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Dynamic properties of gel-type biopolymer-treated sands evaluated by Resonant Column (RC) Tests

Jooyoung Im [1a], An T.P. Tran [1b], Ilhan Chang [2c] and Gye-Chun Cho [*1]

[1] *Department of Civil Engineering, Korean Advanced Institute for Science and Technology,*
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[2] *School of Engineering and Information Technology, University of New South Wales,*
Canberra, ACT 2600, Australia

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Abstract. Due to numerous environmental concerns in recent years, the search for and the development of sustainable technologies have been pursued. In particular, environmentally friendly methods of soil improvement, such as the potential use of biopolymers, have been researched. Previous studies on the use of biopolymers in soil improvement have shown that they can provide substantial strengthening efficiencies. However, in order to fully understand the applicability of biopolymer treated soils, various properties of these soils such as their dynamic properties must be considered. In this study, the dynamic properties of gel-type biopolymer treated soils were observed through the use of resonant column tests. Gellan gum and Xanthan gums were the target gel-type biopolymers used in this study, and the target soil for this study was jumunjin sand, the standard sand of Korea. Through this study it was demonstrated that biopolymers can be used to enhance the dynamic properties of the soil, and that they offer possibilities of reuse to reduce earthquake related soil failures.

Keywords: biopolymer treatment; gellan gum; xanthan gum; shear modulus; damping ratio

1. Introduction

Sustainable development and accompanying technologies are extremely important in today's society due to the increasing threats of global climate change and natural hazards. In the field of geotechnical engineering, one of the most important challenges is to improve the soil strength and stability via physical or chemical approaches. The most commonly accepted strengthening practices for soil strengthening are based on the usage of ordinary cement. Soil-cement mixtures show high strengthening and durability with low costs. However, the supply of cement is severely restricted in underdeveloped countries (mostly in Africa) and high amounts of greenhouse gases are emitted during its production (Chang *et al*. 2015b). Thus, various strategies are being pursued to develop alternative soil binders and application methods to reduce the usage of cement in light of sustainability concerns (Chang *et al*. 2016b, Mitchell and Santamarina 2005, Sidik *et al*. 2014).

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*Corresponding author, Professor, E-mail: gyechun@kaist.edu
[a] Ph.D. Candidate, E-mail: jooyoungim@kaist.ac.kr
[b] Ph.D. Candidate, E-mail: phuongan313@gmail.com
[c] Lecturer, E-mail: ilhan.chang@adfa.edu.au

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Among others, soil treatment with microbial induced biopolymers is a promising engineered soil approach in terms of sustainability (Ayeldeen *et al*. 2016, Chang *et al*. 2016b, Nugent *et al*. 2009). Recent studies have shown the potential of applying biopolymer-soil technology to soil strengthening, soil permeability control, erosion reduction, fine dust or particle control, and even vegetation improvement (Chang *et al*. 2016a, 2015d, Chen *et al*. 2014, Khachatoorian *et al*. 2003, Peng *et al*. 2011). Due to the bio-clogging characteristic of biopolymer hydrogels, biopolymers such as guar gum, xanthan gum, and sodium alginate can be applied to control the hydraulic conductivity of highly permeable soils (Bouazza *et al*. 2009, Chang *et al*. 2016a). Biopolymers (*e.g*., chitosan) also show possibilities to be applied in drinking water treatment as a natural flocculent to remove polluted suspensions in reservoirs (Zemmouri *et al*. 2013).

One of the strongest advantages of biopolymer treatment in geotechnical engineering is high strengthening efficiency with relatively small quantities compared to ordinary cement mixing. In detail, it is found that only 1% biopolymer (ratio to the mass of soil) treatment lends higher strength than 10% cement treatment (Chang and Cho 2012, Chang *et al*. 2015a). However, most recent studies have focused on the static behavior of biopolymer treated soils, and therefore dynamic considerations are needed.

