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Investigation of mechanical behavior of sustainable construction materials: Recycled glass sand stabilized with natural binder material — Biopolymers

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ABSTRACT

Presented in this paper is a study on the biopolymer treated recycled glass sand (BRGS). The effect of curing period, temperature, initial mixing moisture content and biopolymer concentration on mechanical behaviors of BRGS were examined through unconfined compaction strength (UCS), consolidated and drained triaxial test and scanning electron microscopy (SEM) analysis. The results revealed that biopolymer had a significant improvement on the soil stability. The mixing moisture content, biopolymer concentration and curing condition had a strong influence on soil strength. The strength of BRGS increased with dehydration, while further addition of biopolymer concentration may result in a decrease in strength. It was found that different types of biopolymers had their own preferences for curing conditions. The strength of agar treated RGS (thermal induced biopolymer) cured at 105 ℃ for 30 days was six times stronger than that cured at room temperature, while the optimal curing temperature of alginate treated RGS (ionic gelation biopolymer) was 50 ℃. The BRGS presented a slight decrease in friction angle but a significant increase in cohesion. The SEM image showing biopolymer uniformly wrapped RGS particles.

1. Introduction

Sand is a limited material and the second important natural resource in this world. It also plays an important role in many civil engineering applications, including concrete/asphalt aggregate, road base stabilization, construction fill, and other mortars. Due to the rapid growth of urbanization and modernization, the demand for sand had increased in recent years. There was 130 billion worth of sand used by construction industry every year [1]. It has been reported that sand mining has greatly exceeded the natural renewal rates and is now increasing exponentially [2]. The practice of sand mining became a worldwide environmental issue due to the demand for sand [3]. The impacts of sand mining on the environment, especially on coastal and river habitats has drawn much attention to many researchers [4]. It has been found that the amounts of sand mined from river and lake could affect the soil organic carbon (SOC) storage and N-removal in the riparian area, which could increase 12% global CO_2 storage and reduce the N-removal up to 57% [5]. The large demand for sand in infrastructure development eager civil engineers to find sustainable substitutes. In recent year, recycling the waste glass to replace the sand in the civil engineering attracts people's attention due to their similar composition. Glass is a common material in daily life, including jars, bowls, and windows. It has been reported that 11.5 million tons of waste glass produced at U.S. in 2014, and 73% of them were direct disposal of landfill [6]. With the increasing demand for glass by building materials and people's daily use, the waste glass produced will increase constantly, which will have a negative impact on the environment [7]. For the environmental concerns, some environmentally friendly materials and methods are being studied in the civil engineering [8–10]. Siad et al. [11] replaced silica sand to recycled glass sand in the cement and tested the compressive strength. The results illustrated that the compressive strength of recycled glass sand-cement (7.3 MPa) had a significant increase than that of silica sand-cement (2.2 MPa) in the first 7 days. With the curing time over 120 days, the compressive strength of recycled glass sand-cement also showed a similarity to that of silica sand-cement. Lam et al. [12] used the waste glass and lime to substitute the natural river sand and cement in the textile reinforced mortar composite system. Although the flexural strength and compression strength decreased with the increase of waste glass and lime, this eco-friendly material could be used to be compatible with ancient building materials.

Biopolymers, an environmentally friendly method used in soil improvement, have been shown to have several promising features like

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mechanical improvement, low environmental impact and biodegradation [13,14]. For example, mixing directly with biopolymer and soil could form a biopolymer-soil mixture provided high strength without high CO_2 emitted. Specifically, the UCS of 2% gellan gum-treated sand (434.6 kPa) is similar to that of 12% cement-treated sand (380 kPa) [15]. Because of their unique integration of solid and liquid properties, biopolymer has been explored in varied applications [16,17]. In civil engineering, as an adhesive for the soil particles, biopolymers could improve the shear strength, durability and reduce the hydraulic conductivity [18–20]. Hataf et al. [13] mixed the chitosan biopolymer solution with clay sand and found the significant improvement on mechanical properties of the chitosan treated clay sand. Wen et al. [14] reported that biopolymer could improve the geotechnical properties of cohesionless sand in a short time (cured for 1 day). Kwon et al. [21] demonstrated the feasibility of biopolymer reducing sand surface erosion. The erosion test showed that the critical shear stress increased ten-fold and the erodibility coefficient reduced 90%. Seo et al. [22] reported a site application of biopolymer-treated sandy soil on the slope stability improvement. They mixed the biopolymers (xanthan gum, Beta-glucan, starch) and sandy soil in the field for 20 mins before site application and sprayed the mixture on the slope surface to form a 5 cm cover for slope protection. Kwon et al. [23] used xanthan gum-treated soil to improve the internal erosion of earthen embankment. The untreated embankment eroded rapidly and collapse within 1500 s by the seepage flow, while no considerable erosion was observed on 1% xanthan gum-treated embankment until 2500 s. However, previous research has mainly focused on the natural soil with biopolymer treatment, while the effect of biopolymer treatment on recycled artificial materials is unknown. Therefore, three different types of commonly used biopolymers were used in this study to investigate the mechanical behaviors of recycled glass sand with biopolymer treatment: agar gum (thermal induced), xanthan gum (self-assembled) and Ca-alginate (ionic gelation).

The goal of this study is to develop sustainable and environmentally friendly geomaterials by applying biopolymers on recycled glass sand. In this study, the mechanical behaviors of biopolymer-treated recycled glass sand (BRGS) were evaluated through unconfined compression strength (UCS) test and consolidated-drained triaxial test. The impacts of different biopolymer concentrations, mixing moisture content and curing conditions on mechanical behaviors of biopolymers were explored in this study. The micro-structure of BRGS was also analyzed by scanning electron microscope (SEM) images.

2. Materials and methods

2.1. Recycled sand

The Recycled Glass Sand (RGS) was used in this study. The RGS L4 was produced by Glass Half Full in New Orleans. Glass Half Full's product comes from soda lime glass food and beverage containers. Glass is collected via the free drop-off hubs as well as paid pickup services for residents and businesses in the Greater New Orleans region from July 2021 to July 2022. Once it reaches the facility it is crushed down into sand and gravel and separated by size for each use. Glass Half Full currently uses the Andela 05 L machine which is capable of processing 1 ton of glass into sand and gravel per hour. According to the Unified Soil Classification System (USCS) classification, L4 was classified as a poorly graded sand (SP). As shown in Fig. 1, the particle size distribution between L4 and Ottawa standard sand was close. Its permeability is 1.9 × 10–03 m/s and its bulk density is 1.28 g/cm3. The detail components of the RGS are shown in Table 1.

2.2. Biopolymers

Biopolymers could be categorized into three major classes: polynucleotides, polypeptides, and polysaccharides [15]. The most common

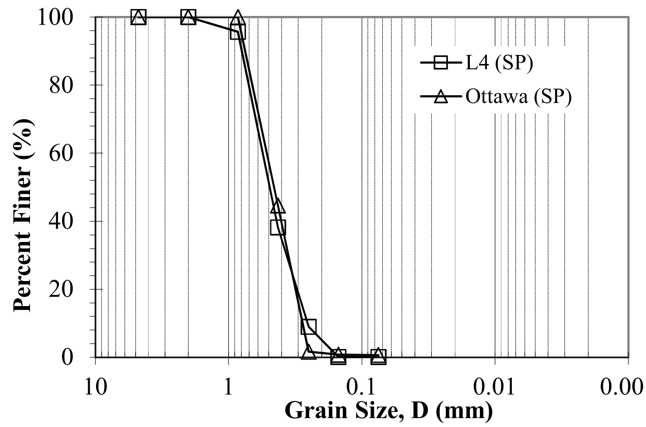

Fig. 1. Particle size distribution curves of recycled glass sand L4 and Ottawa sand.

