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Geotechnical engineering behaviors of gellan gum biopolymer treated sand

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ABSTRACT

Biological approaches have been explored as environmentally friendly alternatives to engineered soil methods in geotechnical engineering practices, recently. The use of microbial induced calcite precipitation, reactive enzymes, and microbial polymers, such as biopolymers, in soil improvement has been studied by researchers around the world. In the present study, gellan gum, a microbial polysaccharide generally used in the food industry due to its hydrogel rheology, was used to strengthen sand. The effects of gellan gum on the geotechnical behaviors of cohesionless sand were evaluated through a series of experimental programs including an unconfined compression test, direct shear test, falling head permeability test, and scanning electron microscopy. The geotechnical properties (friction angle, cohesion, and unconfined compressive strength) of gellan gum-treated sands were determined based on varying moisture conditions: initial, dried, and re-submerged. Gellan gum has a distinct strengthening effect on cohesionless sands through artificial cohesion which varies with the moisture conditions. The strengthening effect of gellan gum on sand appears to be a result of the combination of enhanced bonding between unreactive sand particles and the agglomeration of sand particles through hydrogel condensation, in which the agglomerated sand particles behave as enlarged aggregates in soil.

Keywords: Gellan gum biopolymer, Unconfined compressive strength, Friction angle, Inter-particle cohesion, Hydraulic conductivity

INTRODUCTION

Biological approaches for soil improvement recently have been studied in an effort to address environmental concerns related to improving existing soil materials (*e.g.*, an increased shear strength). A number of studies have investigated the possibility of directly implementing microbial induced calcite precipitation (MICP) using microbes in the soil with the goal of strengthening the soil using a lower carbon footprint than that of ordinary engineering soil practices such as cement mixing (Cheng et al. 2013; DeJong et al. 2006; DeJong et al. 2010; van Paassen et al. 2010; Whiffin et al. 2007). Although MICP is an innovative and environmentally friendly alternative soil treatment method, several drawbacks of this approach have been noted including difficulties in obtaining a uniformly treated soil layer due to the uncertainty of the microbial activity and the secretion quality of the soil, which restricts its application to loose and collapsible sands (Soon et al. 2013). Moreover, microbial ureolysis in the ground releases 2 moles of ammonium ions, NH_4^+ , for every 1 mole of calcite CaCO_3 precipitation, which increases the soil pH, forms toxic salts, and emits toxic gas into the atmosphere (Akiyama and Kawasaki 2012; Ferris et al. 2004).

Meanwhile, several attempts to use biological organic matter, such as biopolymers, have been reported to stabilize soil aggregates directly instead of activating microbial responses in the soil, (Chang and Cho 2012, 2014; Chang et al. 2015d; Ferruzzi et al. 2000; Orts et al. 2007; Ringelberg et al. 2014). For example, direct biopolymer mixing of a high-molecular chain structure glucan-type biopolymer, β -1,3/1,6-glucan, results in sufficient workability due to the pseudoplastic rheology of the biopolymer. This enables the formation of a uniform biopolymer-soil mixture providing high strengthening with a low carbon dioxide footprint (Chang and Cho 2012). Specifically, the unconfined compression strength provided by 0.25% β -1,3/1,6-glucan mixing (2.17 MPa) is similar to that obtained with 10% cement mixing (2.65 MPa) showing that biopolymers are capable of achieving similar strengths at significantly lower concentrations (1/10 or lower). Thus, biopolymer soil treatment for geotechnical purposes has the potential to reduce the net amount of mixing materials, particularly materials such as cement that involve a high amount of carbon dioxide emissions during production (8 % of all global emissions) (Chang et al. 2015b; International Cement Review 2015).

28 In addition, recent studies have shown the possibility of using gel-type biopolymers, such as agar
29 gum, xanthan gum, and gellan gum, to enhance the strengthening efficiency in geotechnical soil
30 treatment (Chang et al. 2015a; Chang et al. 2015c; Khatami and O'Kelly 2012). Specifically, thermo-
31 gelation biopolymers such as agar gum and gellan gum provide significant strengthening. Thermo-
32 gelating biopolymers initially form a hydrocolloid phase when dissolved in water with a temperature
33 above 90 °C and then, transform to a hydrogel phase with significantly increased viscosity when
34 cooled to below 40 °C. The firm hydrogel of the thermo-gelation biopolymers forms matrices with
35 mediating particles and enhances the overall strength of the whole network (Huang et al. 2007;
36 McHugh 2003).

37 The use of gellan and agar biopolymers involves different strengthening mechanisms depending on
38 the soil type. Thermo-gelation biopolymers show stronger adhesion with clayey particles, making it
39 possible to achieve an unconfined compressive strength of 13 MPa for 3%, relative to the soil mass,
40 gellan gum biopolymer mixed kaolin under a dried condition (Chang et al. 2015c).

41 However, most previous studies have only provided preliminary work introducing biopolymers as a
42 possible new binder material for civil and geotechnical engineering purposes. Although gellan gum
43 forms stronger biopolymer-soil matrices with clayey particles than it does with cohesionless coarse
44 particles, in practical applications, sandy soils are generally preferred over clayey soils due to their
45 superior workability and drainage control. Moreover, sandy soils have a higher strengthening
46 efficiency than that of clayey soil based on the unconfined compressive strength (UCS) of untreated
47 natural soils (Chang et al. 2015a), and many aspects of geotechnical engineering require
48 cohesionless soils with an improved shear strength behavior. For these reasons, sand was used as the
49 target soil for this study.

50 Using a series of experimental approaches, this study examined in detail the effect of gellan gum
51 biopolymer treatment on cohesionless sand focusing on geotechnical engineering design parameters,
52 specifically, the friction angle, cohesion, and hydraulic conductivity. Furthermore, possible
53 applications of gellan gum biopolymers for geotechnical engineering purposes are recommended based
54 on the findings of these experimental studies and analyses.

55

56 **MATERIALS AND METHODS**57 ***Materials***58 ***Jumunjin sand***

59 Jumunjin sand is a typical standard sand in Korea that has been widely used in various studies
60 (Chang et al. 2015c; Min and Huy 2010; Park et al. 2008). Using the USCS classification, Jumunjin
61 sand is classified as a poorly graded sand (*SP*). Fig. 1 shows the particle size distribution of Jumunjin
62 sand. The coefficient of uniformity (C_u) and the coefficient of gradation (C_c) are 1.94 and 1.09,
63 respectively. It has particulate structures between a minimum void ratio of 0.64 and a maximum void
64 ratio of 0.89; its specific gravity (G_s) is 2.65.

65

66 ***Biopolymer: Gellan Gum***

67 Gellan gum is a high molecular weight polysaccharide that is fermented from *Sphingomonas elodea*
68 microbes. Low acyl gellan gum biopolymer supplied by Sigma Aldrich (CAS No: 71010-52-1) was
69 used in this study. Low acyl gellan gum partially hydrates in cold water and fully dissolves at
70 temperatures above 90 °C forming a hydrocolloid phase solution. The viscosity of a gellan gum
71 solution increases with decreasing temperature, and finally, a highly viscous hydrogel is formed below
72 40°C (*i.e.*, thermo-gelation). Thus, hydrogel formation is expected to occur naturally during the
73 mixing process with soil through decreasing temperature.

74

75 ***Sample preparation***

76 All gellan gum-sand samples were prepared by following the same sample preparation method.
77 First, a gellan solution was prepared by dissolving pure gellan gum into distilled water at 100°C
78 according to the target concentration (0.5, 1.0, 1.5, 2.0, and 5.0% relative to the mass of the soil) of
79 the gellan gum-sand mixtures. The initial water content for mixing was set at 30% of the dry sand
80 weight because it was found that an initial water content of 30 % is sufficient to fully fill the inter-
81 granular voids with biopolymer gels, which leads to a fully saturated condition for gellan gum-sand

82 mixtures during sample preparation. Thus, 1.67%, 3.33%, 5.0%, and 6.67% gellan gum solutions
83 were prepared to finally deliver 0.5%, 1.0%, 1.5%, 2.0%, and 5.0% gellan gum-sand mixtures (by
84 weight), respectively.

85 To prevent immediate cooling and thus ensuring sufficient mixability, dry sand was heated in an
86 oven to 100 °C before mixing. The heated gellan gum solution and sand were mixed on a laboratory
87 hot plate to minimize temperature reduction during mixing and to form a uniform gellan gum-sand
88 mixture. After mixing, the hot gellan gum-sand mixtures were immediately placed into molds relevant
89 for tests before cooling. Cube samples (50 mm × 50 mm × 50 mm) were prepared for the unconfined
90 compression tests, while disk samples (diameter = 60 mm, height = 20 mm) were molded for use in
91 the direct shear tests.

