Strength durability of gellan gum biopolymer-treated Korean sand with cyclic wetting and drying

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HIGHLIGHTS

- Strength durability of gellan gum biopolymer is verified in this study.
- Wetting and drying cycles are performed on gellan gum-treated sand.
- Unconfined compressive strength was measured with cyclic wetting and drying.
- Gellan gum-treated sand shows hysteretic strength path along wetting-drying cycles.
- Dry strength remains 80% even after severe wetting-drying cycles.

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ABSTRACT

Various biological approaches recently have been explored as alternative environmentally-friendly soil improvement strategies in the fields of construction and geotechnical engineering, with the aim of reducing the use of high greenhouse gas emitting construction binders such as cement. Previous studies have shown the effectiveness of microbial biopolymers in soil improvement. However, there are still concerns about the durability and serviceability of biopolymer treated soils, resulting from the biodegradation and hydrolysis behaviors of the biologically produced compounds. In this study, the strength and durability of gellan gum biopolymer treated *Jumunjin* sand (standard sand of the Republic of Korea) was evaluated under cyclic wetting and drying. The results obtained indicate that the cyclic wetting and drying of gellan gum-treated sands results in a gradual degradation of strength, due to the dissociation of the gellan gum monomers under wetting and imperfect recomposition during re-drying, with an approximately 30% strength reduction over 10 cycles. However, a certain degree of strength recovery and resistance was observed even after numerous cycles, indicating that gellan gum-treated soils can potentially be applied for temporary or medium-term purposes in practical construction.

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1. Introduction

Recently, several attempts to strengthen soil using biological processes or excretions (*e.g.*, biologically produced materials) for construction and geotechnical engineering applications have been reported [1–3]. For example, microbes such as *Sporosarcina pasteurii* have been injected into sandy soils to precipitate calcite between soil particles, which induces a cement-like effect but with a low carbon footprint [4–7]. Meanwhile, biologically produced biopolymers have been used directly as mixing additives or binders for soil improvement and strengthening, and have shown remarkable enhancement of inter-particle interactions, even at low concentrations (*e.g.*, a 1% or lower ratio to the mass of soil has yielded unconfined compressive strength higher than 4 MPa) [8–11]. A previous study involving the use of xanthan gum biopolymer for soil strengthening showed that xanthan gum mixed at 1% content with Korean residual soil increased the compressive strength (4.9 MPa) almost twofold relative to the compressive strength (2.6 MPa) of 10% cement treatment on the same soil [12]. Recent studies introduced thermo-gelation biopolymers such as gellan gum and agar gum as a new soil treatment binder for clayey and sandy soils [9,13]. Differences in soil types become important when considering biopolymer-treated soils: both gellan gum and agar gum exhibited especially significant strengthening

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efficiency with clayey soils (reaching up to 13 MPa for clayey soils) [9]. For pure sand, gel-type biopolymer treatment provides inter-particle cohesion on cohesionless soil which results in significant ground bearing capacity increase [13].

Biological approaches have environmentally-friendly advantages due to their low greenhouse gas emissions [14,15] and high ability to prevent soil erosion [16], whereas cement, the most commonly used binding material in the field of construction and building engineering, is known to contribute heavily to carbon dioxide emissions (*i.e.*, cement production accounts for approximately 7% of total global emissions) [17,18]. In light of growing environmental concerns, new construction materials [8,12] and methods [19,20] involving the use of biological processes and compounds (*e.g.* calcite precipitating micro-organisms, biopolymers) are being actively studied to reduce the usage of cement in the field of construction, especially for geotechnical engineering.

The main characteristics of cement that led to it becoming the most commonly used material in construction and geotechnical engineering are its excellent durability and serviceability [21]. Solid cement-aggregate mixtures (*i.e.*, concrete) are known to have a long service life depending on service conditions, and in some cases have been designed so that their service life is greater than 100 years [22]. Heterogeneous cement-soil mixtures (*e.g.*, deep cement mixed soils) also endure for many years depending on the site application type (*e.g.*, auger mixing, jet injection) and service conditions [23]. In contrast, biological excretions and compounds accompany concerns regarding their biodegradation and hydrolysis [24,25].

Although recent studies on soil strengthening using polysaccharide type biopolymers have shown significant strengthening due to direct hydrogen bonding and matrix formation with clayey particles [9,12,26], the factors affecting the durability and strength behavior of biopolymer treated soils should be considered and verified to ensure the broader usage of biopolymers as reliable construction and geotechnical engineering materials in practical implementations. In particular, sandy soil is expected to show poor durability because it does not directly interact with biopolymer molecules [12].

In a previous study it was shown that when thermo-gelating gellan gum biopolymer was used as a sand treatment and improvement material, and the treated sample was submerged in water, the unconfined compressive strength of the 1% gellan gum-treated sand suddenly diminished to 1/10th of the unconfined compression strength of the dried state [9]. Moreover, the strength of gellan gum-treated sand that was re-submerged (that is, sub-merged twice) was reduced to 1/5th of the strength of single-submerged gellan gum-treated sand (250 kPa) for the same gellan gum concentration (*i.e.*, 1%) and water content (*i.e.*, around 25%) conditions [9]. In this light, in order to test the durability concerns of gellan treated samples in relation with the moisture content, repeated drying and wetting cycles were performed in this study.

Because gel-type biopolymers generally show minimal or virtually no interaction with cohesionless sand, due to the neutral surface of the sand particles [12], sand is an appropriate soil type for clearly examining the strength behavior of gel-type biopolymers. For this reason, the durability, that is, the reduction in strength of gellan gum biopolymer treated sand under cyclic wetting and drying, was evaluated in this study through laboratory programs.

2. Experimental program

2.1. Materials

2.1.1. Sand

Jumunjin sand, which has served as a standard and is the most commonly adopted sand in Korea [9,27,28], was used. Jumunjin sand is classified as a poorly graded sand (SP) with a specific gravity of 2.65 and mean grain size (D_{50}) of 0.52 mm, where the uniformity coefficient (C_u) and coefficient of gradation (C_c) are 1.94 and 1.09, respectively. Jumunjin sand has a structural composition between e_{min} = 0.64 and e_{max} = 0.89, having an inter-particle friction angle (ϕ) of 29.3°. The particle size distribution curve of jumunjin sand can be seen in Fig. 1.

2.1.2. Gellan gum biopolymer

Gellan gum is a high molecular weight polysaccharide fermented from the *Sphingomonas elodea* microbe [29]. In this study, a low acyl gellan gum biopolymer purchased from Sigma Aldrich (CAS No: 71010-52-1) was used for the experimental programs. Low acyl gellan gum is an efficient gelling agent that is capable of forming gels even at low concentrations of 0.05–0.25%, and it also has excellent thermal and acid stability [30,31]. Low acyl gellan gum partially hydrates to form viscous gels in cold water, while temperatures above 80 °C are required to fully hydrate gellan gum monomers to form a uniform hydrocolloid state. Once heated, if the gellan gum hydrocolloid is then cooled to temperatures below 40 °C, the hydrocolloids are transformed into firm hydrogels. This transformation is accompanied by a remarkable increase in viscosity [32]. Gellan gum hydrogels begin to interact via hydrogen bonding with clayey particles, instead of water molecules, when
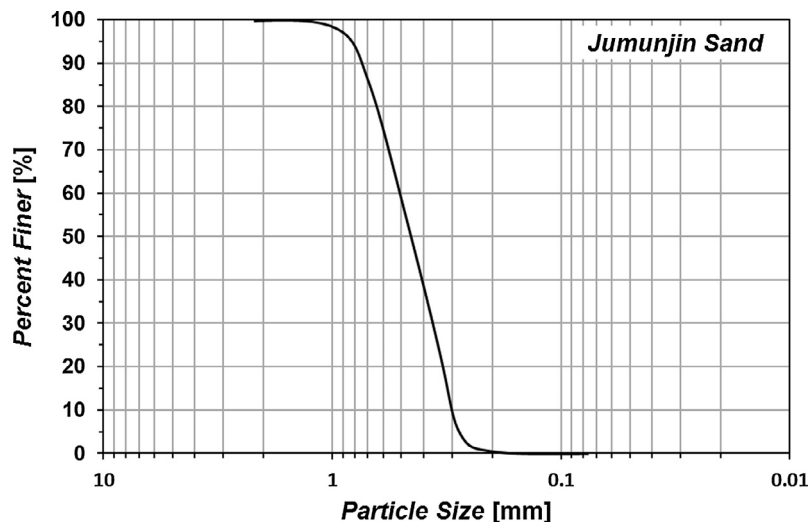