Table 1
Recycled glass sand chemical properties.

SiO_2	CaO	Al_2O_3	Na_2O
73%	8.5%	0.5%	13%

biopolymer type is polysaccharides in the civil engineering practices due to being highly hydrophilic, which can form viscous hydroxyl by mixing water to improve the strength of soil. The polysaccharides biopolymers are very easy to produce and convenient to use. Three different types of commonly used biopolymers were used in this study to investigate the mechanical behaviors of recycled glass sand with biopolymer treatment: agar gum (gel formed with temperature change), xanthan gum (gel formed in the air condition) and Ca-alginate (soil improvement through the ionic exchange). Compared with other biopolymers, these three biopolymers have the advantage of lower cost [24,25] and are widely studied in the civil engineering application [14–15 and 19]. What's more, previous research explored that these three biopolymers had good performance on the natural soil improvement, while the effect of biopolymer treatment on recycled glass sand is unknown [22–28].

Thermal-induced biopolymer (*Agar gum*): Agar gum is a form of double helices. The water molecules were moved into the space between the double helices of agar during the process of agar gelation formation, which can contribute to the stability of agar double helices [24]. In this process, agar is formed to reversible gels by cooling heated solutions without additional chemical treatment. The agar gum can be fully dissolved at temperatures over 85 °C and forms a hydrocolloid solution. In recent studies, researchers implied that agar gum had important potential use to improve the strength of soil and decrease the erosion of surface [26,27].

Ionic gelation biopolymer (*Ca-Alginate*): The Ca-Alginate solution was prepared from Sodium alginate mixing $CaCl_2$ solution, and the major reaction of this process is the exchange of sodium ions with Ca^{2+} cations in the solutions. The alginate solution was prepared from alginate powder mixed with Deionized water (DI water) at room temperature.

Self-assembly biopolymer (*Xanthan Gum*): Molecular self-assembly is mediated by weak noncovalent bonding, including hydrogen bonds, van der Waals forces, and hydrophobic interactions. It is adopted as a common strategy for protein-based biopolymers. Xanthan gum is a polysaccharide biopolymer produced by Xanthomonas campestris and can be dissolved at room temperature. It has been widely used in the food industry due to the high temperature and pH stability [28]. With the increase of xanthan gum content, the viscosity of xanthan gum solutions significantly increased.

2.3. Sample preparation

The soluble ability of different biopolymers was shown in Table 1. The concentration of biopolymer solution (C_b) was measured by the ratio of weight of dry biopolymer powder to the weight of dry RGS (Eq. (1)). The initial mixing moisture content(ω_b) was determined by the ratio of weight of biopolymer solution to the weight of dry RGS (Eq. (2)).

$$C_b = M_b / M_s \tag{1}$$

$$\omega_b = M_w / M_s \tag{2}$$

Where, M_b is weight of biopolymer; M_s is weight of RGS, M_w is weight of biopolymer solution.

The sample preparation methods for the biopolymer-treated recycled glass sand (BRGS) samples were as follows.

2.3.1. Hot mixing for Agar gum treated sample

The gelation of the thermal induced biopolymers occurs in response to a temperature change. The agar powder was dissolved in hot water at 100 ℃ before mixing with RGS. The RGS didn't have preheat treatment before use. To provide better homogenous mixing, the RGS and biopolymer solution were mixed on a hot plate at 100 ℃ during the hot-mixing process. After mixing, the mixture was compacted into the cylinder mold (38.1 mm * 76.2 mm) and the agar could bind the sand particles when the temperature cools down to room temperature (Fig. 2). Meanwhile, the RGS with preheated process was used as the control sample to explore the effect of curing temperature on the strength of thermal induced biopolymer.

2.3.2. Immersing for Ca-alginate treated sample

For the alginate treated sample, the sodium alginate powder was dissolved in DI water at room temperature. The RGS was mixed with the alginate solution to a workable status for further treatments. The mixture was compacted into compaction mold with a diameter of 38.1 mm and a height of 76.2 mm at room temperature. After compaction, the sample was extruded out and merged into 0.5 M $CaCl_2$ solution for 3 days (Fig. 3) [14]. The $CaCl_2$ solution was used as an ionic cross-linking agent with sodium alginate to form the Ca-alginate gel. The formatted Ca-alginate gel can cement the sand particles together and improve the mechanical performance of sand.

2.3.3. Xanthan gum treated sample

The xanthan gum powder was mixed with DI water at room temperature to prepare xanthan gum solution (Fig. 4). Since the xanthan gum does not need any exterior reaction to achieve the gelation, the RGS was directly mixed with xanthan gum solution. Then, the mixture was compacted into the mold for further curing.

In the compaction process, the biopolymer-sand mixture was compacted into the mold with three layers. The total weight of each soil sample was controlled around 160 (± 5) g. All samples were produced in accordance with the American Society for Testing and Materials (ASTM D698 [29]).

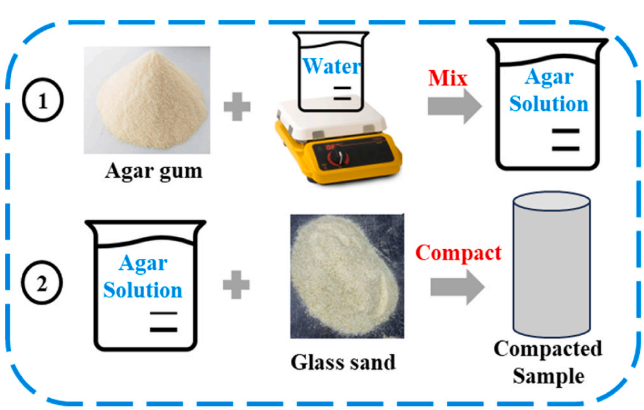

Fig. 2. The procedure of sample preparation for Agar gum treatment.

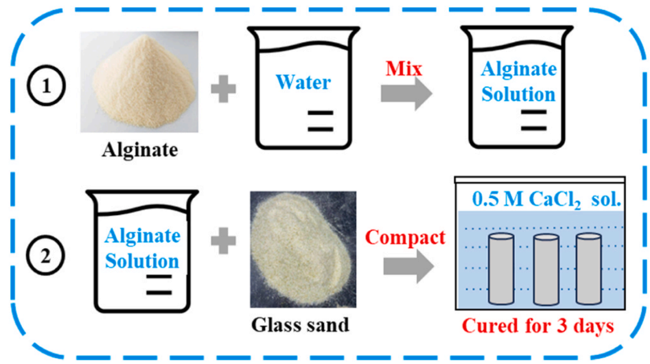

Fig. 3. The procedure of sample preparation for Ca-alginate treatment.

