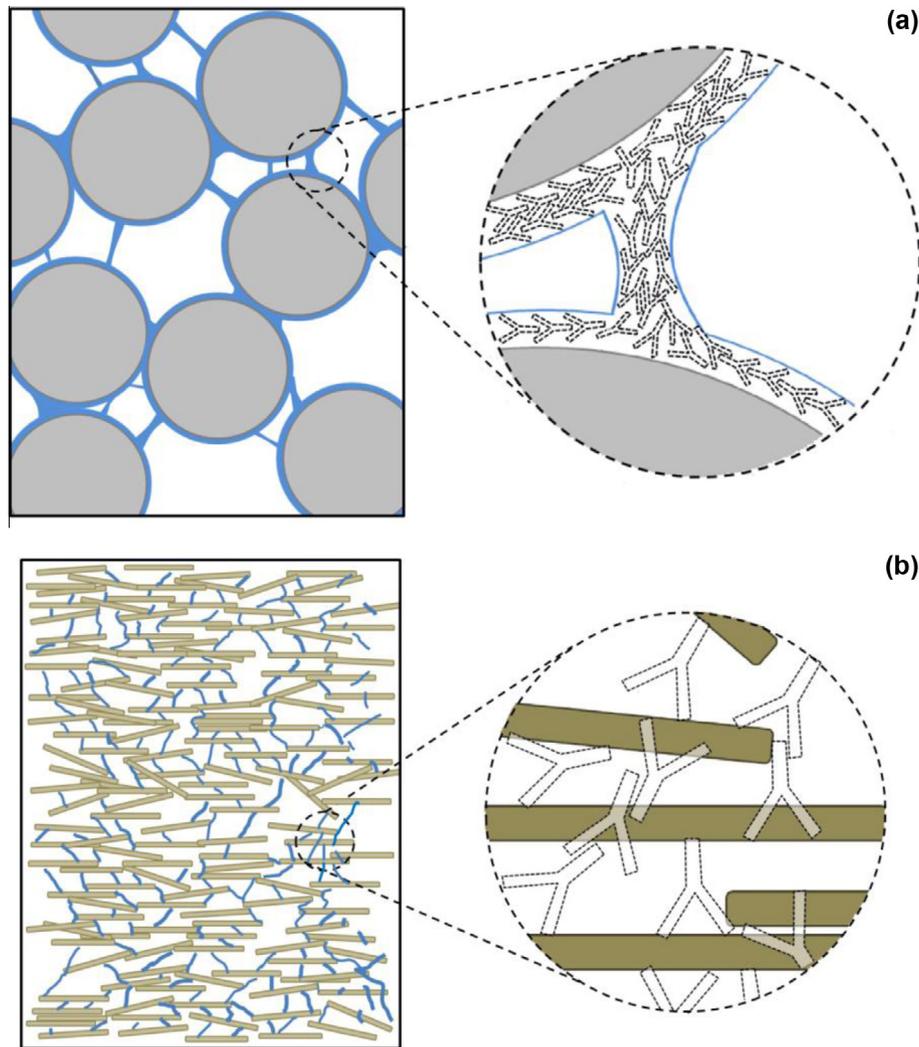


Fig. 8. Xanthan gum–soil interaction model. Coarse soil (a) and fine soil (b). According to the electrically neutral particle surfaces, Xanthan gum molecules accumulate and align as thread and textiles. The strength of Xanthan gum–coarse soil mixture strongly depends on the strength of Xanthan gum gels. As fine soil particle surfaces are electrically charged, fine particles directly interact with Xanthan gum fibers in microscale. Moreover, Xanthan gum fibers also form threads providing reinforcement between soil clods.

neutral particle surfaces (Fig. 2a). Therefore, Xanthan gum does not interact with the soil itself but instead accumulates and aligns as threads and textiles (Fig. 8a).

Considering that Xanthan gum threads and fabrics coat grain particles, the strength of the treated soils depends on the Xanthan gum matrix. The Xanthan gum matrix further strengthens the soil through enhanced inter-particle interactions, resulting in greater strength, higher stiffness, and a more brittle structure induced by dehydration, because the Xanthan gum matrix shrinks due to water loss from curing and becomes more like a hard plastic.