92 The strength of biopolymer treated soils strongly depends on the water content of the biopolymer-
93 soil mixture (Chang et al. 2015c). Thus, three different moisture conditions were considered in the
94 experimental studies: 1) the initial condition, in which samples were tested immediately after cooling;
95 2) a dry condition, in which samples were fully dried for 28 days at room temperature (20°C) with a
96 final water content less than 1 %, and 3) a re-submerged condition, in which the dried samples were
97 submerged in water for 24 hours before testing. Due to the hydrophilic characteristic of the gellan
98 gum, dried gellan gum gels immediately adsorb water and re-hydrate within 2 hours while higher
99 concentrations require up to 6 hours. Full saturation of all the samples was obtained in less than 6
100 hours. However, the gellan gum-treated sands were submerged for 24 hours to provide sufficient time
101 for re-hydration and stabilization, in which the gellan gum gels inside the soil recover to the initial
102 concentration before drying. The water content (w / m_s) and biopolymer concentrations (biopolymer to
103 water ratios in mass; m_b / w) of the gellan gum-treated sands at different moisture conditions are
104 summarized in Table 1.

105 For the re-submerged condition, we think that the adsorbed water interacts with the hydrophilic
106 gellan gum biopolymers rather than with the electrically neutral sand particles. However, this
107 hypothesis is inappropriate for soils that contain clay particles which have hydrophilic double-layer
108 surfaces.

Unconfined compression tests

Cubic samples (50 mm × 50 mm × 50 mm) of the gellan gum treated sands were prepared at gellan gum concentrations of 0.5%, 1.0%, and 2.0%. Unconfined uniaxial compressive testing was performed with a Universal Testing Machine (UTM). The axial strain rate was controlled at a rate of 0.5 mm/min (1% strain/min). The maximum strength and the stress-strain behaviors were obtained by averaging three different measurements for a single condition.

Direct shear tests

Disk shaped gellan gum-sand samples with a 50 mm diameter and 20 mm height were placed into a direct shear apparatus with porous stones placed above and beneath them and confined at 50, 100, 200, and 400 kPa with a pneumatic actuator for 12 hours before applying horizontal shear. Direct shear tests were performed for the three different moisture conditions mentioned in Section 2.2. The samples for the initial and the re-submerged conditions were tested under a saturated condition by filling the inside of the shear box with water before applying vertical confinement. Horizontal shear with a shear rate of 2% strain/min was applied under a consolidated-drained condition following the ASTM D 3080 standard (ASTM D3080 / D3080M-11 2011) with confining pressures of 50, 100, 200, and 400 kPa. Horizontal shear was applied for 500 seconds to finally induce a 10 mm horizontal displacement. Horizontal load, vertical strain, and horizontal displacements were obtained automatically through load cell and linear variable differential transformer (LVDT) measurements, for which the electronic measurements were attained with a computerized data acquisition system.

Hydraulic conductivity tests

The initial void ratios of the gellan gum-sand mixtures were within a relatively narrow range between 0.82 and 0.87, regardless of the gellan gum content in the soil mass. Gellan gum-sand mixtures were prepared and poured into a cylindrical cell with an inner diameter of 70 mm and a height of 140 mm (height to diameter ratio = 2:1) before thermo-gelation. The cylindrical cells were

sealed with parafilm and left to cool for 7 days to prevent loss of moisture from the gellan gum-sand mixtures and thereby preserving the initial mixing conditions.

Permeability tests were performed according to the ASTM D 5084 standard (ASTM D5084-10 2010) using a flexible wall permeameter at room temperature ($20\pm 1^\circ\text{C}$) while the inlet and outlet flows were controlled and maintained using a pressure panel. A head difference of 150 mm was applied to fully saturate the specimens, and a confining pressure of 30 kPa was applied. When the Skempton B-values (Skempton 1954) of the samples exceeded 95%, the samples then were considered as fully saturated. After saturation, falling-head permeability tests were performed with a hydraulic gradient of 20 or less. Only the initial condition was considered for the laboratory permeability tests to simulate the bio-clogging effect (Mitchell and Santamarina 2005) induced by instant gellan gum-treatment (*e.g.*, mixing) for saturated (below ground water table) sand deposits *in situ*.

Scanning Electron Microscopy (SEM)

SEM images were taken to observe the micro-scale direct interactions between the sand particles and the gellan gum biopolymers. Undisturbed and disturbed 1% gellan gum-treated sand samples were examined by collecting 0.5 cm^3 bulk cubic samples from dried gellan gum-sand mixtures that had not been subjected to any testing, and disturbed samples were prepared by attaching the 1% gellan gum-sand specimens that had been subjected to failure on an SEM mount (diameter 25 mm) using carbon conductive tabs. Carbon paint was applied to the edges and bottoms of both the undisturbed and disturbed sample to provide sufficient grounding. Specimens were coated for 20 seconds using an Osmium Plasma Coater (OPC) with osmium tetroxide (OsO_4) as the source of osmium. An extreme high-resolution scanning electron microscope was used to observe the surface of the gellan gum-sand samples.

RESULTS AND ANALYSIS

Unconfined Compressive Strength (UCS) of the gellan gum-treated sand samples

The values for the unconfined compressive strengths and accompanying water contents of the gellan gum biopolymer treated sands are summarized in Fig. 2 and Table 1. The strength of the gellan gum-sand mixtures increased with increasing biopolymer content regardless of the moisture conditions, while the fully dried condition resulted in the highest values for the unconfined compressive strengths at 130.2, 241.9 and 434.6 kPa for the 0.5%, 1%, and 2% gellan gum, respectively (Fig. 2a). In comparison with the cement treatment, even a small amount of gellan gum treatment increased the dry strength of sand significantly. For instance, the UCS of the 2% gellan gum-treated sand (434.6 kPa) is higher than that of 12% cement-treated sand (380 kPa), even though the gellan gum-treated sand has a lower dry density ($1,430 \text{ kg/m}^3$) than that of the cement treated sand ($1,770 \text{ kg/m}^3$) (Yoon and Abu-Farsakh 2009). Moreover, the UCS of 2 % gellan gum-treated sand is identical to the UCS of densely compacted ($1,930 \text{ kg/m}^3$) 8 % cement-sand mixtures after 7 days of curing (470 kPa) (Cheng et al. 2013).

The UCS behavior of the gellan gum-treated sands is consistent with the varying concentrations of gellan gum gels (m_b / w ; gellan gum to water ratio, in mass) in the soil (Table 1). Dehydration of the gellan gum gels from the initial to the dried state increases the m_b / w significantly, while a higher gellan gum content (m_b / m_s) results in the retention of a higher final water content (w / m_s) after drying due to the strong hydration characteristics of the gellan gum biopolymer (Nussinovitch 1997). The increased m_b / w with drying is highly correlated to the strengthening efficiency of the gellan gum treatment. Therefore, an increase in strength can be attributed to the densification of the gellan biopolymers, which results in higher m_b / w ratios. Previous studies have been conducted on the strength of gels based on the concentration of the biopolymers to the water mass (Banerjee and Bhattacharya 2011). In an earlier study, it was found that the strength of the gels increased with higher m_b / w ratios. Because the gellan gum biopolymer has strong hydration capabilities (Nussinovitch 1997) exceeding that of sand particles, the water content of the samples interacts mostly with the gellan gum. Therefore, a change in the water content of the samples can be attributed to a similar change in the m_b / w ratios.

For the re-submerged condition, although the m_b / w values were similar to that of the initial state ($\approx 30\%$), the UCS values of the re-submerged samples were lower than those of the initial condition samples (17-23% lower). Therefore, not only the gellan gum gel concentration but also the hydro-rheology (*e.g.*, swelling and disturbance) is an important factor regarding the strength behavior of gellan gum-treated sands. This indicates that even though re-submergence recovers the specimen water content and gellan gum concentration to levels similar to the initial state, subsequent re-wetting after the primary dehydration process does not recover the strength of the gellan gum hydrogels up to the initial condition. However, the strength of the gellan gum-treated sand without any variations in the water content are known to remain stable regardless of the time (Chang et al. 2015c). Thus, it can be concluded that the initial state and strength of gellan gum hydrogels is not recoverable once the gellan gum gel is condensed via dehydration. Further studies are recommended to characterize the strength and micro-rheology variations of the gellan gum-treated sands under subsequent repeated drying and wetting cycles with additional analytical methods such as infrared or EDX (Energy Dispersive X-ray) spectroscopy.

The stress-strain relationships of the gellan gum-treated sands (shown in Fig. 3) provide a better explanation, showing that the dried gellan gum-treated sand had higher stiffness compared to the other conditions (initial and re-submerged). This indicates that inter-particle strengthening results from the formation of thick and high-tensile biopolymer dehydrates (*e.g.*, films) among the sand particles, which has also been observed in previous studies (Chang and Cho 2012; Chang et al. 2015a). However, once the primary dried samples are re-submerged, and the water content is recovered through hydrophilic absorption, the strength of the soil greatly diminishes due to the swelling of the biopolymer hydrogels and the weakening of the biopolymer bonds, while the ductility increases to a level higher than that of the initial conditions. This appears to be the result of partial and sequential swelling of the gellan gum hydrogels beginning at the outermost boundary of the dehydrated gellan gum gels, which initially form thick layers on the sand particles during the primary drying process.