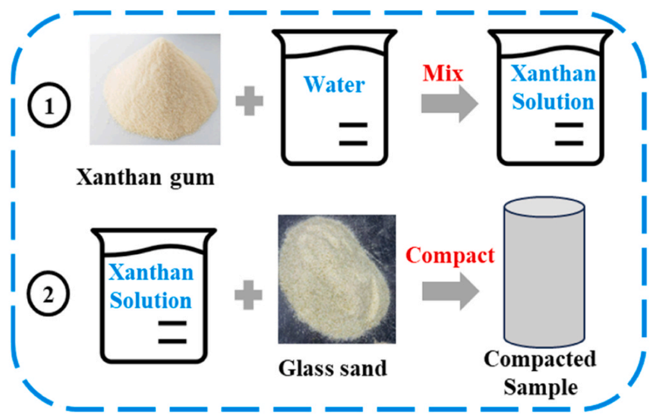

Fig. 4. The procedure of sample preparation for Xanthan gum treatment.

2.4. Biopolymer recipe development

The effects of the biopolymer concentrations and initial mixing moisture content on RGS were studied in this paper. Three different biopolymer concentrations and initial mixing moisture content were used in this study as shown in Table 2. The drying temperature and mixing moisture content were determined from literatures. The mixing moisture content and drying temperature of very poorly graded sand is ranged from 20% to 30% and 25 ℃ to 105 ℃, respectively [14,28]. The mechanical behavior of the BGRS sample under each condition was evaluated through the unconfined compression strength test. All the tested samples were oven-dried at 105 °C for 24 hrs. The optimal recipe of BRGS with different types of biopolymers were developed for further investigation.

Table 2
Biopolymer content and soluble environment.

Biopolymer	Soluble ability	Biopolymer Conc.	Initial mixing moisture content
Agar	Soluble above 85 °C	1.25%, 2.5%, 3.75%	20%,23%,25%,28%
Xanthan gum	Room temperature	1%, 2%, 3%	20%,23%,25%,28%
Alginate	Room temperature	0.3%, 0.4%, 0.5%	20%,23%,25%,28%

2.5. Curing condition

Three different curing conditions were selected to investigate the effect of curing temperature on the properties of BRGS. The prepared BRGS was cured for 1, 3, 7, 14, 30 days at (1) at room temperature (air-dried), (2) oven-dried at 50 ℃, and (3) oven-dried at 105 ℃. The moisture changes of BRGS were also monitored during the curing period.

2.6. Unconfined compression test

The BRGS samples for the unconfined compression strength test (UCS) were cylinder shaped with 2:1 ratio (diameter = 38.1 mm, height = 76.2 mm). The major purposes of UCS were to test the mechanical properties of BRGS and explore the optimum recipe of each biopolymer. The UCS strain rate was controlled at a rate of 1.5%/min in accordance with American Society for Testing and Materials (ASTM D2166[30]). All testing samples were prepared in triplicate and their average was taken. GeoJac - Digital Load Actuators (https://geotac.com/) were used in this compression test.

2.7. Consolidated and drained triaxial test

The consolidated drained triaxial tests were conducted to investigate the shear strength parameters of BRGS. Consolidated and drained triaxial tests were conducted under 50, 100 and 200 kPa cell pressure at a constant axial strain rate of 0.1%/min (American Society for Testing and Materials-ASTM D7181 [31]). The tests terminated after the strain reached 15%. Sigma-1 - Automated Load Test System were used in this Consolidated and drained triaxial test.

2.8. Scanning electron microscopy (SEM) analysis

SEM images were using a TESCAN LYRA3 device to observe the micro-scale bonding between biopolymer and RGS particles. Samples were oven dried (105 ℃) for 1 day before the testing and mounted on the stubs with adhesive carbon conductive tab.

3. Results and discussion

3.1. Effect of biopolymer concentrations on strength improvement

The unconfined compression test was conducted to explore the stress-strain behaviors of BRGS with different types of biopolymers after 24-hrs oven-dried at 105 ℃. Three different types of biopolymers, Ca-alginate, Agar, and Xanthan Gum were studied.

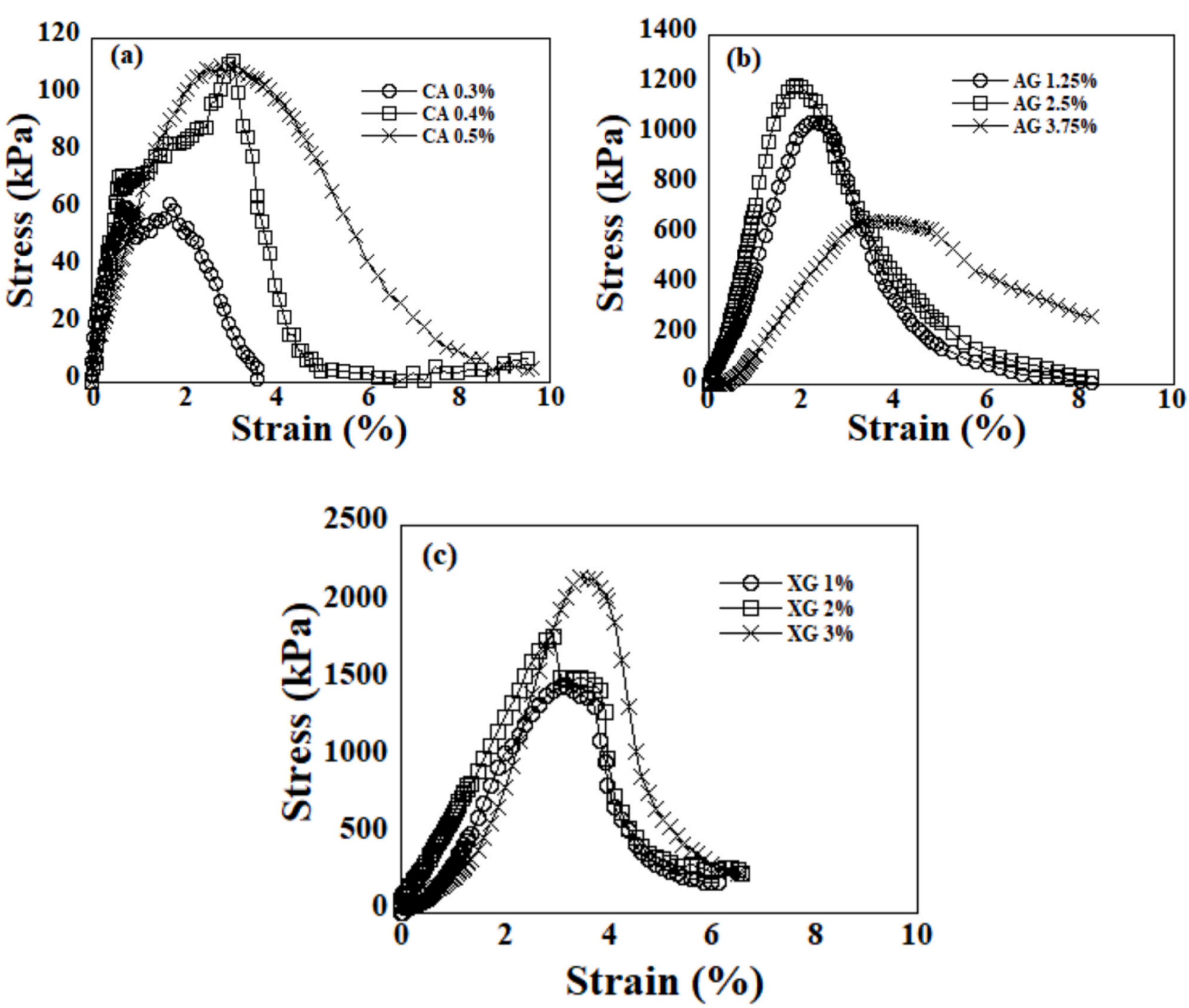

Fig. 5. The stress-strain curve of (a) Ca-alginate (CA); (b) Agar Gum (AG); and (c) Xanthan Gum (XG) cured at 105 ℃ for 1 day.