For pure fine soils, Xanthan gum polymers interact with soil particles independently and directly (Fig. 2c), rather than forming thread or textile type matrices. Moreover, the effect of curing (*i.e.*, time) does not dramatically change the structural alignment of the Xanthan gum–a fine soil matrix (Fig. 8b), except for volumetric shrinkage due to drying. Thus, interactions remain ductile and the material does not become as brittle as that formed when using coarse grained soils.

The higher strength of Red Yellow soil compared to natural soil (Fig. 6) emphasizes the importance of fine contents in Xanthan gum treated soil (*i.e.*, fine content of red yellow soil is higher than 60%, while that of natural soil is less than 10%). Direct interaction between fine soil particles and Xanthan gum (Fig. 2b) via hydrogen

or electrostatic bonding leads to higher soil strength. Therefore, in the case of coarse and fine compositions, Xanthan gum–fine soil matrices (Fig. 8b) are expected to replace the Xanthan matrix (Fig. 8a) by providing stronger inter-particle bonding governed by the strength of the Xanthan gum–fine soil matrix.

5. Conclusions

The use of cement for soil improvement may have many beneficial effects, but in terms of eco-friendliness cement has notable shortcomings. Accordingly, many eco-friendly methods for soil improvement have been studied. The use of Xanthan gum for soil treatment shows viable results, reflecting that it can be used to greatly increase the compressive strength of soil.

Strengthening effects in relation to soil type were studied using sand, natural soil, Red Yellow soil, and clay. The results show that the strengthening effect of Xanthan gum increases in the presence of fine grained soil. This is most likely the result of Xanthan gum's interactions (*i.e.*, hydrogen bonding) with the charged surfaces of clayey soils. However, this interaction does not mean that Xanthan gum treatment is ineffectual for poorly graded sand. In terms of strengthening efficiency (*e.g.*, the compressive strength ratio between Xanthan treated and non-treated soils), sand shows

greater compressive strength enhancement than does clay. Moreover, experimental test results on Xanthan gum treated soils cured for a long period of time show that the Xanthan gum did not decompose and the compressive strength and elastic modulus did not decline.

Xanthan gum is shown to have a significant strengthening effect on the treated soil. This strengthening is achieved by increasing the inter-particle relations within the soil and, thereby, increasing the cohesive forces within the soil. For the case of Xanthan treated coarse grained soils, the strength increase dominantly comes from the Xanthan matrix that is formed on the surface and in the void spaces of the soils; this strengthening is therefore very dependent on the strength of the Xanthan gum itself. This Xanthan matrix increases the stiffness and makes the soil more brittle as the soil cures. On the other hand, the majority of the strength of Xanthan treated fine grained soils originates from hydrogen or electrostatic bonding between Xanthan monomers and fine soil particles. Direct interaction between Xanthan gum and clayey soil forms firm biopolymer–soil matrices, which act as cementitious binders between sandy (*i.e.*, coarse) particles. Therefore, strengthening is maximized, especially with soils that are well graded instead of poorly graded. Thus, adding fine particles (around 10% or less) is a possible alternative to treat poorly graded sand in field applications. However, the soil strengthening induced by Xanthan gum treatment has other influencing factors such as the presence of ions (*e.g.*, alkali- or alkali-earth metal ions), biopolymer rheology, soil composition and mineralogy, and so on. Further studies are thus recommended for deeper understanding of Xanthan gum soil treatment.

The effect of soil strengthening with Xanthan gum content is shown to increase nonlinearly and level off at higher concentrations of Xanthan gum. Furthermore, high Xanthan gum content should be avoided due to material cost and workability (*e.g.*, high viscosity leading to poor mixing) problems. The most economical and efficient concentration of Xanthan gum for soil treatment thus appears to be approximately 1–1.5%.

With little or no adverse effects in terms of durability, as well as environmentally friendly properties, Xanthan gum can be recommended as a viable soil improvement material, especially for cases of dry soil. Above all, the findings from this study are expected to provide quantified, strong data for the application of *Xanthomonas campestris* bacterium treated soil in the field of bio-soil implementation.

Acknowledgements

The research described in this paper was financially supported by the Basic Science Research Program, through the National Research Foundation (NRF) of the Republic of Korea, funded by the Ministry of Education (NRF-2012R1A1A2007002) and by a grant from the Strategic Research Project (Development of Key Excavation Solutions for Expandable Urban Underground Space), funded by the Korea Institute of Civil Engineering and Building Technology (KICT) of the Republic of Korea.

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