Fig. 1. Particle size distribution curve of jumunjin sand.

the overall soil-biopolymer gel mixture is dehydrated [9]. Thus, the final strength of pure gellan gum biopolymer-treated soils (*i.e.*, without additives such as Ca^{2+} or Mg^{2+}) strongly depends on the water content, and the loss of the original strength level after wetting is irreversible; that is, it cannot be recovered when the treated soil is fully dried and then hydrated (re-wetted) again [9].

Fig. 2. Specimen conditions (a) 1st cycle; (b) drying samples; (c) UTM measurement on dry condition; (d) sample wetting (submergence) for 24 h; (e & f) before and after loading of a dry specimen; (g) loading of a 10th wet specimen; (h) Dry specimen after 10 cycles of wetting and drying.

Table 1
Order of Experimental Testing Conditions.

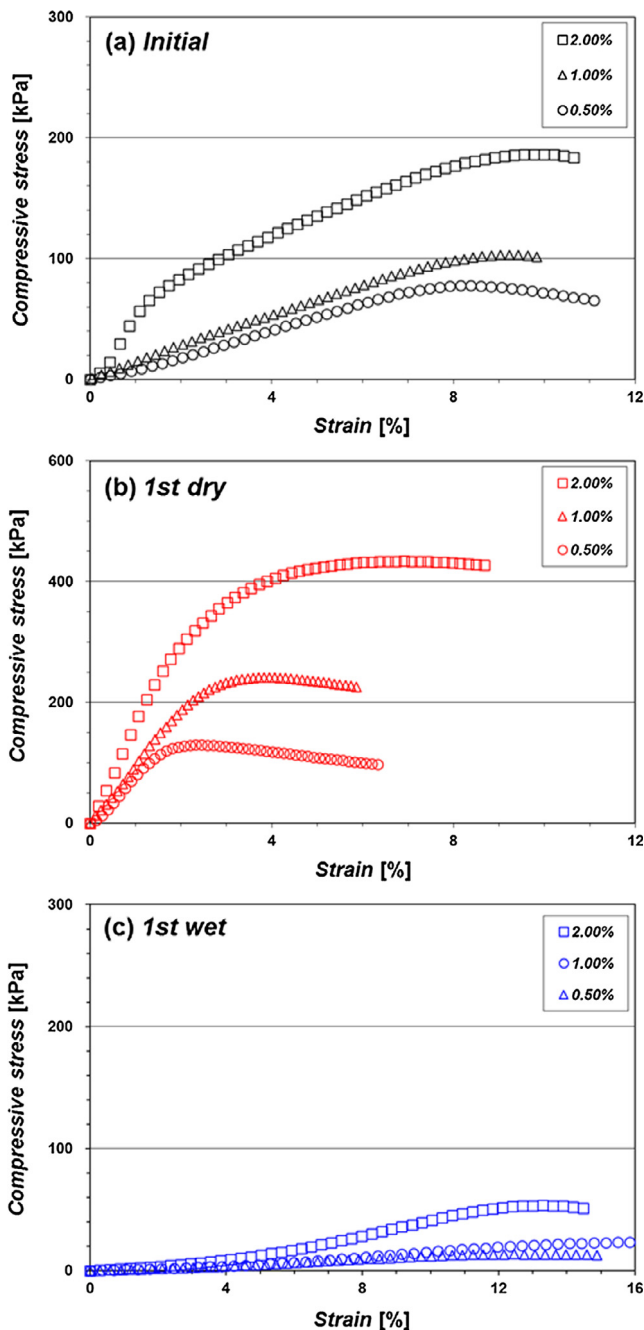|	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10
Initial	1										
Dry		2	4	6	8	10	12	14	16	18	20
Rewet		3	5	7	9	11	13	15	17	19	21

Fig. 3. Stress-strain curves of gellan gum-treated sands obtained from unconfined compression tests for (a) initial, (b) 1st dried, and (c) 1st wet conditions.

Fig. 4. Stress-strain curves of dry (a) and wet (b) m_b/m_s = 1% gellan gum-treated sands obtained from unconfined compression tests at different cycles.

2.2. Sample preparation

For the first step of sample preparation, gellan gum biopolymer solutions were prepared with different biopolymer to soil ratios in mass (m_b/m_s) of 0.5%, 1%,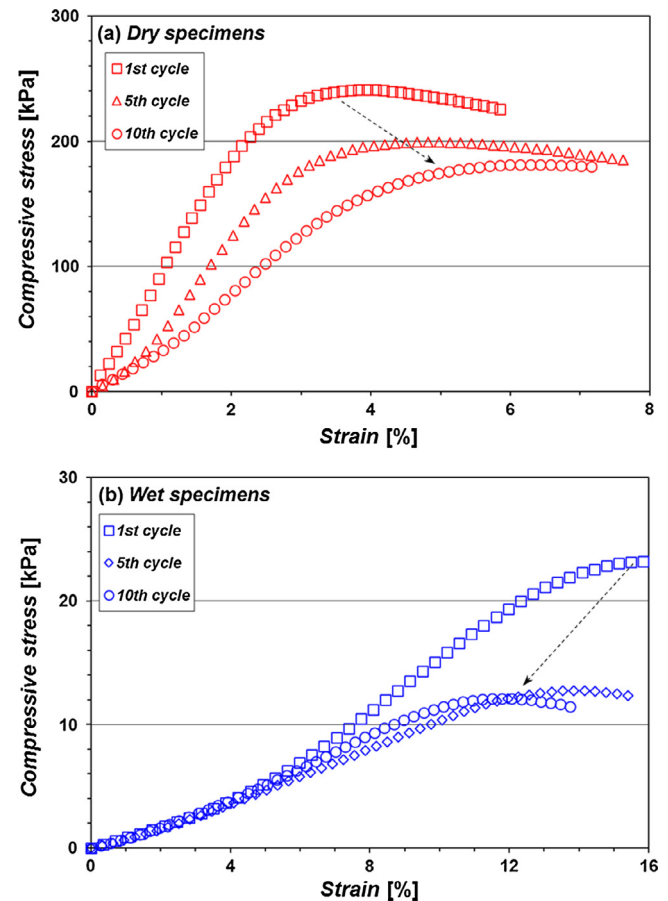 and 2%. Previous attempts [9,12] have shown that 30% water content is appropriate for mixing gel-type biopolymer with sandy soils. Thus, 1.67%, 3.33%, and 6.67% gellan gum solutions were respectively prepared by dissolving low acyl gellan gum powder into distilled water that was heated to a temperature of 100 °C using a hot plate with a magnetic stirrer. After full hydration of the gellan gums and hydrocolloid formation, the gellan gum solution was mixed with oven dried jumunjin sand at high temperatures (above 90 °C) via a laboratory mortar mixer. Thoroughly mixed gellan gum-sand mixtures, which had 30% initial water content, were poured into cubic molds that had dimensions of 50 mm × 50 mm × 50 mm (in length, width, and height).