Direct shear strength of the gellan gum-treated sand

216 *Peak shear behavior*

217 The peak strengths of the gellan gum-treated sands at different moisture content levels, obtained by
 218 direct shear testing, are shown in Fig. 4. The peak shear strength (τ_{peak}) values of the gellan gum-sand
 219 mixtures are increased with the higher biopolymer contents, regardless of the moisture conditions.
 220 With the higher biopolymer contents, increased strengthening of the samples is clearly seen for both
 221 the initial and dried conditions (Figs. 4a & b), while the strengthening effect appears to diminish for
 222 the re-submerged samples (Fig. 4c).

223 Fig 5 shows the peak strength properties (cohesion and friction angle) of the gellan gum-treated
 224 sand samples. Once the gellan gum hydrocolloids are mixed with the sand (initial condition), the
 225 cohesion of the highly viscous hydrogels increases immediately while the peak friction angle remains
 226 almost constant without any noticeable variation identical to the friction angle of 28° for the untreated
 227 wet sand. As the gellan gum gels become denser with drying, both the peak interparticle cohesion
 228 (c_{peak}) and the peak friction angle (Φ_{peak}) increase significantly with increasing gellan content.
 229 Although the c_{peak} values show a continuous increment up to a 5% gellan gum content regardless of
 230 the moisture condition, the Φ_{peak} increment appears to level off and converge after the 2% gellan gum
 231 content. Meanwhile, dehydration of excess gellan gum gels above 2% does not affect the structural
 232 composition of the sand particles. Instead, the particles exhibit enhanced interparticle cohesion due to
 233 the higher strength of the highly concentrated gellan gum hydrogels which coat the particle surfaces,
 234 enhance the inter-particle contacts and fill the void spaces.

235 A previous study showed that cement-treated sand, with a 10% cement to sand ratio by volume or
 236 8% by mass, remarkably improves the friction angle (as great as 44°), while having a negligible effect
 237 on the inter-particle cohesion (at a value of 0.42 kPa) (Krantz 1991). In comparison, the friction angle
 238 of an 8% cement treatment sample is equivalent to that of a sample with a 5% gellan gum mixture;
 239 however, the increase in the cohesion for the cement treatment sample cannot be compared to the
 240 remarkable improvement in cohesion for the gellan gum-treated sands (as great as 166.17 kPa for 5 %
 241 gellan gum in a dried state).

The strengthening during gellan gum treatment is due to the condensation and aggregation effects of the high tensile gellan gum hydrogels among the sand particles; on the other hand, the strengthening of the cement treated sand is dominated by the formation and pore filling of newly formulated Calcium-Silicate-Hydrate (C-S-H) crystals inside the particle voids.

Re-submerged specimens experienced a remarkable reduction in c_{peak} (Fig. 5a) with values even lower than the c_{peak} of the initial conditions, while Φ_{peak} (Fig. 5b) remains higher than that of the initial condition. These results indicate that the re-wetting and swelling of the primary dried gellan gum hydrogels is not reversible. In particular, the decrease in cohesion indicates the possibility that the molecular structures and the bonding of the gellan gum biopolymers have been disturbed.

Overall, c_{peak} and Φ_{peak} increase with higher biopolymer contents; however, at around 2-5% of the gellan gum biopolymer, the rate of increase in c_{peak} and Φ_{peak} decreases regardless of the moisture conditions. This indicates that there likely is an optimal biopolymer concentration ($\approx 2\%$) for the sand treatment when the goal is effective shear strengthening.

Residual shear behavior

Fig. 6 shows the residual shear strengths of the gellan gum-treated sands under different moisture conditions. The residual strength of the gellan gum-treated sand has a similar behavior regardless of the moisture condition unlike the peak shear strength behavior described above.

The samples for the initial, dry, and re-submerged conditions all show an increase in the residual friction angle (Φ_{res}) and residual cohesion (c_{res}) with higher gellan contents, while the c_{res} values of the gellan gum-treated sands are almost equal for all of the gellan gum contents regardless of the soil moisture conditions (Fig. 7a). This indicates that the strengthening effect induced by the gellan gum hydrogels in sand persists at high levels of strain which implies persistent inter-particle interlocking and adhesion induced by the hydrogen bonding and high tensile strength of the gellan gum hydrogels (Lee et al. 2004).

However, the Φ_{res} values for both the initial and re-submerged gellan gum-sand mixtures are similar at low gellan gum contents, 1.0% and lower, while the values at the initial state are slightly

higher than those of the re-submerged state for gellan gum contents higher than 2%. Meanwhile, the dried condition sample shows a distinctly higher Φ_{res} than that of the moist condition sample (Fig. 7b). Of note, for the gellan gum content below 1%, the Φ_{peak} is clearly higher than the Φ_{res} , while the difference between the Φ_{peak} and Φ_{res} decreases when the gellan gum content exceeds 1% (Figs. 5b and 7b).

In general, the shear strength of coarse soil increases with greater dry density (Bolton 1986; Terzaghi et al. 1996). Fig. 8a shows the relationship between the peak shear strengths and the dry densities of the gellan gum-treated sand, for which the dry density reflects the actual particle composition. As the dry density increases, the peak shear strength generally increases, regardless of the biopolymer content and wet conditions.

Meanwhile, with an increase in the biopolymer content relative to the mass of soil, the shear strength increment decreases, shown in Fig. 8b, due to a unit dry density (1 g/cm^3) increment (*i.e.*, the ratio between the *change in shear strength* for a subjective *change in dry density*; $\Delta\tau_{DS} / \Delta\gamma_d [\text{MPa}\cdot\text{cm}^3 / \text{g}]$). This indicates that the soil composition has less of an effect on the strengthening mechanism of the gellan gum-treated sands at higher gellan gum contents, and instead, the majority of the strengthening results from the interparticle bonding provided by the gellan gum hydrogels. The $\Delta\tau_{DS} / \Delta\gamma_d$ ratio shows a dramatic degradation with increased gellan gum content and finally levels off at the 2-5% gellan gum content. However, the peak interparticle cohesion (c_{peak}) increases inversely to the $\Delta\tau_{DS} / \Delta\gamma_d$ trend. Thus, the strengthening mechanism of the gellan gum-treated sands appears to be less dependent on the structural composition of the sand particles, whereas it is strongly affected by the rheology and strength of the gellan gum hydrogels existing inside.

Shearing mechanism of the gellan-treated sand samples

The condensation and aggregation mechanism of gellan gum-treated sands is schematically shown in Fig. 9. Natural (untreated) sand has no chemical inter-particle bonding between sand particles, only along the shear band (Fig. 9a), resulting in individual particle movement, rotation and overturning (Fig. 9b). Meanwhile, gellan gum hydrogels provide artificial inter-particle cohesion which

strengthens with condensation and finally binds particles into agglomerates through increased particle connections and inter-particle bridging. This causes several soil particles to act as a larger single aggregate which requires a larger dilation angle and rotational frustration as well as an increased peak friction angle shown in Figs. 4, 5b and 9c. As such, gellan treated sands have high interparticle cohesion and friction angle values, especially in the dried state compared to those of untreated sand.

The values for the residual friction angle (Φ_{res}) of the dried gellan gum-treated sands are higher than those of both moist (*i.e.*, initial and re-submerged states) gellan gum-sand mixtures in all cases (Fig. 7b). This can be attributed to the microscopic structure of the crushed gellan gum-sand mixtures; this microstructure is identical to that of the residual condition sample that was subjected to shearing. Dried and condensed gellan gum gels break into fragments under large strains; these fragments are expected to behave as frictional materials, improving interlocking between sand particles even in the residual state. Although their viscosities are lower than those of the dried gels, the initial and re-submerged gellan gum hydrogels also have higher Φ_{res} values than those of the untreated sand. Moist hydrogels are expected to be partially crushed due to the motions of the sand particles; this can also possibly enhance the friction characteristics of the sand particles at large strain shearing through interface attractive adhesive forces between the sand surfaces and the viscous gels (Gong et al. 1999; Tominaga et al. 2008). Thus, it becomes clear that the existence of gellan gum hydrogels inside soil increases both the peak and residual friction properties through hydrogel condensation.

Scanning Electron Microscopy (SEM)

SEM images of the 1% gellan gum-sand mixtures are shown in Fig. 10. Undisturbed gellan gum-treated sand (Fig. 10a) shows that the gellan gum biopolymers coagulate into gellan gum films which form connection bridges between adjacent particles (Fig. 10b). This results in an increase of both the peak strength and the elastic modulus (Fig. 3) which was also observed in previous biopolymer studies, including research on beta-glucan (Chang and Cho 2012) and xanthan gum (Chang et al. 2016; Chang et al. 2015a). Therefore, the gellan gum-sand matrix formation and hardening

mechanism through dehydration is expected to be governed by the densification (m_b / w increase; Table 1) of the gellan gum hydrogels inside the sand pores.