3.1.1. BRGS with Ca-alginate

In Fig. 5(a), the UCS of Ca-alginate treated RGS increased with the increase of Ca-alginate concentration. The strength of RGS was doubled when the Ca-alginate concentration increased from 0.3% to 0.4%. With a further increase in the Ca-alginate concentration, the UCS did not have any significant improvement. This is in agreement with what Wen et al. [14] reported that the UCS of Ca-alginate treated Mississippi local sand increased with the increase of alginate concentration. Meanwhile, with the alginate concentration increased, it became more difficult to fully dissolve them in water. In this study, the Alginate-treated RGS showed an improvement in brittle behavior that the failure strain of Ca-alginate treated RGS improved from 2% to 3% with increasing in concentration. Arba et al. [32] reported a different trend that the failure strain of alginate-treated silty soil decreased from 5.5% to 4.3%. The authors stated that the more brittle behavior of alginate-treated soil may attributed to the flocculated structure of the treated clay component. They also conducted micro-scale analysis through SEM analysis and confirmed their conclusion.

3.1.2. BRGS with Agar

Fig. 5(b) shows the UCS of different concentrations of Agar-treated RGS dried for 24 h at 105 ℃. The UCS of agar treated RGS was slightly improved when the agar concentration doubled (the UCS from 1050 kPa to 1200 kPa). With the further addition in agar concentration (3.75%), the UCS of RGS with agar treatment plummeted to approximately half of the agar in 1.25%. It could be due to the fact that the agar with higher concentration (3.75%) is too thick to mix with the RGS (Fig. 6). However, the failure strain of RGS with 3.75% agar treatment reached 4%, and the residual stress showed a better performance. Agar biopolymers bond sand particles by forming adhesive materials on the sand surface, and the mechanical friction play a major role during the process of agar-treated sand. The extra agar gel acts as a lubricant in the RGS particles, resulting in a reduced friction angle.

3.1.3. BRGS with Xanthan gum

The stress-strain behavior of xanthan gum-treated RGS is presented in Fig. 5(c). The addition of xanthan gum showed a significant improvement in the soil strength. However, with the further addition in Xanthan gum concentration, the strength did not show a significant improvement. The strength only increased less than 50% when the concentration tripled. It was also observed that with further increasement of Xanthan gum concentration, the viscosity of the biopolymer solution increased significantly, and it was difficult to fully dissolved at room temperature. Chang et al. [28] explored the effects of xanthan gum on strength improvement of sandy soil. They indicated that the Xanthan gum could create gel matrices and indirectly interact with sand particles on surfaces, and the bonding between particles improved the mechanical behavior of the sandy soil. Their results indicated that the UCS of treated sand increased with increasing of the Xanthan gum concentration. They also concluded that the optimum Xanthan gum concentration appears to be approximately in the range of 1–1.5%, and larger amount of Xanthan gum lead to lower workability. The finding from this study aligned well with their conclusion.

3.2. Effect of initial mixing moisture content on strength improvement

The initial mixing moisture content is an important parameter that may affect the strength of BRGS. To achieve a workable status on BRGS, a minimum mixing moisture content of 20% was applied. However, the sample with alginate treatment was unable to be removed from the mold (as shown in Fig. 7). For the alginate-treated sample, the 20% moisture could not provide sufficient bonding to bond the sand particles together. This is consistent with the fact that the lower the molecular weight, the lower the viscosity. For L4 RGS, it does not contain too much fines, especially the clay component, thus it required more initial mixing moisture to achieve a workable status. As shown in Fig. 8, the UCS increased with the increase of initial moisture content up to 25%. However, the UCS declined with further increment. Bozyigit et al. [33] reported a similar trend by testing the UCS of clay with xanthan gum treatment at the different moisture content (25%, 30%, 35%, and 40%). This behavior can be attributed to the biopolymer gels present in the soil particles which reduces the friction between soil particles and causes

Fig. 7. The failure Alginate-treated sample with 20% mixing moisture content.

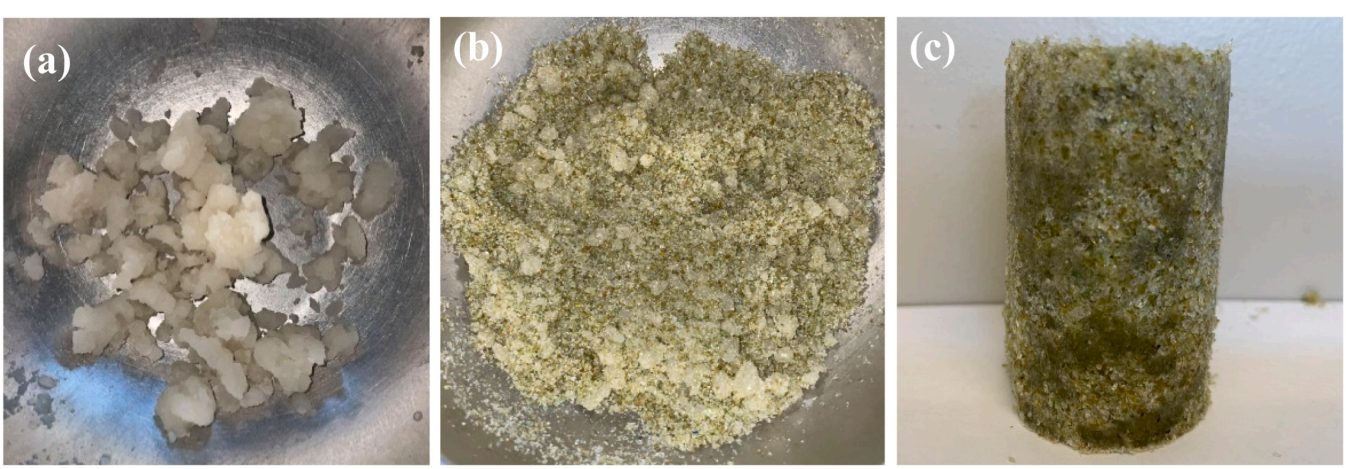

Fig. 6. Agar gum (a) at 3.75% concentration; (b) difficult to mix with the sand; and (c) uniform mixed sample.

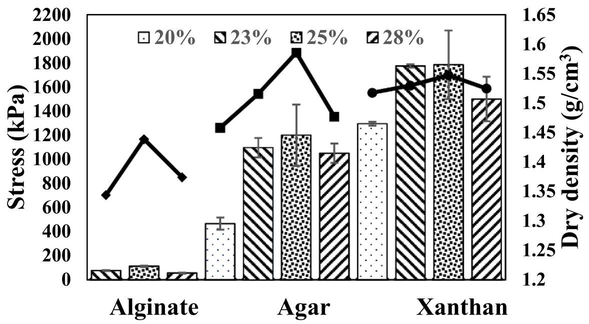

Fig. 8. The UCS and dry density of L4 BRGS on different mixing moisture content (cured at 105 °C for 1 day).

contact lubrication of the soil matrix during the compaction process. The dry unit weight of the xanthan gum-treated clay at different initial mixing moisture content was also evaluated. The optimum initial mixing moisture content is not only to provide sufficient binding mechanism to the soil particles but also allowed the soil particles to reach the maximum compaction state. Thus, further addition on the moisture may results a decline on the dry density and strength behavior.