The specimens were not compacted, in order to represent unconfined ground surface conditions, which are most susceptible to drying and wetting processes in nature. The initial dry densities of the gellan gum-treated sand cubes were set at 1.3 g/cm³, whereas the compacted gellan gum-treated sand cubes in a previous study [9] showed a higher dry density value of 1.77 g/cm³.

More than 60 cube specimens were prepared at once for each ratio of gellan gum-sand mixture (i.e., 0.5%, 1.0%, and 1.5% gellan to sand ratios in mass). All cubes were cured in controlled room

conditions (*i.e.*, temperature of 20 °C and relative humidity of 40%) and allowed to gradually cool and dry. For the remainder of this report, the use of the term '*initial*' condition refers to specimens that were fully cooled for 2 h with vacuum sealing to prevent drying. The term '*dried*' condition represents specimens that were fully dried for 28 days, corresponding to the most common curing time for ordinary cement-treated soils.

Previous studies with gellan gum as a thermo-gelation biopolymer for soil improvement showed that the strength variability of gellan gum treated soils was largely dependent on the moisture content of the samples [9]. Therefore, in this study the temperature and humidity of the samples were left at uniform conditions regardless of the natural changes in weather in order to isolate the effects of the wetting and drying cycles on the soil specimens. Additional studies on durability concerns with regard to weather and environmental factors will need to be carried out in the future for an in-depth analysis of the performance of gellan treated soils in the field.

2.3. Experimental procedure

The unconfined compressive strengths (q_u) of the initial gellan gum-treated sand specimens were measured immediately (*i.e.*, 2 h) after molding and curing, while the primary (1st) dried gellan gum-treated sands (Fig. 2a) were evaluated after 28 days of drying. Three measurements (Fig. 2b) were performed with a UTM (Universal Testing Machine; Instron 5583) device to obtain the stress-strain relationships of all gellan gum-treated specimens (Fig. 2c). Meanwhile, the remaining specimens were submerged in water for 24 h (Fig. 2d) to implement the re-wetted '*wet*' condi-

tions. After submergence, three cubes were randomly selected from the group to obtain the q_u of the wet gellan gum-treated sands (Fig. 2e and f). Then, both the dry and wet q_u of the 1st cycle were evaluated.

All of the remaining cube samples were then dried for another 28 days at room temperature, and the q_u of the next cycle of both the dried and wet conditions was subsequently obtained by following the same procedure described earlier (Fig. 2g). Finally, the last six samples (Fig. 2h) that remained after the 10th cycle were put through 10 iterations of drying and wetting, over a period of more than 280 days.

Both the unconfined compressive strength and the volumetric strains were observed and recorded after each drying and wetting cycle. The unconfined compression tests were conducted at a 1% strain rate (*i.e.*, 0.5 mm/min). The strength and volumetric strain behaviors were obtained by averaging three different measurements of a single condition. Secant modulus of elasticity (E_{50}) values were obtained and adopted to represent the elastic stiffness of the gellan gum-treated sands by measuring the slope between the origin and 1/2 strength (q_{u50}) coordinates for all stress-strain curves, simultaneously. The overall sequence of the experimental tests with drying and wetting can be seen in Table 1.

3. Results and analysis

3.1. Stress-strain relationships of the gellan gum-treated sands at initial, 1st dry, and 1st wet conditions

The stress strain relationships of the gellan gum biopolymer-treated sands for initial, 1st dried, and 1st wet conditions with
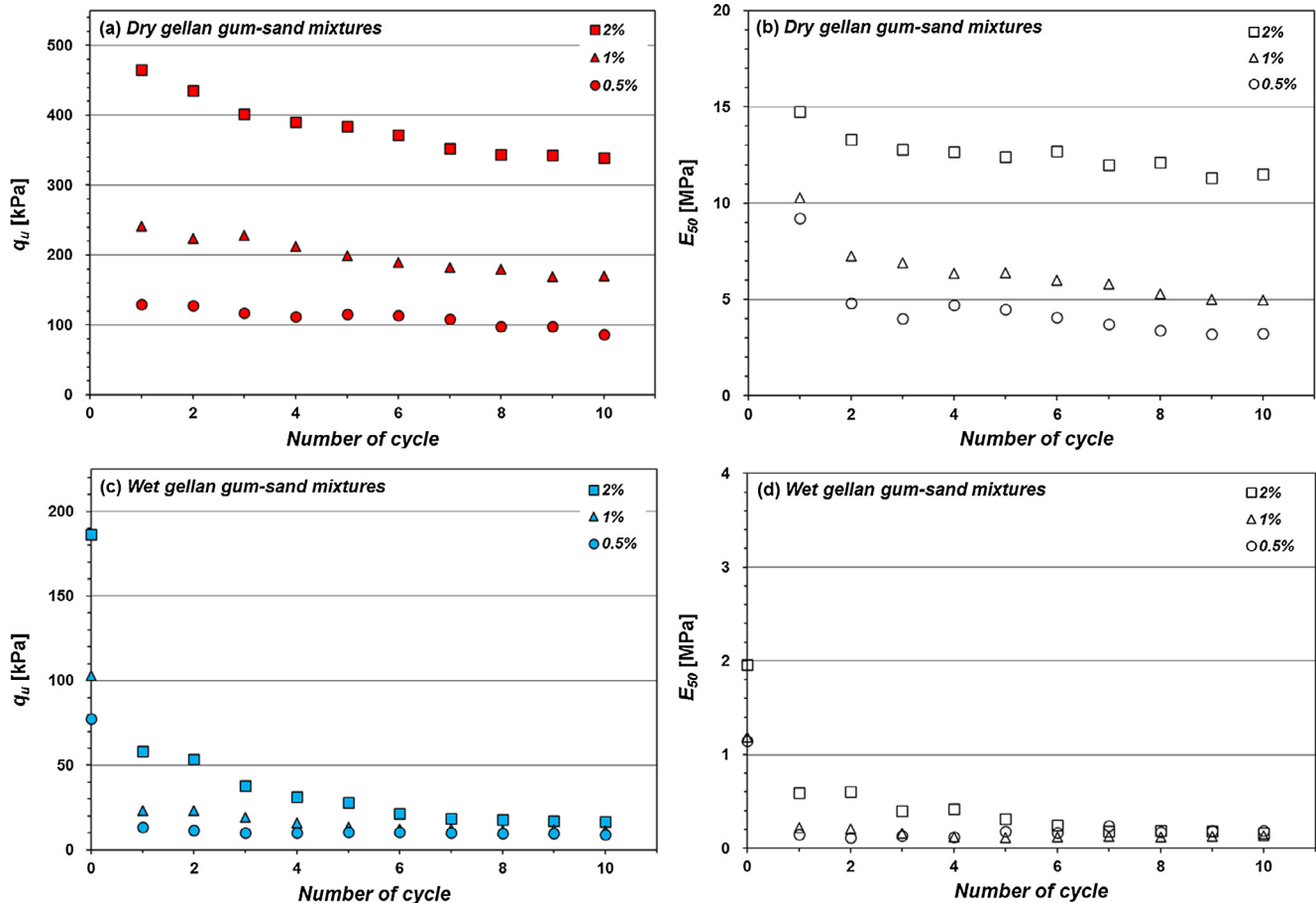

Fig. 5. Unconfined compressive strengths () and secant modulus of elasticity (E_{50}) of gellan gum-treated sands with wetting/drying cycles.

different gellan gum contents (m_b/m_s) are shown in Fig. 3. Wetting and drying curves for each cycle show similar trends with negligible variation. Therefore, the 1st drying and wetting cycle was taken to show the approximate drying and wetting trends for the specimens in relation to the volumetric strain and water content over time.