Effect of water on the behavior of the gellan gum-treated sands

One drawback to the strengthening mechanism of gellan gum-treated sand is the decrease in strength when the primary dried gellan gum-sand mixtures are re-submerged in water. With dehydration, the condensed gellan gum hydrogels force sand particles to interact more directly and tightly because the gellan biopolymers form increased particle interactions (Fig. 10a) and fibrous clumps (Fig. 10c) which enhance the strength of the gellan gum-treated sand samples. When the dried gellan gum-treated sands are subjected to water again, the hydrophilic gellan gum-water interaction and accompanying swelling (Fig. 2b) appear to degrade the strength properties such as the strength and stiffness (Fig. 3) as well as the inter-particle cohesion (Fig. 5a) of the gellan gum gels inside soil, regardless of the gellan gum to sand ratio. This is consistent with the phenomenon of an unrecoverable initial state of gellan gum hydrogels once they are condensed through dehydration outlined in section 3.1. Thus, it can be concluded that the initial state and strength of the gellan gum hydrogels is not recoverable once the gellan gum gel is condensed through dehydration.

The hypothesis that gellan gum-treated sand with varying water contents has different geotechnical engineering behaviors is shown in Fig. 11. In the initial state, the gellan gum hydrocolloids uniformly disperse between sand particles, and the viscosity increases by thermo-gelation (cooling) (Fig. 11a). As the gellan gum hydrogels undergo dehydration, the thickened gels begin to coagulate around the sand particles, while the decrease in volumetric moisture content leads to the formation of discrete air voids along the gellan gum gels (Fig. 11b). Once the gellan gum gels are dried, condensed film-like gellan gum gels enhance the inter-particle interaction (Figs. 3 and 5a) through biopolymer matrix formation (Figs. 10a & b) among the sand particles (Fig. 11c). However, once the dried gellan gum-treated sand is re-submerged, the dried gels are expected to absorb water due to their hydrophilicity. Gradual swelling of the gellan gum gels from the outside rim results in weaker viscosity (or stiffness) of the re-hydrated gellan gum gel relative to that of the initial / uniform hydrocolloid state (Fig. 11a).

The strength difference of the gellan gum gels between the initial and re-submerged conditions (Figs. 2 and 5) implies that a uniform initial gel matrix cannot be recovered by the re-wetting and accompanying swelling of the dehydrated biopolymer gels without post thermal treatment.

Hydraulic conductivity of the gellan gum-treated sand samples

The hydraulic conductivity of the gellan gum-treated sand in the initial state decreases exponentially, from an untreated condition ($\sim 2.1 \times 10^{-4}$ cm/s) to 1% gellan gum content ($\sim 2.6 \times 10^{-8}$ cm/s) shown in Fig. 12. Then, for higher gellan gum contents, the hydraulic conductivity converges to a very low value ($\sim 8.2 \times 10^{-9}$ cm/s) which correlates with an impermeable layer.

The convergence of gellan gum-treated sands above a 1% gellan gum content toward a stabilized hydraulic conductivity behavior appears to be induced by a combination of the water holding capacity and the pore-filling characteristic of the gellan gum hydrogels under a saturated condition. Within a fixed pore size, the water content of a fully saturated specimen remains constant; as such, an increase in the gellan gum content will decrease the permeability by reducing the number of easily moveable water molecules inside the specimen. Moreover, thick gellan gum hydrogels are expected to fill the pore spaces of the sands by creating multiple film-type gellan gum layers on the sand particle surfaces, consequently reducing the pore spaces (bio-clogging). Thus, it can be concluded that gellan gum shows promise in terms of controlling the hydraulic conductivity, a feature that can be applied to various environmentally friendly water control purposes in geotechnical engineering.

The bio-clogging efficiency increased with greater gellan gum content; once the gellan gum hydrogel reached a concentration for which the water molecules inside the pores completely interacted with the biopolymer molecules, the hydraulic conductivity stabilized to a lower bound. From this point, the excess amount of gellan gum no longer had a large effect on decreasing the hydraulic conductivity. However, for higher hydraulic pressure gradient conditions ($i > 20$), it is expected that a greater amount of gellan gum will be required to produce a similar hydraulic conductivity control effect. It is hence recommended that further studies be performed to investigate the hydraulic conductivity behavior of gellan gum treated soils under large hydraulic pressure

376 conditions and to evaluate the potential of gellan gum biopolymer use in deep grouting or mixing
377 purposes.

378

379 **DISCUSSION**

380 *Economic feasibility of gellan gum use for geotechnical engineering purposes*

381 Currently, the economic feasibility of using gellan gum to replace ordinary cement in geotechnical
382 engineering applications appears to be rather low. Specifically, the current material price of gellan
383 gum is roughly 20,000 USD/ton¹, while the price of ordinary cement is only 100 USD/ton² (Kelly
384 and Matos 2014; Morris et al. 2012).

385 Taking into account that lower concentrations of gellan gum are required compared with cement,
386 for instance, 1% gellan gum treatment has an equivalent strength to a 10% cement treatment, and the
387 material price to treat 1 ton of soil amounts to approximately 200 USD for gellan gum and 10 USD
388 for cement. This large difference in price makes the current use of gellan gum in soil treatment
389 impractical. However, the current market price is for food grade gellan gum, and the market for lower
390 grade gellan gum has not yet been developed.

391 If the market for gellan gum were to develop further, allowing for greater commercialization of
392 gellan gum, the prices could decrease significantly. This is what transpired with the
393 commercialization of xanthan gum, with the price dropping from 30,000 USD/ton to 3,000 USD/ton
394 within 20 years (Imeson 2010). With proper marketing and commercialization, it can be assumed that
395 the price of gellan gum could reach the current price of xanthan gum (3 USD/kg). Additionally, high
396 purity food grade gellan gum is unnecessary for construction purposes, and with a lower required
397 purity, production costs could be greatly reduced. Without the cost of additional purification, the total
398 cost could be significantly lower than the anticipated cost of 3 USD/kg, reaching 1.5 - 2 USD/kg. At
399 this point, the cost of treating 1 ton of soil with 1% gellan gum would be approximately 15 – 20 USD,
400 which would be comparable with that of cement (10 USD).

¹ Material trade price of bulk (1 ton) low acyl gellan gum (www.alibaba.com)

² Market price of cement in the United States in 2014.

For future implementation, a heated gellan gum solution (over 90 °C) can be injected (*e.g.*, grouting) or mixed (*e.g.*, deep auger mixing) directly with *in-situ* soil, to facilitate quick setting by thermo-gelation due to a temperature decrease during implementation. With the cost for heating the gellan solution for soil treatment, a rough calculation of the required energy was performed assuming an overall 50% efficiency with gas heating equipment (Nakićenović et al. 1998). In detail, approximately 588 MJ is required to treat 1 ton of soil with 300 kg of heated 3.3 % gellan gum solution. Generally, gasoline has an energy density of 46.4 MJ/kg (Nakićenović et al. 1998), and thus, the average fuel cost to treat 1 ton of soil with thermo-gelated gellan gum treatment becomes approximately 9.63 USD/ton, considering the average market price of gasoline in the U.S. in 2014 (Kilian 2014). This value is only the cost for the required energy and is highly susceptible to change depending on many variables such as heating mechanisms and methods.

Possible applications of the gellan gum treatment in geotechnical engineering practices

Gellan gum is a biodegradable biopolymer with a high sensitivity to the presence of water. Therefore, any permanent application using gellan gum-treated soils may be difficult. However, because the material is non-toxic and ecofriendly, its use in temporary construction may be extremely beneficial. As the results of the current study show, the use of gellan gum in sand provides a cohesive strength not found in such sands.

The increased inter-particle cohesion and the friction angles of the gellan gum-treated sand are expected to provide significant ground improvement in practical geotechnical applications, regardless of exposure to water. To address considerations for foundation engineering, the ultimate bearing capacities ($q_{ult(square)}$) at a 1 m depth of gellan gum-treated sand deposits for square-type (1 m × 1 m) foundations are presented in Table 1. Table 1 is shown in accordance with Terzaghi's formulas on ultimate bearing capacities (Das and Sobhan 2014). Table 1 shows a significant increase in the $q_{ult(square)}$ values with higher gellan gum content. Although both the interparticle cohesion and the friction angle values of gellan gum-treated sand vary with different moisture conditions, the strengthening effects for all moisture conditions improve the $q_{ult(square)}$ of the sands remarkably. For

instance, even at the weakest gellan gum treatment condition (0.5%), $q_{ult(square)}$ increased by 266% from that of the untreated sand, 269 kPa, reaching a final value of 983 kPa. The highest $q_{ult(square)}$ was obtained from 5% gellan gum treated sand in a dry condition, reaching an extremely high value of 44 MPa. Thus, it can be cautiously concluded that the strengthening efficiency of the gellan gum treatment on sandy soils provides effective and sufficient ground improvement for various geotechnical engineering applications including foundation design.

In terms of temporary construction purposes, the proposed treatment may be valuable in applications such as erosion resistance at construction sites, by reducing the amount of airborne dust particles produced by the construction process and the problems that arise with such aeolian dust particles (Pye 1987). It can also provide temporary strengthening of unpaved ground at construction sites, including that used for temporary roads, allowing easier movement and use of heavy machinery.