3.3. *Effect of curing conditions on strength improvement*

The curing conditions including the curing temperatures and curing period can significantly influence the mechanical behavior of biopolymer treatment. Three different curing conditions (air-dry, oven-dry at 50 °C, and oven-dry at 105 °C) under 1, 3, 7, 14, and 30 days were studied in this paper.

3.3.1. *BRGS with Ca-alginate*

The UCS and mixing moisture content of RGS with 0.4% alginate treatment cured at different dry conditions was shown in Fig. 9. The UCS of 0.4% alginate-treated RGS cured at 50 °C oven-dried condition did not show a significant increase in the first 7 days curing period. With further curing, the strength was improved by 30% after 30 days of curing (from 132 kPa to 172 kPa). While the UCS of RGS cured at room temperature showed a slight improvement in the first 7 days. With the further curing period increasing, the UCS had a slight decrease. This slightly decrease could be caused by the increasing in mixing moisture content as the dry sample may absorb the moisture from the air when curing them in the air-dry condition (Fig. 9(b)). Fatehi et al. [34] researched the effect of the curing period on the strength of alginate-treated silt sand and explored a similar trend that more than 90% of UCS was achieved in the first 7 days. However, in the 105 °C oven-dried curing condition, the UCS of alginate-treated RGS showed a different trend. With the increase in the curing period, the UCS decreased dramatically in the first 7 days and remained at a consistent value in the further curing periods. This may be caused by that the reduction of ionic cross-link force when the temperature is high (more than 100 °C). Kong [35] et al. reported the effect of different temperature on the calcium alginate degradation. The result illustrated that the higher temperature, the lower calcium alginate fiber weight. For example, the weight of calcium alginate fiber was decreased by 20% when the temperature reached 200 °C. Moreover, it was fund that the calcium carbonate was formed in the calcium alginate fiber when the temperature was heated up to 150 °C. In the Fig. 9(a), the optimal curing temperature of RGS with alginate treatment was drying at 50 °C. Wen et al. [14] (2019) also reported a similar trend that the UCS of poorly graded sand with alginate treatment cured at oven 50 °C was improved by 430 kPa, which is triple that of the air-dried curing conditions.

3.3.2. *BRGS with Agar*

Fig. 10 shows the UCS and mixing moisture content of 2.5% agar treated RGS on different curing temperatures with time. In the higher temperature curing condition (oven 105 °C), the UCS of agar treated RGS increased with the increase of curing period. It can be seen that the strength gradually improved with the curing period increased. Moreover, the UCS of RGS cured at 105 °C was more than two times of the sample cured at 50 °C after curing for 30 days. Chang et al. [27] compared the UCS of agar-treated soil with and without thermal treatment. They preheated the treated soil at 100 °C before mixing it with agar solution and the result illustrated that the UCS of agar-treated soil with the thermal treatment (3200 kPa) was doubled to the soil without thermal treatment (1600kPa). In the mixing process, the agar-treated sand without thermal treatment cooled faster than that of sample with thermal treatment, which allowed sufficient time for the agar-treated sample with thermal treatment to mix thoroughly to improve the strength. Fig. 10 (a) also showed the strength of agar treated RGS with thermal treatment had a better performance than the non-preheated samples. Meanwhile, the mixing moisture content plays an important role in the mechanical behavior of agar treated RGS cured at room temperature. It has been found that the higher the moisture level, the lower the molecular weight and viscosity of agar gel [34]. Therefore, the strength was gained while the moisture level was reduced. However, the strength of agar treated RGS jumped down 40% after curing for 30 days at room temperature (Air-dry). Mao et al. [36] have concluded that the elastic modulus of agar gel becomes weaker as the curing period increases when the curing temperature is below 35 °C. At this point, the

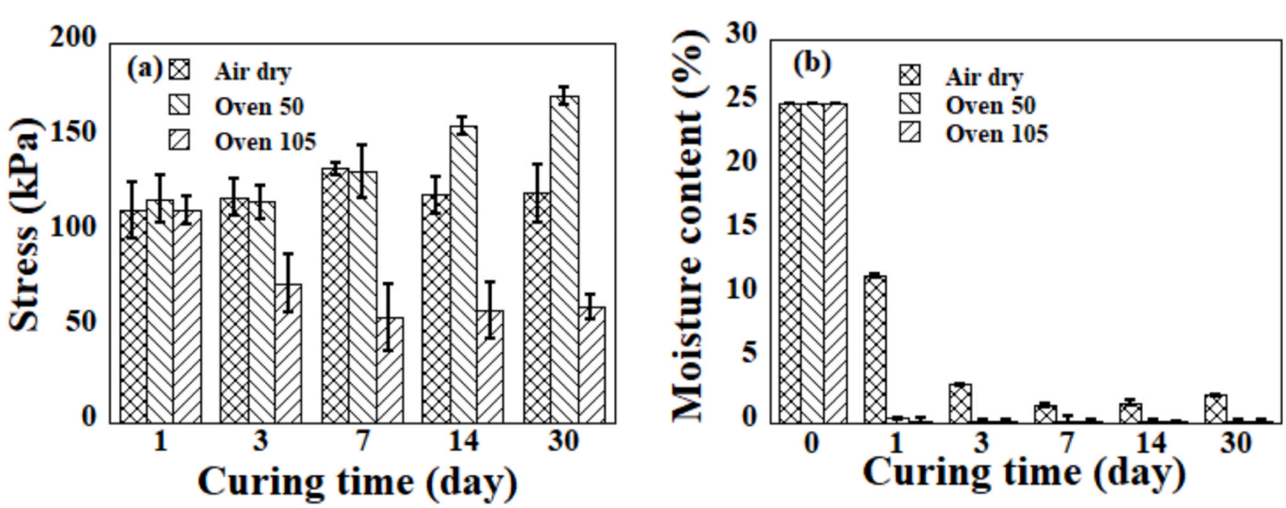

Fig. 9. The effect of 0.4% Alginate-treated L4 with Different Curing Conditions on (a) UCS; and (b) mixing moisture content.