It can be seen that gellan gum treatment with higher m_b/m_s in sand increases both the peak unconfined compressive strength and the failure strain for all of the gellan gum-treated sands, regardless of the moisture condition. Moreover, the reduction of post-peak stress is more gradual with higher m_b/m_s, which suggests that the inter-particle adhesion and the tensile strength of the gellan gum gels effectively maintain the inter-granular structure of sand against high strain deformation.

The primary formation of thermo-gelation results in a firm inter-granular hydrogel matrix, which leads to significant strengthening (Fig. 3a). The increased strength should remain consistent, regardless of time, when there is no further variation in moisture content [9]. Dehydration (drying) increases the brittleness of the gellan gum-treated soils because it results in the formation of highly condensed inter-granular gellan gum matrices between sand grains, which results in higher strength as well as stiffness (Fig. 3b).

Meanwhile, the 1st wetting (Fig. 3c) reduces the strengths of gellan gum-treated sands to even lower values than those of the initial conditions (Fig. 3a), regardless of m_b/m_s content. This implies that the disturbance of fresh (i.e., initial and 1st dried) gellan gum gels produces swelling via hydrophilic water absorption, due to the absence of direct hydrogen bonding between the gellan gum and sand particles [9].

3.2. Stress-strain relationships of gellan gum-treated sands with cyclic wetting and drying

The typical stress-strain relationships of the m_b/m_s = 1% gellan gum-treated sands following cyclic (i.e., 1st, 5th, and 10th) wetting and drying procedures are summarized in Fig. 4. The stress-strain curves of dry (Fig. 4a) and wet (Fig. 4b) gellan gum-treated sands show that cyclic wetting and drying effectively degrades q_u and E_{50} for both dried and wet conditions.

The dry strength of the m_b/m_s = 1% gellan gum-treated sands is reduced with increases in the wetting and drying cycles, while the maximum elastic strains are increased (Fig. 4a). This implies that the cyclic gellan gum gel disturbances increase the possibility of higher ductility and strain softening of the gellan gum-treated soils. Fig. 4(b) provides enlarged views of the stress-strain curves of wet conditions, where both q_u and the maximum strain of elasticity decrease with increased wetting cycles.

Dried and wet strengths show an oscillation around the initial strength (i.e., 100 kPa for m_b/m_s = 1%), indicating that even though the wetting processes involve a significant reduction in strength, the subsequent drying partially recovers the strength of the gellan gum-treated soil, not perfectly, but close to the previous dried condition.

The deterioration of both the wet and dried strengths of the gellan gum-treated sands can be attributed to the hydrophilic characteristic of the gellan gum biopolymer [30,33]. Once the dried gels are subjected to water, the gellan gum gels surrounding the sand particles begin to adsorb water from the outer surface, and to desorb gellan gum fibrils that have broken off from the main structure. The detached gellan fibrils have almost no interactions with the remaining gellan gel structure, and this disengagement accompanies decreases in both the wet (saturated) strength and the resistible (maximum) strain.

Meanwhile, when the wet gellan gum-sand mixtures are re-dried, the detached gellan gum fibrils attach to the remaining gel-

lan gum matrix due to the loss of moisture, but the original structure is not recovered. Due to this break-off and re-drying cycle, the overall strength diminishes. With this cyclic deterioration, the dried gels tend to lose their density, lowering the Young's modulus of the gels, resulting in a more ductile structure and a larger maximum strain. This explains why gellan gum-treated sands show a gradual strength reduction under cyclic wetting and drying, instead of showing a sudden collapse at the early steps of cyclic wetting and drying, as is typically observed in cement- or lime-treated soils [34,35].

The strength of saturated (re-wetted) gellan gum-treated sands tends to level off and converge to an equilibrium (residual) point, approximately 14 kPa, after a certain number of cycles (Fig. 4b). Regardless of the gellan gum concentrations relative to the mass of soil, all wet strengths approach and level off at a similar value, while higher concentrations require more cycles of re-wetting to
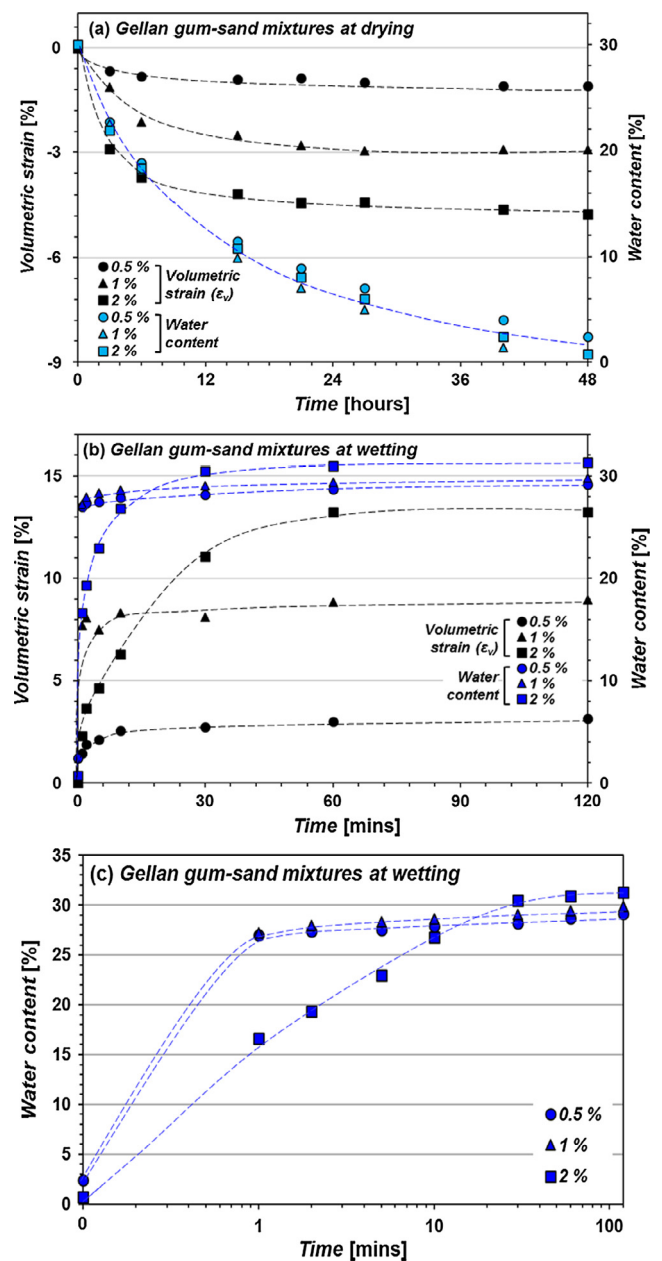

Fig. 6. Typical volumetric strain and water content variations of gellan gum-treated sands at (a) drying, (b) wetting, and (c) water content wetting in log scale (for the 1st drying and 1st wetting).

reach the residual point. The residual strength indicates the final stage, where the gellan gum is fully re-hydrated into hydrocolloids between sand grains, which has almost no strengthening effect but only plays a role in inter-granular holding.