This technology also shows promise as a practical solution for quick permeability control. Unlike cement, because gellan gum does not require a long period of time to set, a quick injection of a gellan gum solution may allow for rapid application of a permeability control, and such quick applications can be helpful in reducing time and material costs (Nimah et al. 1983).

The major benefit of biopolymer soil treatment technology is that after the service period of a given temporary support or ground improvement, the biodegradability of biopolymers will allow for natural decomposition while simultaneously providing a carbon food source for local vegetation without any demolition waste.

CONCLUSIONS

As an environmentally friendly biopolymer used for soil improvement, the gellan treated sands showed relatively high strengthening even at low concentrations. The unconfined compression test results for the gellan sands (434 kPa) were comparable to those of 12% cement treated sands (380 kPa). In terms of shear strength, the gellan sands showed large improvements in the cohesion and the friction angle of the sands. With large improvements in the cohesion and the friction angle at low concentrations, gellan gum can be easily implemented to improve the strength and quality of shallow

455 soils.

456 Additionally, due to the pore filling effects of the gellan hydrogels, the use of gellan has been
457 shown to be capable of decreasing the permeability of sands to 1×10^{-8} cm/s. The decrease in
458 permeability when applying gellan gum into the soil is almost immediate; therefore, when used as a
459 permeability-controlling barrier, gellan gum can provide a fast alternative to sufficiently reduce the
460 permeability of soils.

461 Although gellan gum is highly sensitive to water, the retention of the strength and friction angle
462 even in the re-submerged state indicates a certain degree of durability with drying and wetting cycles.
463 With sufficient durability, the working life of biopolymers will be adequate for numerous construction
464 purposes. In addition, because gellan gum is biodegradable and eco-friendly, its use will allow for
465 natural disposal of the biopolymer into the ecosystem without causing any harm to the environment.
466 Therefore, this method of soil improvement offers many benefits compared to current methods,
467 especially in applications involving temporary improvement. The use of cement may allow for strong
468 and durable engineered ground construction, but due to its overly high durability and difficulties in
469 disposal, its use in temporary applications is highly undesirable. The present results show that gellan
470 gum has various benefits for ground improvement including improvements in strength, friction angle,
471 and reduction of permeability.

472

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Table 1. Water content (w / m_s) and biopolymer concentration (biopolymer to water ratios in mass; m_b / w) of gellan gum-treated sands at initial, after drying, and after re-submergence.

Gellan gum content, m_b / m_s [%]	Water content [%]					
	Initial		Dry		Re-submerged	
	w / m_s	m_b / w	w / m_s	m_b / w	w / m_s	m_b / w^*
0.5	30.0	1.67	0.5	100	26.0	1.92
1.0	30.0	3.33	0.7	143	28.0	3.57
1.5	30.0	5.00	0.8	187	28.3	5.30
2.0	30.0	6.67	0.9	222	29.5	6.78

*Maximum possible biopolymer to water ratios for the re-submerged condition

Table 2. Bearing capacities of gellan treated soils

Gellan gum content [%]		0 (untreated)	0.5	1	2	5
c [kPa]	Initial	0.0	24.7	33.2	85.6	103.5
	Dry	0.0	32.6	67.8	114.3	166.2
	Submerged	0.0	18.0	23.3	40.6	44.7
ϕ [°]	Initial	27.9	28.3	29.77	29.7	29.5
	Dry	27.9	34.6	36.85	42.7	47.3
	Submerged	27.9	29.3	30.35	33.4	36.0
$q_{ult(square)}$ [kPa]	Initial	269	1,127	1,618	3,612	4,243
	Dry	269	2,536	5,726	17,340	44,166
	Submerged	269	983	1,304	2,611	3,713
Improvement efficiency [%]	Initial	-	319	502	1,245	1,480
	Dry	-	844	2,032	6,356	16,343
	Submerged	-	266	385	872	1,282

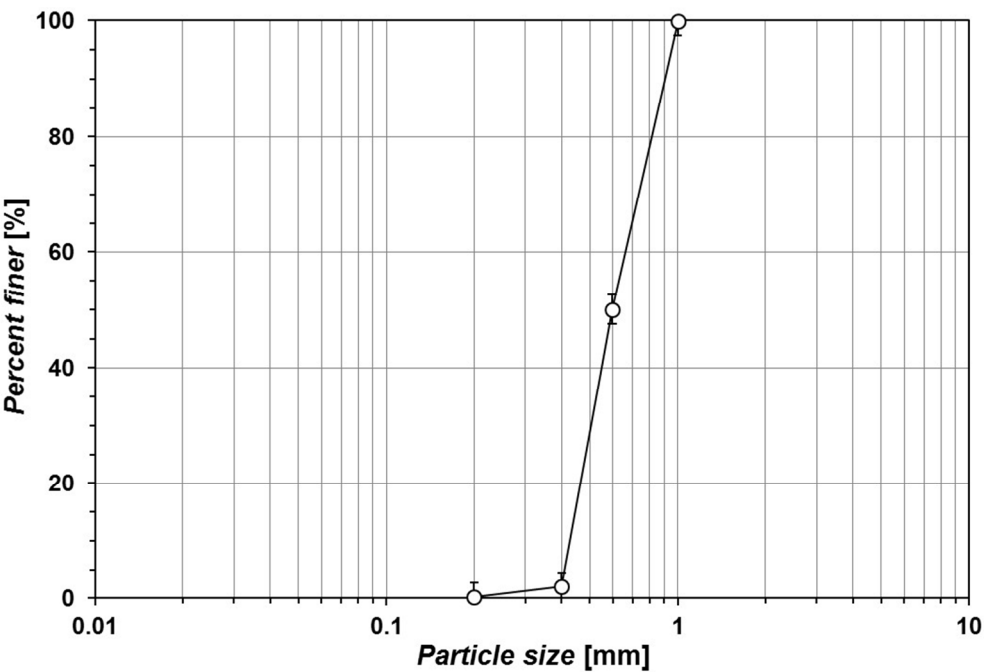


Figure 1. Particle size distribution of Jumunjin sand.
180x120mm (150 x 150 DPI)

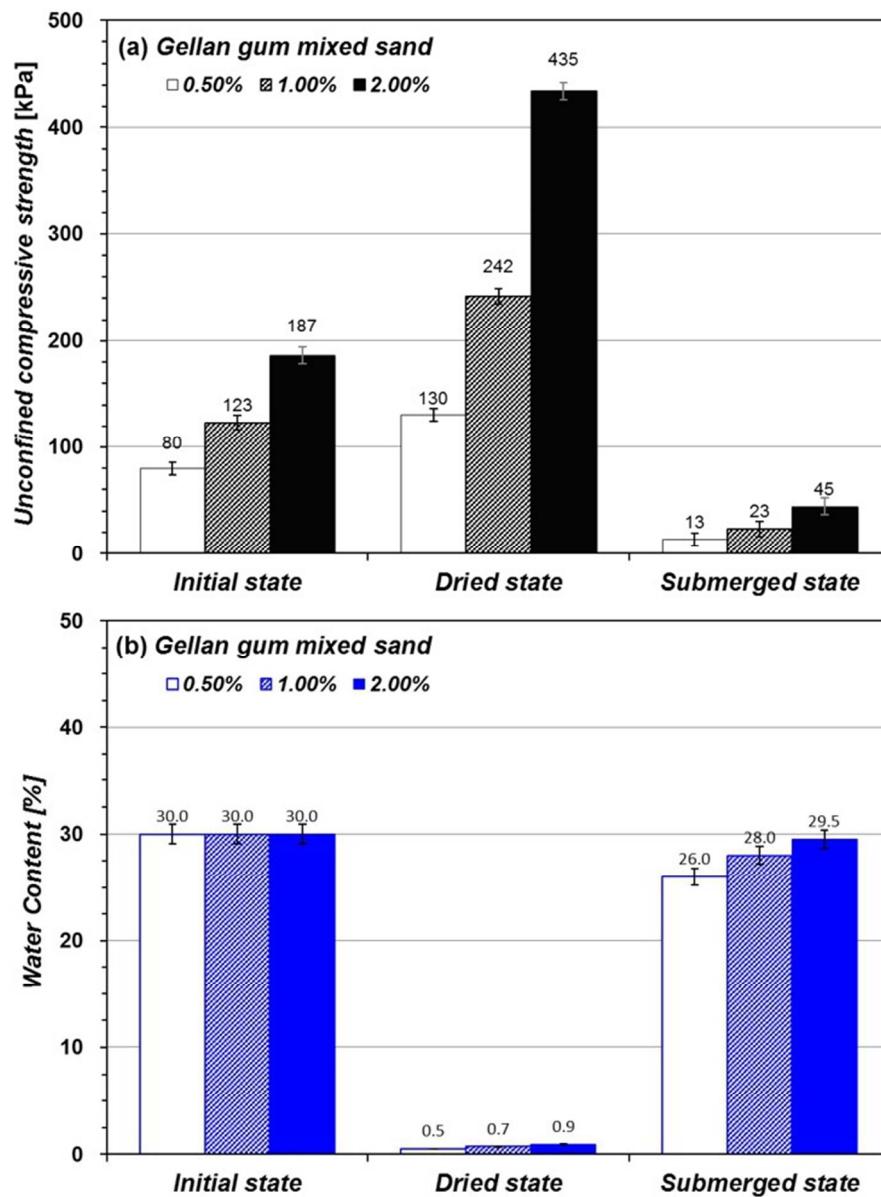


Figure 2. Unconfined compressive strength (a) and water content (b) of gellan gum-treated sand. 126x168mm (150 x 150 DPI)