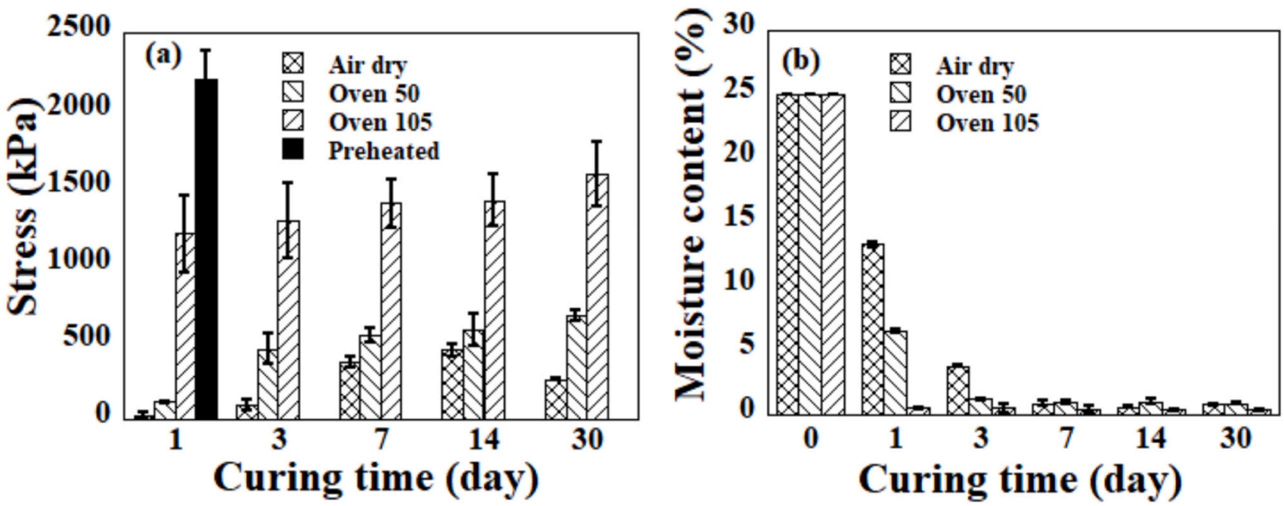

Fig. 10. The effect of 1.25% Agar Gum-treated L4 with Different Curing Conditions on (a) UCS; and (b) mixing moisture content.

strength of the gel itself plays a decisive role in the strength of the sample. From this phenomenon, it can be concluded that the increase in the strength was major contributed by the dehydration of the agar gel in the early curing period, and the elastic modulus of the agar gel itself decreased with the increase of curing period when it was cured at a lower temperature (below 35 ℃), thereby weakening the sample performance in a long-term curing period. Fatehi et al. [34] also reported a similar trend that the optimal curing period of agar-treated silt sand cured at room temperature was 14 days.

3.3.3. BRGS with Xanthan gum

The UCS and mixing moisture content of 2% xanthan gum treated RGS cured at different conditions was depicted in Fig. 11. The UCS of RGS with xanthan gum treatment increased with curing period at the different temperature conditions. For 105 ℃ curing condition, the mixing moisture content of sample remained a same level after curing for 1 day (Fig. 11 (b)), but the UCS of sample continued to increase with increasing curing period. Meanwhile, the UCS of air-dried and 50 ℃ oven-dried samples showed a relatively low strength in the early curing stage, but the strength increased with the decreasing of the mixing moisture content (gel dehydration), and subsequently showed a similar trend to 105 ℃ curing condition. This increase in strength was majorly caused by the hardening or aging of the specimen over time. As shown in Fig. 11, after 30 days of curing, the strength reached 1860 kPa for the air-dried sample which was 80% of the oven-dried sample. This trend indicated that the curing temperature did not have a significant impact on the long-term performance of xanthan gum treated RGS. Chang et al. [28] revealed the effect of curing period on the xanthan gum-treated soil improvement through the UCS of xanthan gum-treated soil with different curing periods and soil types. The stress-strain behavior indicated that the UCS of 1% xanthan gum-treated sand was increased by 600 kPa when curing for 21 to 63 days (the UCS from 800kPa to 1400 kPa) at room temperature. This also aligned with the conclusion in this study that the increase in strength was contributed by the aging of the xanthan gum over time.

3.4. Triaxial shear strength of the BRGS

Consolidated-drained (CD) triaxial tests were performed in this study to measure the engineering properties of biopolymer-treated RGS with different confining pressures (50 kPa, 100 kPa and 200 kPa), including friction angle and cohesion. The untreated RGS was the controlled group (relative density = 60%) in this study. The Mohr-coulomb failure envelope of untreated and biopolymer-treated RGS as shown in Fig. 12. Compared to the untreated RGS, the friction angle of RGS with biopolymer treatment had a slight decrease, but the cohesion was significantly improved. Biopolymers strengthens the RGS by enhancing the inter-particle interactions, which resulted in greater strength and

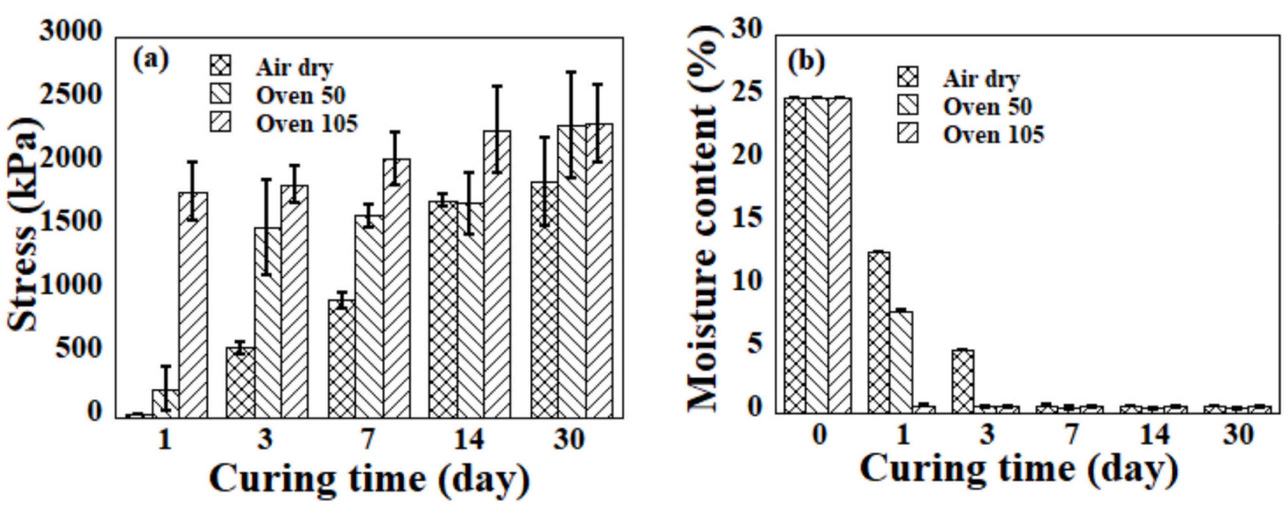

Fig. 11. The effect of 2% Xanthan Gum-treated L4 with Different Curing Conditions on (a) UCS; and (b) mixing moisture content.