3.3. Q_u and E_{50} of gellan gum-treated sands under cyclic wetting and drying

The variations in the unconfined compressive strength (q_u) and secant modulus of elasticity (E_{50}) of the gellan gum-treated sands for each cycle (Fig. 5) show that the maximum unconfined compressive strength and stiffness (E_{50}) of the dried samples deteriorated nearly linearly (Fig. 5a&b), while the wet samples show a relatively large reduction compared to the strength of the initial condition, and level off after a certain number of cycles (Fig. 5c).

With wet strength, the $m_b/m_s = 0.5\%$ gellan treated sands reached a residual strength of 14 kPa after the 1st drying and wetting cycle, while the $m_b/m_s = 1\%$ and 2% sands reached this residual strength at approximately the 5th and 10th cycle, respectively. The E_{50} of the wet samples (Fig. 5d) showed relatively constant values for the $m_b/m_s = 0.5$ and 1% sands, while the $m_b/m_s = 2\%$ samples converged with the other two gellan concentrations at around the 8th to 10th cycle.

Overall, higher gellan gum concentrations provide greater resistance against strength deterioration under wetting (saturation). Meanwhile, even though dry samples show similar linear reductions, a higher m_b/m_s induces greater strength deterioration. Further linear extrapolations of the strength deterioration of dried gellan gum-treated sands (Fig. 5a) converge to a single point at approximately the 35th cycle, where the compressive strength becomes zero, regardless of m_b/m_s. This implies that the artificial cohesion provided by gellan gum biopolymers to cohesionless sands remains effective up to the 35th cycle of wetting and drying, regardless of m_b/m_s.

3.4. Volume and density variations of gellan gum-treated sands under cyclic wetting and drying

The variations in the volumetric strain of gellan gum treated by primary (1st) drying and subsequent (1st) wetting are summarized in Fig. 6. For drying, the water content of the gellan gum-treated sands decreases simultaneously regardless of m_b/m_s. A higher m_b/m_s produces a larger volumetric contraction during drying (Fig. 6a) and the opposite trend is observed for wetting (Fig. 6b). Meanwhile, the water content recovers to almost the same value (30%) after wetting. This implies that the sample had a similar amount
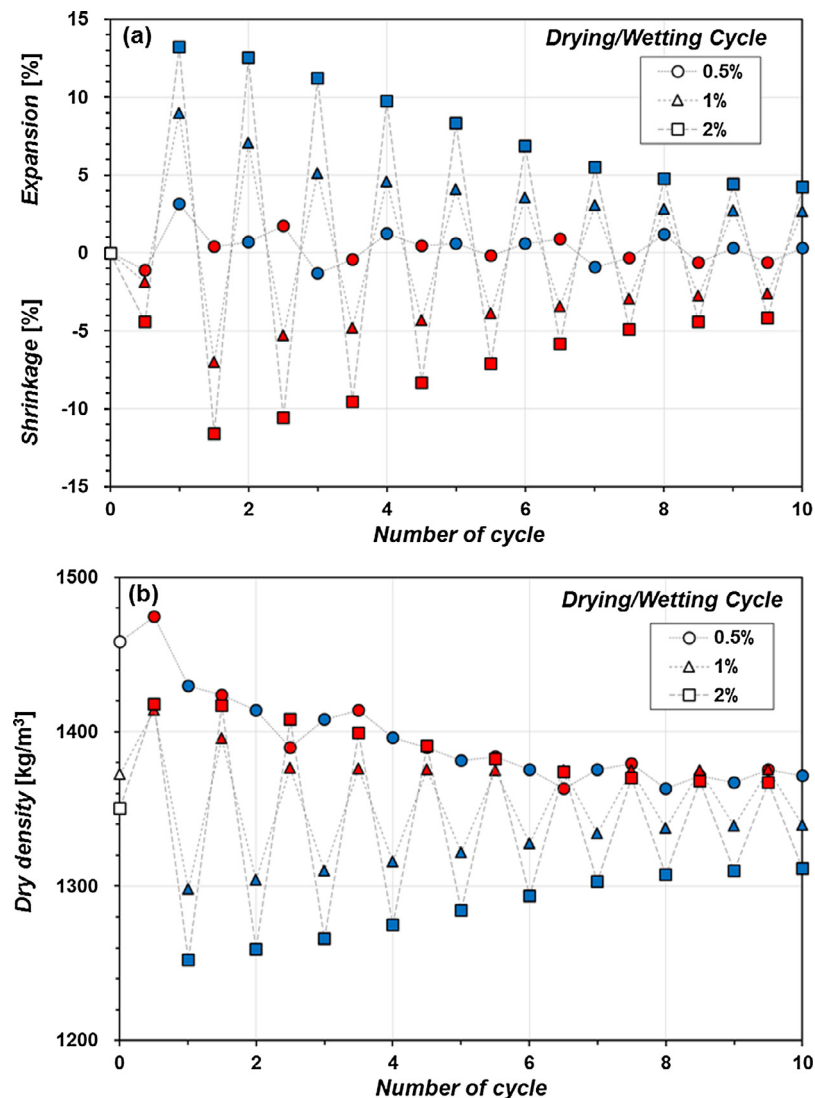

Fig. 7. Volumetric strains (a) and dry density variation (b) of gellan gum-treated sands with wetting and drying cycles.

of inter-granular spaces or voids where the dried gellan gum could adsorb water and swell back into a hydrogel. The water content recovery of low m_b/m_s soil was completed almost immediately (i.e., less than 6 min for $m_b/m_s = 0.5\%$), while higher m_b/m_s sand showed delayed water content recovery (i.e., more than 30 min for $m_b/m_s = 2\%$) (Fig. 6c).

The series of variations in volumetric strain, and accompanying dry density, of the gellan gum-treated sands under wetting and drying cycles are summarized in Fig. 7. Instant volumetric strain variations (i.e., the volume difference between subsequent wetting or drying events) (Fig. 7a) generally show volumetric shrinkage during drying, while volumetric expansion occurs with wetting, due to the water adsorption characteristics of the gellan gum biopolymer. A higher m_b/m_s results in larger variations in volumetric strain, where $m_b/m_s = 0.5\%$ sand showed the lowest volume deviation (i.e., less than 5%) between adjacent wetting and drying cycles.

Previous studies demonstrated that $m_b/m_s = 1\%$ is the optimal condition for gel-type biopolymers to fully fill the pore spaces of sand with their hydrogels, while at lower concentrations such as 0.5% pores are not fully filled, even when fully saturated in water, due to the shortage of water adsorption matter (i.e., gellan gum)

[9,12]. The dry density variation of gellan gum-treated sands (Fig. 7b) shows that higher gellan gum concentrations result in lower initial dry density due to the incompressible gellan gum hydrogels, which fill the pore spaces between sand particles. However, the overall dry density (median point between wet and dried points for the same cycle number) of gellan gum-treated sands diminishes with wetting and drying cycles, while it tends to converge to a certain value after the 6th cycle, similar to the compressive strength of re-wetted samples. Meanwhile, deviations between dried and wet conditions decrease with higher cycles, indicating a reduction of the hydro-sensitivity (e.g., structural disturbance) of the gellan gum gels due to repeated swelling and dehydration.