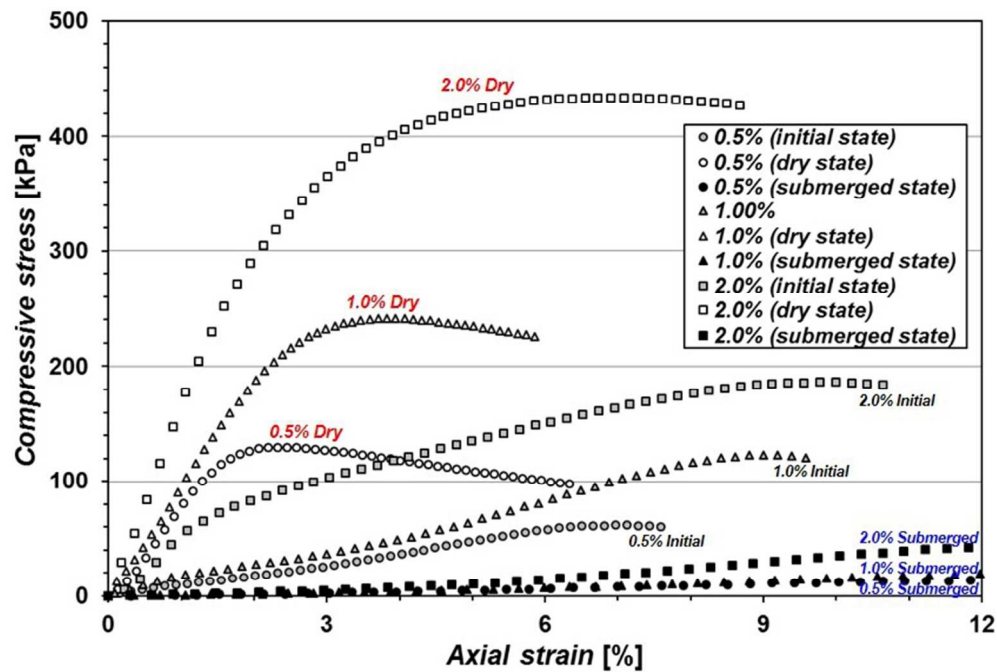


Figure 3. Stress-strain relationships of gellan gum-treated sand under unconfined compression.
144x96mm (150 x 150 DPI)

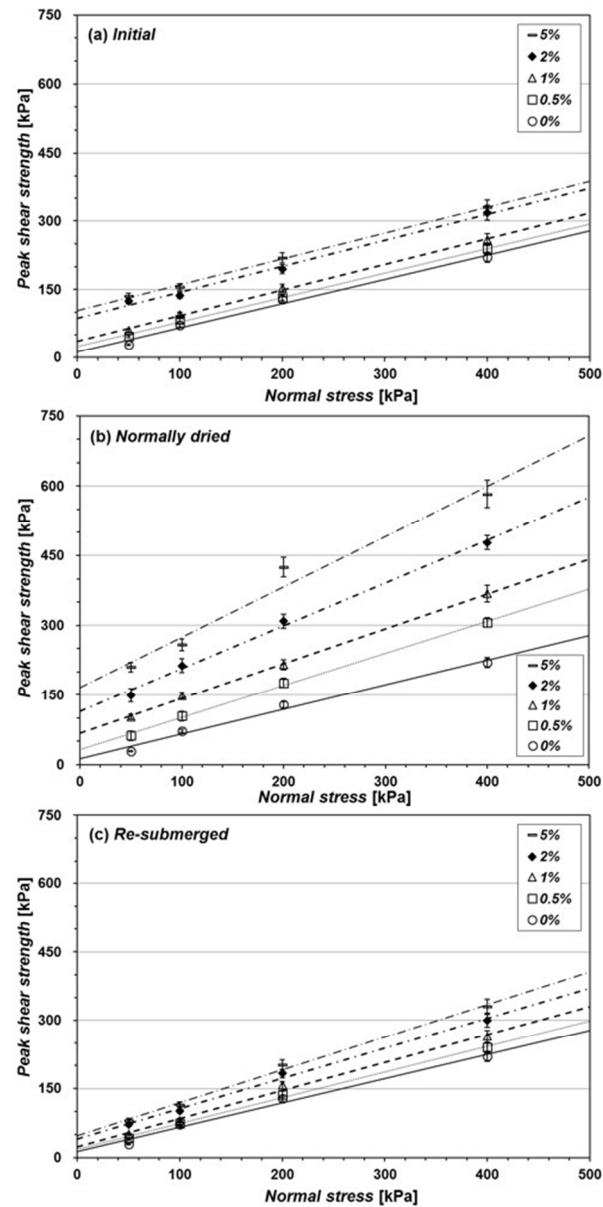


Figure 4. Peak strength of gellan gum-treated sand. (a) Initial condition. (b) Dried condition (28 days). (c) Re-submerged condition (24 hours before testing).

85x171mm (150 x 150 DPI)

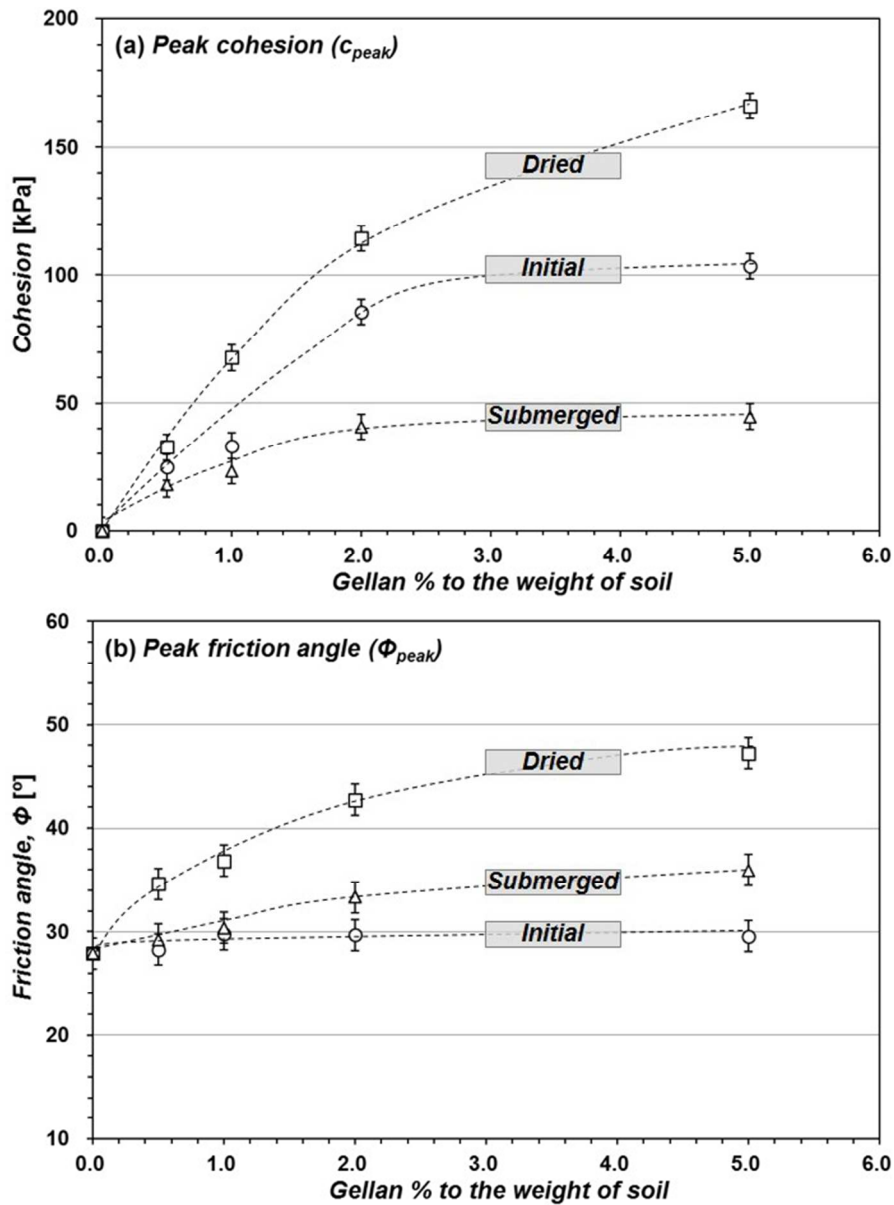


Figure 5. Peak strength properties of gellan gum-treated sand. (a) Cohesion. (b) Friction angle.
120x159mm (150 x 150 DPI)