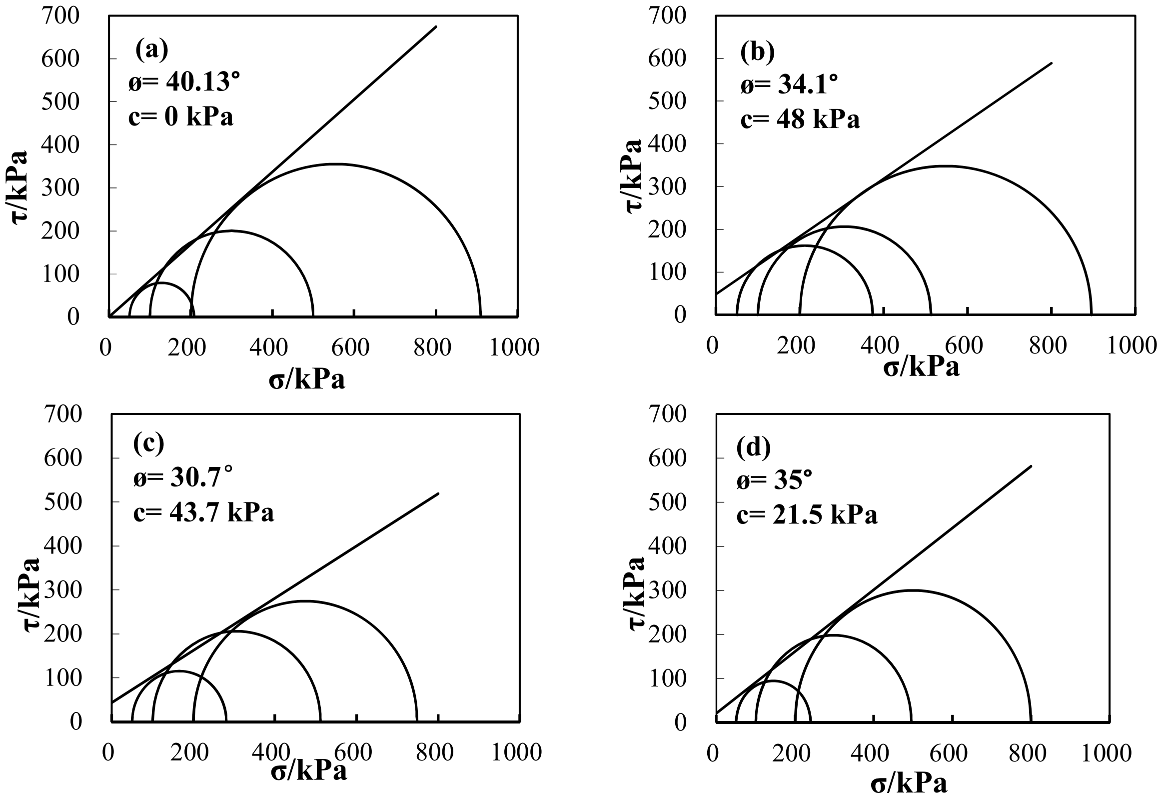

Fig. 12. Mohr-coulomb failure envelope of (a) untreated RGS; (b) Ca-alginate treatment; (c) Agar gum treatment; and (d) Xanthan gum treatment (cured at 105 ℃ for 1 day).

higher stiffness. In this process, biopolymers fill the voids and acts as a lubricant between the RGS particles, resulting in lower mechanical friction force. Meanwhile, the bonding force between RGS particles could be improved due to the higher viscosity of biopolymers. Wen et al. [14] had a similar trend that the friction angle of 0.4% alginate-treated sand (16°) was decreased by double than that of untreated sand (32°), but the cohesion increased up to 150.5 kPa. Compared to the RGS with alginate treatment, the friction angle did not have a significant change (reduced from 40.13° to 34.1°) due to the difference in soil particle shape between RGS and sand. The RGS had a more angular shape which shown in the SEM analysis section.

3.5. SEM analysis

The SEM images of the natural RGS and Ottawa standard sand were shown in Fig. 13 (a) and (b). It could be seen that the shape of untreated RGS was irregular and independent particles and showed a smoother but sharper profile than that of natural sand. Fig. 13 (c) and (d) showed the SEM images of xanthan gum-treated RGS in different mixing moisture content at the same curing condition. Xanthan gum coated the RGS particles and increased the contact area between the RGS particles by creating connection bridge in the particles that are not directly in contact. With the addition in mixing moisture content, the xanthan gum warped the RGS particles more on the particle surface instead of bridging them together. As mentioned in Fig. 8, the further addition of mixing moisture content decreased the strength of RGS with 2% xanthan gum treatment. This may be caused by the xanthan gum gel wrapping the whole surface between RGS particles when the further mixing moisture content addition. Bozyigit et al. [33] also revealed that xanthan gum has a longer and extended structure that easily form a bonding structure wrapped soil particles at high concentration. In this period, the strength of RGS with Xanthan gum treatment did not depend on the friction between RGS particles and the bonding force between biopolymer and RGS particles, but on the Xanthan gum gel itself.

4. Discussion

The chemical treatment method, a primary method applied to improve engineered properties of soil, involves chemical reactions during the process of improving soil properties and creates an artificial binding force in the soil particles. The traditional materials for soil stabilization include cement, lime, calcium, and fly ash. Bu et al. [37] mixed the cement with poorly graded sand and tested the UCS of cement-treated sand. The stress-strain curve showed that the UCS value of 1500 kPa when the cement content was up to 10%, which is similar to the UCS of 2% xanthan gum-treated RGS (1784 kPa) and 2.5% agar-treated (1200 kPa). Meanwhile, the failure strain of 10% cement-treated sand ranged from 1.1% to 2.2%, whereas the BRGS had a much higher failure strain ranging from 2% to 4%. This indicated that the biopolymers-treated sand exhibited better ductility behavior than cement-treated sand. Silvani et al. [38] conducted the UCS test on lime-treated sand. The results illustrated that the UCS of lime-treated sand cured for 28 days was 900 kPa when the lime content was 3%. The UCS of lime-treated sand was similar to the UCS of 1.25% agar-treated RGS (1087 kPa) and 1% xanthan gum-treated RGS (1458 kPa). Karim et al. [39] mixed lime and fly ash to improve the strength of poorly graded sand. The results showed that additional 5% lime mixed with 30% fly ash in the soil had a UCS of 200 kPa, similar to the UCS of 0.4% Ca-alginate-treated RGS (110 kPa) but lower than that of 1.25% agar and 1% xanthan gum-treated RGS. Compared to the traditional addition materials for soil improvement, the biopolymers still have a sound strength performance, especially at low dosages. What's more, biopolymers could provide the strengthening in the soil with the dehydration regardless of curing conditions. These biopolymer-RGS geomaterials have great potential used to quickly improve the slope stability in the civil engineering.