Once initially mixed gellan gum-sand mixtures are subjected to drying, the dry densities of the gellan gum-treated sand increase with decreased moisture content, regardless of m_b/m_s, due to the significant volumetric shrinkage of the gellan gels that fill the pore spaces between sand particles. Dry shrinkage of the gellan gum hydrogels exerts a tensile force on the sand particles, thereby reducing the overall specimen volume, while increasing both the dry density and unconfined compressive strength of the gellan gum-treated sands. The reduction of the dry densities of the dried
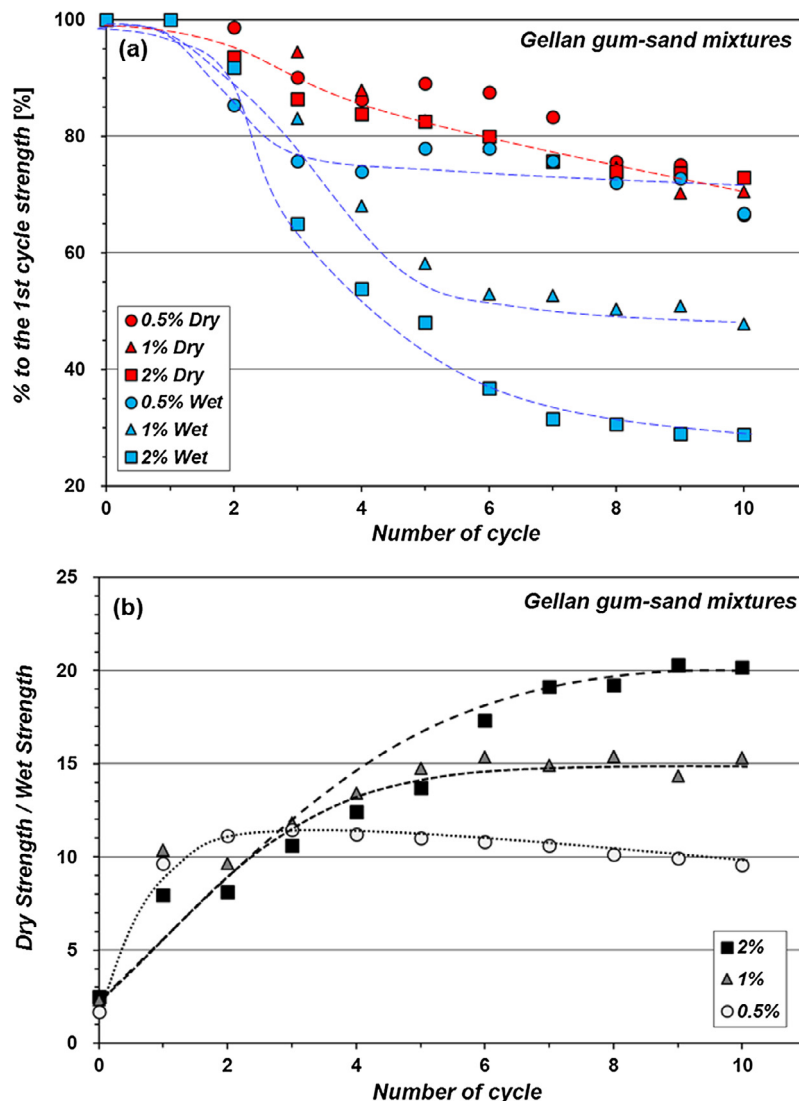

Fig. 8. Dry and wet strengths of gellan gum-treated sand with wetting-drying cycles. (a) Retained strengths at each cycle compared to the 1st cycle strength. (b) Dry strength/wet strength ratios with wetting/drying cycles.

specimens with increasing cycle number indicates that the tensile force provided by the gellan gum hydrogels is reduced with further wetting and drying cycles. This weakening of the dried gellan gels is a result of the reduction in gellan gum monomer interactions, caused by the interference of water molecules.

On the other hand, the dry densities of wet specimens increase with cyclic wetting and drying. For the primary drying, gellan gum monomers accumulate around sand particles, especially near the inter-particle contact points between the sand particles, due to matrix suction. However, when dried gellan gum gels are exposed to water again, hydrophilic swelling of the gellan gum gels repels sand particles, which induces overall volumetric expansion (*i.e.*, dry density decrease) of the gellan gum-treated sand. Meanwhile, with further wetting and drying cycles, more gellan gum monomers disassociate from the main structure, which reduces the total amount of swelling for wet samples. As a result, the overall dry density of saturated gellan gum-treated sands increases with a higher number of cycles, as shown in Fig. 7(b).

Moreover, the similar dry density value of dried samples at the final (10th) cycle, regardless of m_b/m_s, implies that the gellan gum gels have a minor effect on the soil structure due to the structural disturbance and weakening of the gellan gum gels. This point will
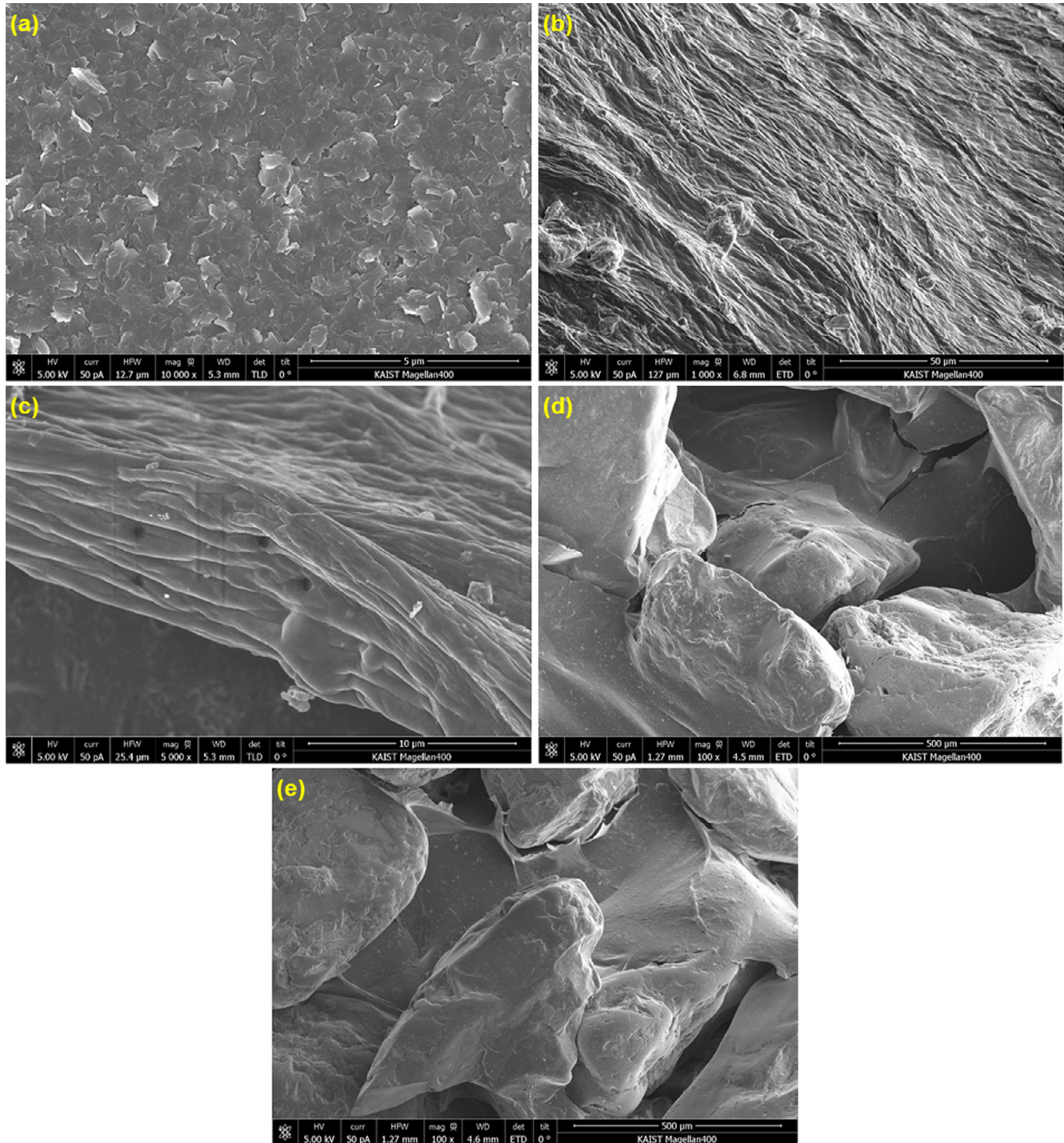