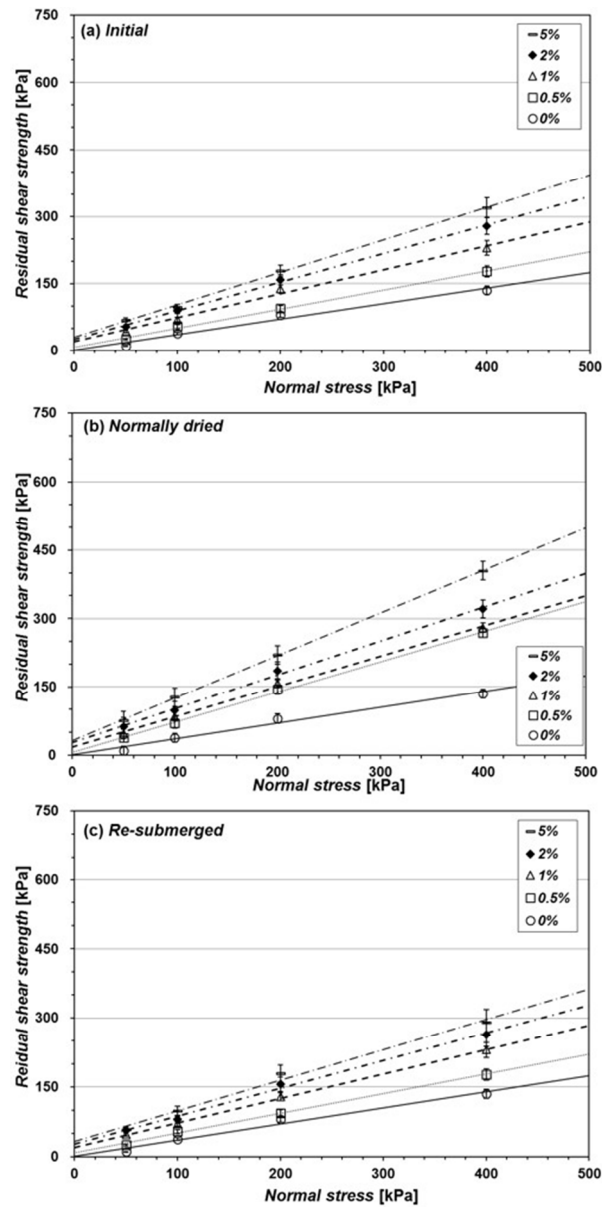


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85x171mm (150 x 150 DPI)

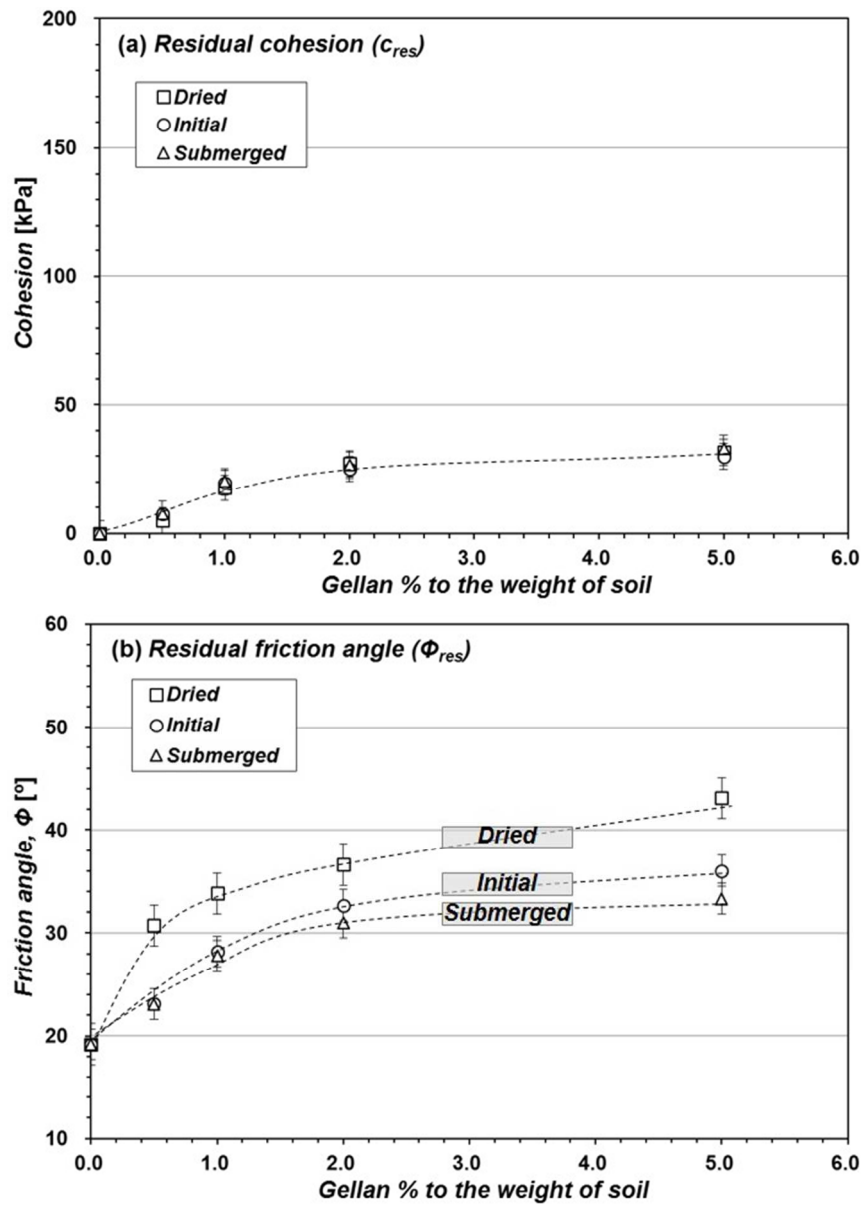


Figure 7. Residual strength properties of gellan gum-treated sand. (a) Cohesion. (b) Friction angle. 120x165mm (150 x 150 DPI)

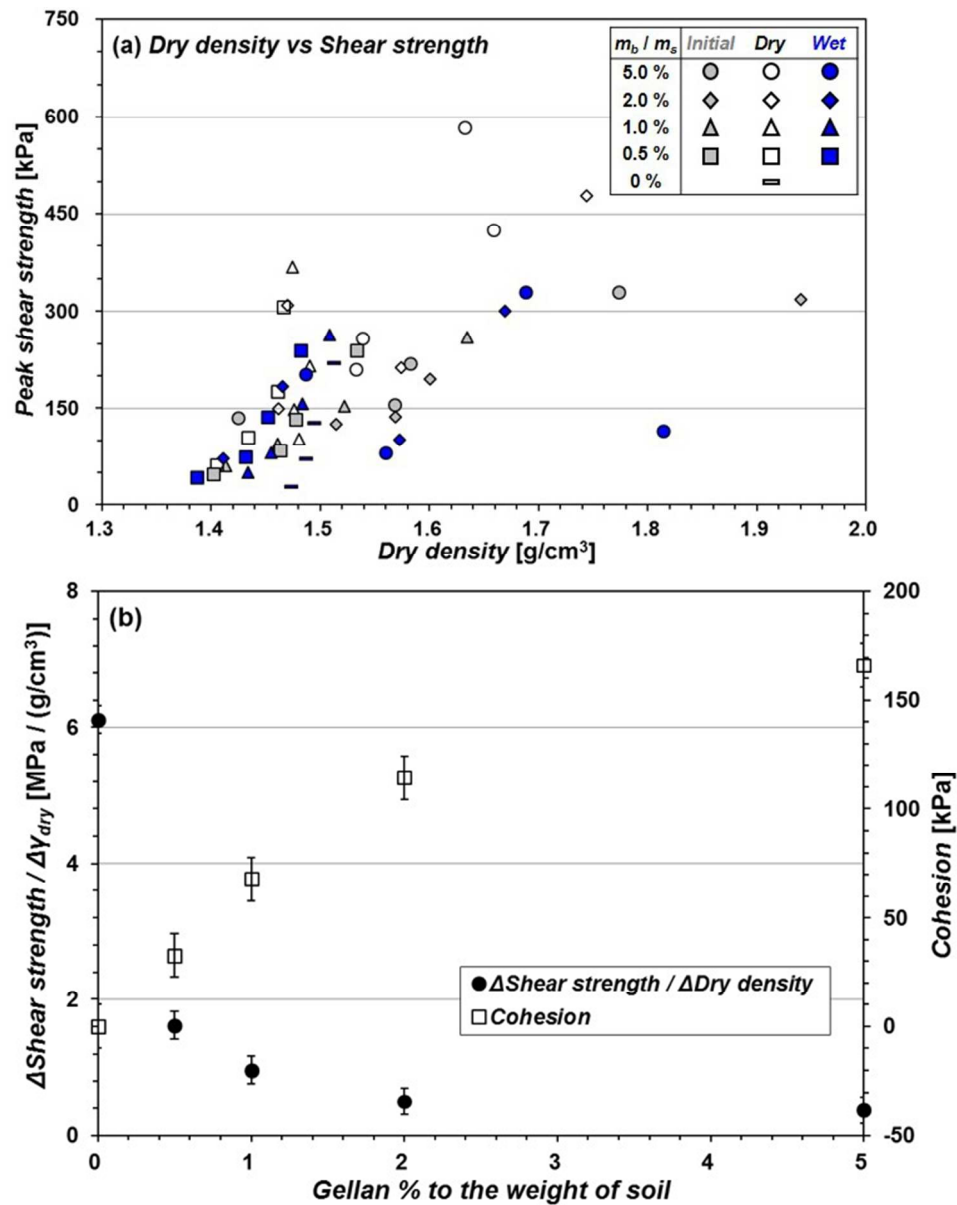


Figure 8. Peak shear strength of gellan gum-treated sand (a) versus dry density (b) versus gellan gum content.