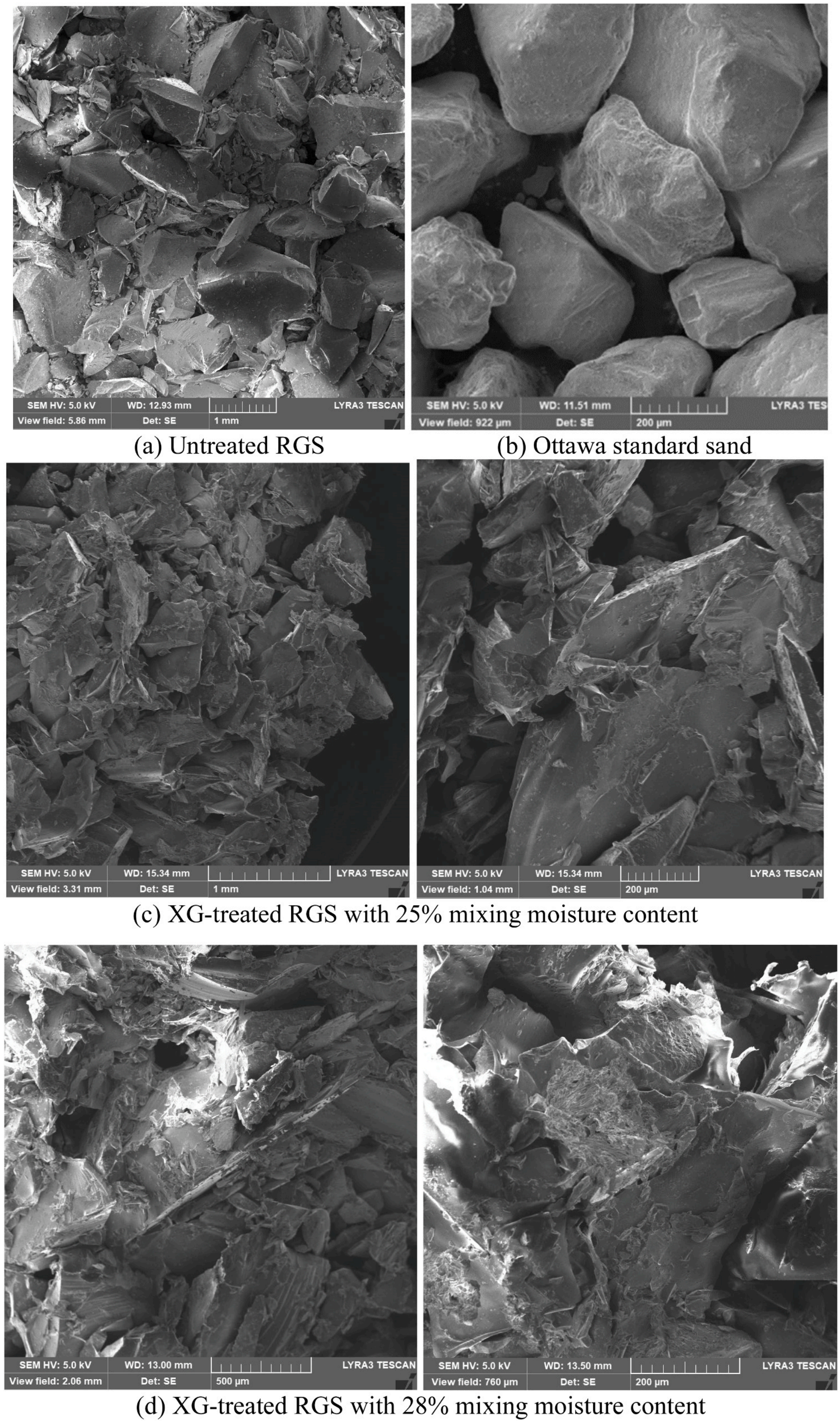

Fig. 13. The SEM image.

In addition, traditional materials used for soil improvement are responsible for greenhouse gas emissions, especially cement. Researchers [40,41] reported that the CO_2 emissions by cement production had up to 9% of the global CO_2 emissions in 2010, and the CO_2 emission of cement in the geotechnical applications amount to 2% of the total CO_2 emission by cement. According to U.S. Energy Information Administration report, replacing 10% of cement usage with low-carbon materials in geotechnical engineering could reduce 6.1 million tons of CO_2, which is close to 10% of Austria's annual CO_2 emissions in 2012 (66.68 million tons). Moreover, the traditional materials for soil improvement could raise the pH of soil up to 12–13, which could have a detrimental effect on the biological organisms of the soil [42]. Meanwhile, Chang [24] explored that a 2.5 cm thick uniform soil-xanthan gum mixture to treat 1 km^2 unite surface area would cost 600,000 USD, which is higher than that of 10% cement treatment (10% cement mixture would cost 240,600 USD for every 1 km^2 treatment). However, they also reported a good example that the price of biopolymer could also reduce due to the expansion of global biopolymer market. And the total cost for 1 ton soil with xanthan gum treatment (12.95 USD) was only 3.6% more expansive than cement (12.5USD) when the CO_2 emission trading is considered [25].

Researchers also reported that the biopolymers had positively promoted vegetation growth, which could reduce the rate of wilting rate to that of untreated soil. For example, Wang et al. [43] mixed the xanthan gum powder with silt sand and recorded the germination and growth of ryegrass. The results illustrated that the germination rate of ryegrass on the xanthan gum-treated silt (82%) was higher than that on the untreated silt (80%). The vegetation length on xanthan gum-treated silt reached 16 cm, which is greater than that of the untreated silt (12.5 cm). Vegetation root reinforcement is also a common ground improvement technology [44]. However, the root system typically requires a 6-month to 1-year growth period to reach a suitable root diameter before it can function as a bio-anchor in the field [45]. For example, when using the vegetation root to reinforce the slope, the slope might be still unsafe during the vegetation growth period. With the combination of the biopolymer treatment, not only the vegetation may benefit from the biopolymer protection, but the slope could also be temporarily stabilized. The long-term durability is essential to evaluate the biopolymer treatment performance in the engineering practice. Due to the biodegradability of biopolymers, it can degrade in the natural environment which would influence the engineering performance of biopolymer-treated soil. Cheng and Geng [46] reported that the optimal curing time of xanthan gum-treated soil is 28 days, while the corresponding decrement ratio is only 5.35% when the curing time reaches to 70 days. With the addition in curing time, the UCS of xanthan gum-treated soil cured for 378 days was decreased by about 10% than that of samples cured for 28 days.

5. Conclusion

In this study, the effect of three different biopolymers on the mechanical strength of RGS with biopolymer treatment as a sustainable construction material for soil improvement was investigated. Through a series of testing, the effects including biopolymer concentration, mixing moisture content and curing condition influencing the strength of biopolymer-treated RGS were studied and the main conclusions can be drawn as follows:

1. Strengthening effects in relation to biopolymer type were studied using Ca-alginate, Agar gum and Xanthan gum. For these three biopolymer-treated RGS samples, mixing moisture content was an important parameter to influence the strength. The higher mixing moisture content, the lower viscosity and molecule weight of biopolymer gel, resulting in lower strength of biopolymer-treated RGS. The results of UCS test revealed that biopolymers could improve the RGS stability even in a low concentration. However, Ca-alginate as an ionic gelation biopolymer, the major process is to exchange the sodium ions with calcium ion to form a calcium carbonate in the particle voids and the strength of RGS with alginate treatment is much lower than that of agar and xanthan gum. Although agar gum had a good performance on the strength, agar must be fully dissolved at temperatures over 85 ℃ and form a hydrocolloid solution. Meanwhile, Xanthan gum could be dissolved into water at room temperature and contributed the strength though dehydration.
2. The strength of the biopolymer-treated RGS first increased with dehydration and then continued to improve in the further curing period up to 30 days. The xanthan gum-treated RGS had a highest strength compared to Ca-alginate and agar gum, because xanthan gum could create gel matrices and indirectly interact with RGS particles on surfaces to better improve the mechanical behavior of RGS. Meanwhile, curing temperatures showed a different trend with time. Thermal induced biopolymer (agar gum) had better performance on the strength at higher curing temperature, while alginate-treated RGS was negatively impacted by higher curing temperature.
3. The friction angle of biopolymer-treated RGS did not have a significantly decrease due to the angular shape of the RGS which enhanced its mechanical friction. Meanwhile, the biopolymer wrapped RGS to form a bonding structure, resulting in increasing in the cohesion of treated sample.
4. Addition of biopolymer is a possible alternative to improve the engineering behavior of sandy soil in the civil engineering. However, there are other factors need to be concerned in term of bring it to engineering practice, including long-term durability, wet-dry cycle and freeze-thaw cycle durability. Further studies are thus recommended for deeper understanding of sand with biopolymer treatment.

CRediT authorship contribution statement

Zhang Bin: Investigation, Data curation. **Li Junjie:** Writing – original draft, Methodology, Investigation. **Wen Kejun:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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