Fig. 9. SEM images of (a) wet gels; (b) dried gels at 50 μm; (c) dried gels at 10 μm (d) & (e) sample condition after wetting/drying cycle.

be the equilibrium point at which the gellan monomers concentrate around the sand particles, and the particle contact points are similar for all of the various gellan gum concentration cases, since the remaining gellan monomers have been disassociated from the main structure into the pore spaces.

3.5. Comparisons between dry and wet conditions of gellan gum-treated sands under cyclic wetting and drying

Fig. 8 shows the strength retention of both dry and wet gellan gum-treated sands compared to the strength values for primary (*i.e.*, 1st cycle) drying and wetting conditions (Fig. 8a) and the *dry strength/wet strength* ratios (q_d/q_w) of gellan gum-treated sands with wetting and drying cycles (Fig. 8b).

Dry specimens show a significantly slower reduction in strength with each cycle than wet specimens (Fig. 8a), which indicates that the drying process of the gellan gum gels recovered some of the strength that was lost during the wetting process. This indicates that even after the gellan gum fibrils are fully detached from the gel structure, the drying process allows gellan gum fibrils to re-interact (*i.e.*, re-attach) with the main gellan gum structure, thereby recovering some of the lost strength. Meanwhile, once a gellan gum fibril is disturbed it is easily detached from the main structure again via water adsorption upon re-wetting. The underlying undisturbed gellan gum layer is then newly disturbed. As a result, under cyclic wetting, the structure of the gellan gum hydrogel can be fully disrupted and converge to a certain strength level, regardless of the gellan gum concentration.

The q_d/q_w of gellan gum-treated sands initially increases and then converges to a steady state depending on m_b/m_s. The initial increase of q_d/q_w is in accordance with the immediate strength and E_{50} reduction of the wet gellan gum-sand mixtures in early wetting-drying cycles (Fig. 5c and d), while convergence at further cycles implies a consistent phase transformation between the dried and wet gellan gum hydrogels inside the inter-granular voids. A higher m_b/m_s produces higher final q_d/q_w values and cycles for the steady state, which correspond to the number of cycles (*i.e.*, 1st, 6th, and 8th cycle for m_b/m_s = 0.5%, 1%, and 2%) where the wet strength of the gellan gum-treated sands converges to equilibrium (Fig. 5c). Moreover, the q_d/q_w of m_b/m_s = 0.5% sand becomes 10 on average at the steady state, while a higher m_b/m_s produces higher q_d/q_w values (*i.e.*, 20 for m_b/m_s = 2.0% and 15 for m_b/m_s = 1.0%) due to the notable strength reduction of wet gellan gum-sand mixtures with higher m_b/m_s (Fig. 8a).

3.6. Microscopic structures of gellan gum-treated sands under cyclic wetting and drying

Fig. 9 provides SEM images of pure gellan gum biopolymers and gellan gum-treated soils in dried and wet conditions. Fig. 9(a)

shows that at the initial state, without any drying or re-wetting, the pure gellan gum hydrogels have a relatively flat and smooth surface structure. Fig. 9(b&c) are images of initially dried gellan gum gels that show the accumulation and alignment of gellan gum molecules into a fibrous structure via dehydration, finally forming a hard and rough textile-type structure. In detail, Fig. 9 (a, b, & c) show that when the gellan gum is initially hydrated, gellan gum monomers randomly compose to form a hydro-swelled gellan gum hydrogel, which transform into fibrils and a fabric-type structure via dehydration.

Fig. 9(d & e) present SEM images of m_b/m_s = 1% sand after the 1st and 10th cycles of wetting and drying, respectively. Both conditions show that the major gellan gum gels remain intact, with occasional breakages forming within the gel structure. This indicates failure and weakening of the gel fabrics due to the stress and strains that are involved with the volumetric shrinkage and expansion accompanying the wetting and drying processes. Meanwhile, gellan gum gels after 10 repetitions of wetting and drying (Fig. 9e) show a higher degree of disturbance and detachment from sand particles, which appears to be a result of the dissociation of the gellan gum monomers from each other due to continuous electrical interactions with water molecules.

4. Discussion

Experimental results and findings on the hydro-variation (*i.e.*, wetting and drying) behaviors of a gellan gum biopolymer reveal that immediately after primary thermo-gelation the thermo-gelated gellan gum biopolymer first forms a uniformly dispersed hydrogel structure with interconnected hydro-swelled gellan gum monomers (Figs. 9a; 10a). When the primary rigid gellan gum hydrogel is subjected to dehydration, the gellan gum monomers begin to accumulate together toward a chain-type alignment due to the volumetric shrinkage involved with the loss of water (Fig. 10b). As the gellan gum gels lose more moisture and become almost fully dried, the gellan gum monomers become more tightly compacted and form a fibrous structure (Figs. 9b and c; 10c).

When dried fibrous- and fabric-form gellan gum gels (Fig. 10c) are subjected to hydration (*i.e.*, re-wetting), the outermost gellan gum monomers adsorb water and dissociate from the main structure, whereas the tightly interacted inner gellan gum molecules remain stable without hydro-disturbance.

In conclusion, the wetting works from the outside in, with the outer surfaces of the gellan fibers disassociating from the fibrous structure and interacting with the water molecules. The inner monomers will not disassociate as easily as the outer monomers due to the higher compaction and densities of the gellan monomers in the center of the fiber, and this results in non-uniform interaction with water within the gellan fibers (Fig. 10d). However, it should be noted that these results reflect tests carried out under
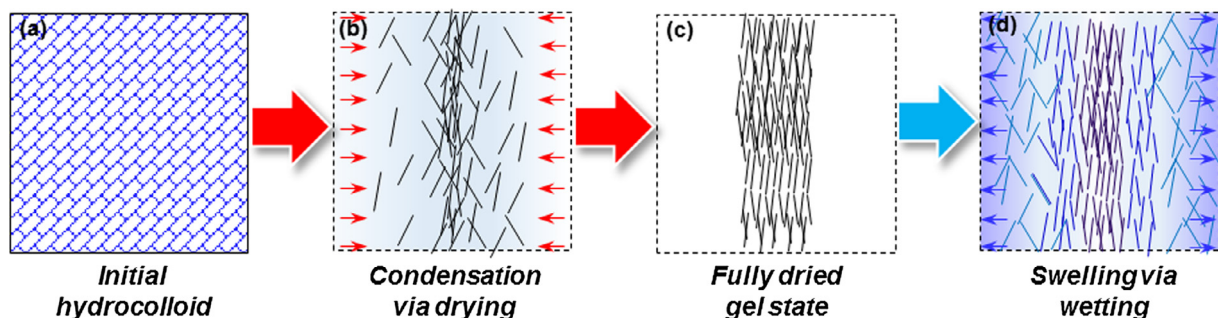