129x162mm (150 x 150 DPI)

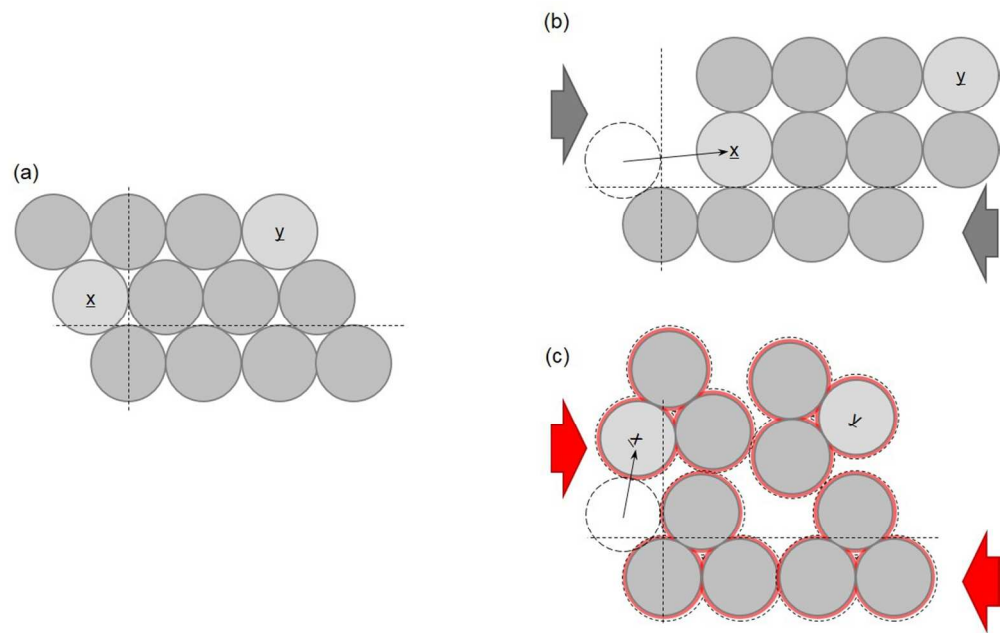


Figure 9. Schematic diagram of sands under shearing. (a) Natural (untreated) sand before shear. (b) Untreated sand under shear in which particles rotate along the shear plane. (c) Aggregation effect of gellan gum-sand mixtures, which induces a higher friction angle (ϕ_{peak}) in a dried condition.
199x126mm (150 x 150 DPI)

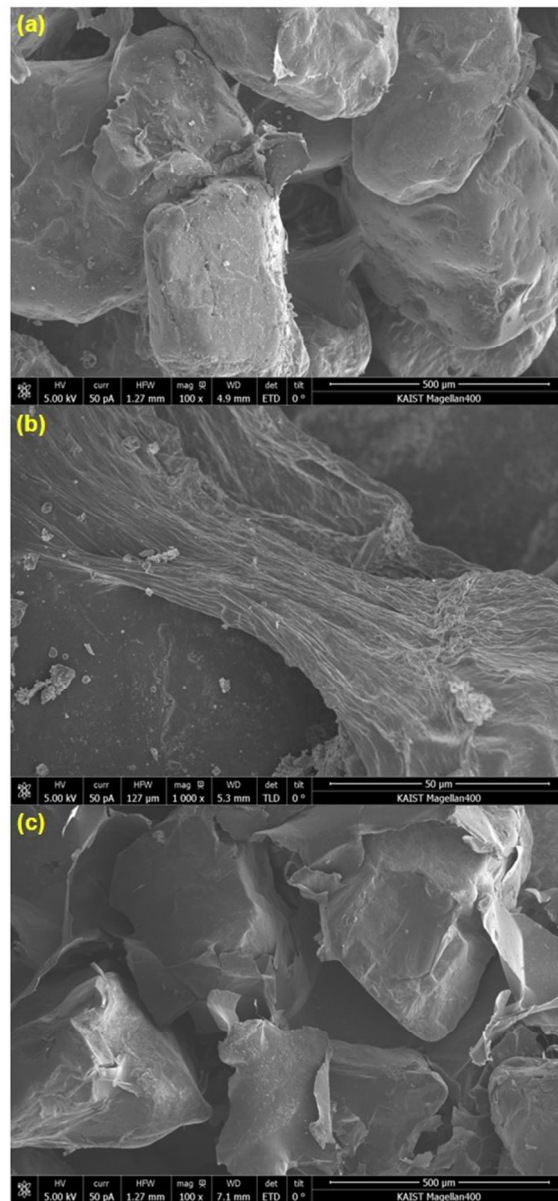


Figure 10. SEM images of 1% gellan gum-treated sand. (a) Before UTM testing (undisturbed). (b) Gellan gum films accumulated between particles (undisturbed). (c) After UTM testing (crushed)
86x183mm (150 x 150 DPI)

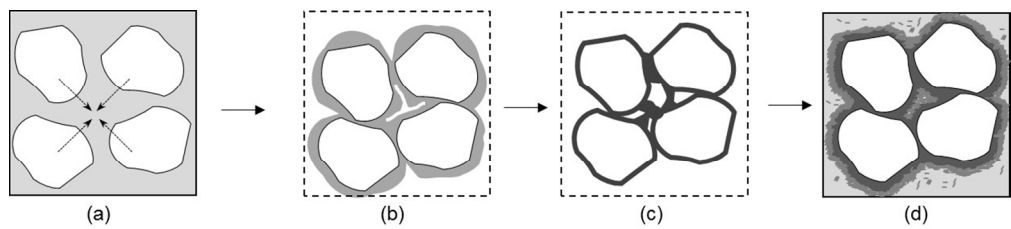


Figure 11. Drying and wetting mechanisms of gellan treated sands (a) Initial condition. (b) Propagation of cracks in gel with drying. (c) Dried condition. (d) Re-submerged condition.
211x48mm (150 x 150 DPI)

Draft

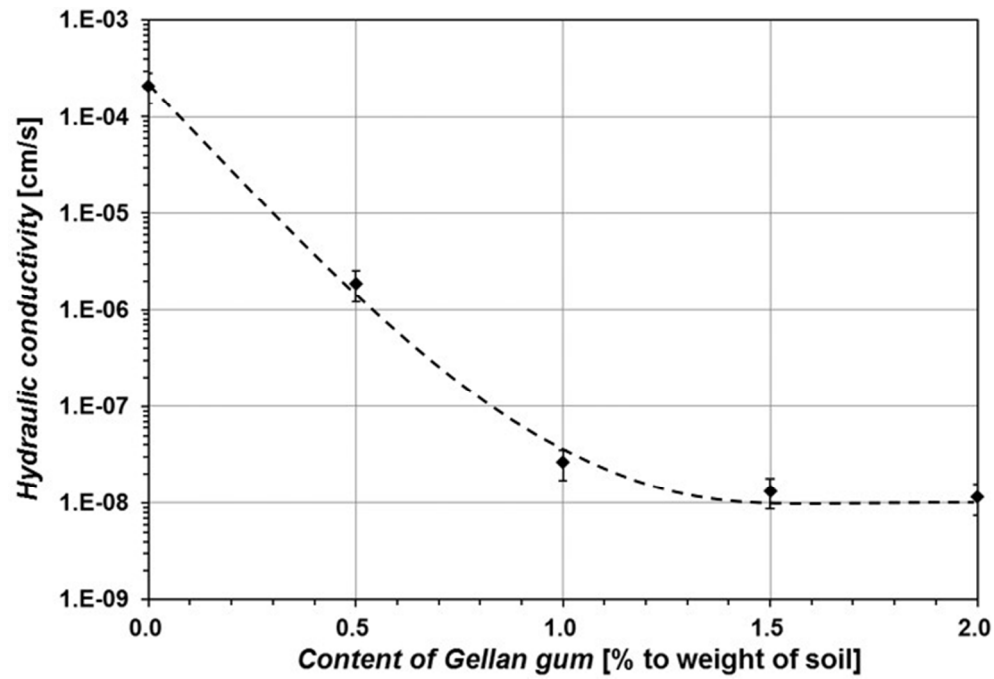


Figure 12. Hydraulic conductivity of gellan gum-treated sand in the initial state (without drying) with biopolymer content (by weight).
120x80mm (150 x 150 DPI)