Fig. 10. Illustration of the phase transformation of gellan gum with drying and wetting. (a) Initial hydrocolloid state. (b) Gel condensation via dehydration. (c) Fully dried gels. (d) Swelling via re-hydration.
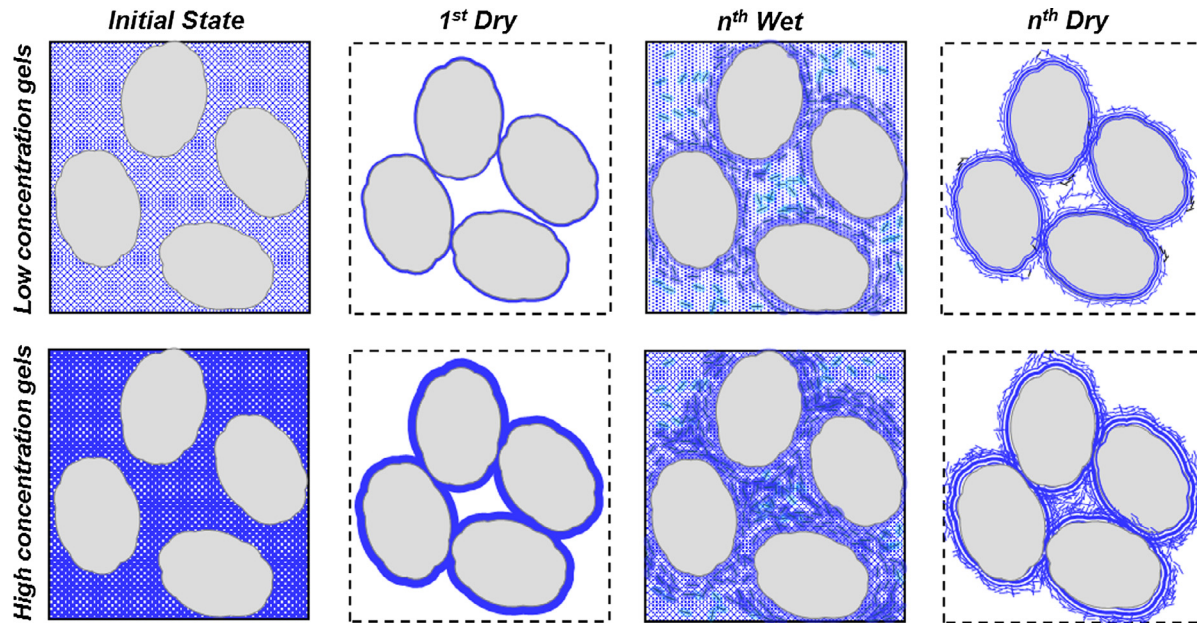
Fig. 11. Schematic diagram of cyclic drying and re-wetting mechanism of gellan gum-treated sands.

uniform drying and wetting conditions of 20° C for 28 days and full submergence for 2 h, respectively. Exact behaviors of the gellan treated jumunjin sand at different drying and wetting conditions are not known, but it is expected that higher drying temperatures may result in faster deterioration of the samples due to the larger moisture variations between the inner and outer surfaces of the gellan fibers whereas higher humidity levels may ease the deterioration of the samples due to the hydrophilic behavior of the gellan gums and the absence of "dry" heat.

Since re-hydration of the dried gels cannot recover (*i.e.*, fully reverse the loss of) the primary (*i.e.*, initial) rigid gellan gum structure (Figs. 9a; 10a), the significant reduction in strength observed between the initial samples (Fig. 3a) and the 1st wet samples (Fig. 3c) can be explained. Additionally, since the re-hydration of gellan gum hydrogels does not fully dissipate the fibrous structure (Fig. 10d), it can be concluded that thicker fibers (*i.e.* having higher biopolymer concentrations) require more drying and wetting cycles to be fully dispersed (corresponding to higher durability) than thinner fibers (*i.e.*, low content gellan gum gels), as was discussed in connection with Fig. 5.

Moreover, the lower reduction in strength of the dried samples compared with the re-wetted conditions (Figs. 5a and 8a) indicates that the dehydration of gellan gum-treated sands can reconstitute dispersed (*i.e.*, swelled and dissociated) biopolymer molecules into the main gellan gum gel body. Although the reattached fibers may not be as strongly bound as the initial fibers and will fail to recover the primary strength of the material, the surface interactions of the biopolymer molecules allow a certain amount of strength retention.

The overall drying and wetting mechanisms within gellan gum-treated sand are described in Fig. 11. In the initial state, rigid and uniform gellan gum hydrogels accumulate into fibrous and fabric structures that coat sand particles upon primary dehydration (1st dry). When the accumulated gellan gum gels are subjected to water (nth re-wetting), the outer bound gellan gum monomers adsorb water molecules and dissociate from the main gel body, while the inner monomers retain their structure and strength to some degree. Higher numbers of wetting and drying cycles result in a larger amount of monomers being dissociated from the main gellan gum gel body. When the re-wetted specimens are dehy-

drated again, the dispersed gellan gum monomers once again conglomerate onto the sand particles. However, due to the dissociation from the main structure, the outer surfaces of the gellan fibers form a disturbed structure, which results in lower surface density and reduced overall compressive strength (nth dry). With larger m_b/m_s, the gellan gum gels become thicker and stronger, while continuous drying and wetting cycles result in disconnection of the outer biopolymer molecules from the fibrous structure.

5. Conclusion

In this study the durability of gellan gum biopolymer treated sands under cyclic wetting and drying was evaluated via a series of laboratory explorations. Cyclic wetting and drying of gellan gum-treated sands results in a gradual degradation of strength due to the dissociation of gellan gum monomers under wetting, and their imperfect recomposition during re-drying. However, the dry strengths show a higher recovery and resistance to these drying and wetting cycles than the wet strengths. This is because the structural disturbance of the drying and wetting cycles is generally irreversible. While the strongly hydrophilic characteristic of the gellan gum monomers results in almost no strengthening because of the dispersed state of the gellan gum monomers when hydrated, dehydration produces a reaccumulation of the dissociated (*i.e.*, swelled) gellan gum monomers around sand particles, leading to a partial recovery of the unconfined compressive strength of the dried gellan gum-treated sand.

Meanwhile, the decrease in dry strength is nearly constant up to the 10th cycle. The wet strength shows a significant reduction after the 1st cycle, after which the reduction in strength appears to level off to a lower-bound (*i.e.*, residual) value of approximately 14 kPa. The residual strength of gellan gum-treated sands under wetting is similar regardless of the gellan gum to soil content in mass.

The strength reduction of gellan gum-treated sands is strongly affected by the transformation of the physico-chemical structure of the gellan gum gels when subjected to subsequent wetting and drying cycles. The dry strength of gellan-gum treated sands after 10 sequential wetting and drying cycles remained high (*i.e.*, more than 70% of its strength before hydro-disturbance), unlike

ordinary cement-treated sands, which undergo a significant reduction in strength at the earlier cycles of wetting and drying, leveling off at a relatively large residual strength. Therefore, the use of gellan gum can provide an environmentally-friendly approach in construction and geotechnical engineering. Gellan gum, unlike concrete, does not require construction demolition, waste treatment or disposal, but rather can be naturally decomposed (*i.e.*, biodegradation) after the expected service period of the gellan gum-treated sand structures in the field. Although decomposition properties and heat control in field application remain as major challenges for gellan gum biopolymer implementation, on the basis of high strengthening efficiency and relatively high mechanical durability characteristics, gellan gum biopolymer is a promising construction and building material for various soil treatment related purposes.

Acknowledgements

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