With seismic considerations in the field of geotechnical engineering, earthquakes and accompanying geotechnical issues such as dynamic stability and liquefaction must be considered due to the increasing threats of earthquakes worldwide (Ardeshiri-Lajimi *et al*. 2016, USGS 2016). During earthquakes, injuries occur due to building collapses, landslides, and other quake related incidents. Liquefaction occurs as a consequence of increased pore-water pressure induced by the tendency of granular materials to compact when subjected to cyclic shear deformation, rendering significant inter-particle strength reduction and accompanying deformation (Youd *et al*. 2001). Therefore, the seismic resistance becomes an important concern to satisfy both static and dynamic stability of engineered soils.

The Korean peninsula has been considered an earthquake-safety region due to the less frequent occurrence of earthquakes compared to neighboring Japan and China. However, recent records present increasing seismic events in Korea, which are becoming much stronger and more frequent (EarthquakeTrack 2016). For instance, the strongest ever earthquake in Korea (Richer scale 5.4) rocked the southern region of Korea on September 12, 2016, and its tremors spread throughout the country including Seoul. Thus, soil stability under seismic events becomes an important concern for geotechnical engineering practices including concurrent development of biopolymer-soil technology.

In geotechnical engineering aspects, important dynamic properties of soil are non-linear and hysteretic soil behaviors such as variation of the shear modulus (G) and damping ratio (D) with shear strain (γ). Many studies have been carried out to investigate the dynamic behavior of chemically engineered soils. For cement, lime, and fly ash stabilized loose sand and silty clay, cementation increases both rigidity ($G_{\max}$) and seismic energy dissipation (damping) characteristics of cemented soils (Chae and Chiang 1973). In the case of expansive clay, lime cementation enhances static stability such as shear strength improvement and swelling reduction, as well as dynamic properties (Chae and Au 1978). Moreover, the threshold strain where the shear modulus begins to fall, increases with higher cement treatment, while higher cement content prevents rapid degradation of the $G/G_{\max}$ curves at larger torsional strain levels (Tsai *et al*. 2012).

However, the seismic behavior and the dynamic resistance of biopolymer-treated soils have not been extensively understood or studied. Questions have been raised about the dynamic behavior and seismic resistance of biopolymer-treated soil. Typical Korean sand (i.e., jumunjin sand) shows a possibility of liquefaction depending on the in-situ density and earthquake scale (Ha *et al*. 2011, Kim and Park 2008). Thus, an in-situ countermeasure to enhance the seismic resistance of sandy deposits is required. Previous studies have already shown the promising strengthening efficiency of gel-type biopolymer-treated Korean sand under a static condition (Chang *et al*. 2016a, 2015c). In this study, dynamic properties of gel-type biopolymer-treated sand are investigated through a laboratory evaluation. Gellan and xanthan gums, typical gel-type bacterial polysaccharides, are used as target biopolymers in this study. Although both gellan gum and xanthan gum are gel-type biopolymers, the thermo-gelation characteristic of gellan gum is a remarkable difference between them (Grasdalen and Smidsr 1987).

2. Materials

2.1 Jumunjin sand

Jumunjin sand is the standard sand in South Korea, and it has been used in numerous studies and researched in the field of geotechnical and environmental engineering. It is classified as a poorly graded sand with a D_{60} and D_{10} of 0.6 mm and 0.31 mm respectively. It has a specific gravity (G_s) of 2.65 and a uniformity coefficient (C_u) and a coefficient of gradation (C_c) of 1.94 and 1.09, respectively (Park *et al*. 2008). The particle size distribution of jumunjin sand is presented in Fig. 1.

2.2 Gellan gum biopolymer

Gellan gum is a polysaccharide biopolymer with a high molecular weight that is fermented from the microbe *Sphingomonas elodea* (Bajaj *et al*. 2007). The gellan gum biopolymer used in this study was purchased from Sigma Aldrich with CAS No: 71010-52-1.

Gellan gum is a linear anionic polymer having molecular weight in the range of 0.5-2 × 10^6 Da (Imeson 2010). In normal commercial production, gellan gum is modified to become a deacylated polymer, which is only partially hydrated in cold deionized water and produces a viscous solution. It can be fully hydrated in water at temperature above 90°C and form gels if suitable cations are

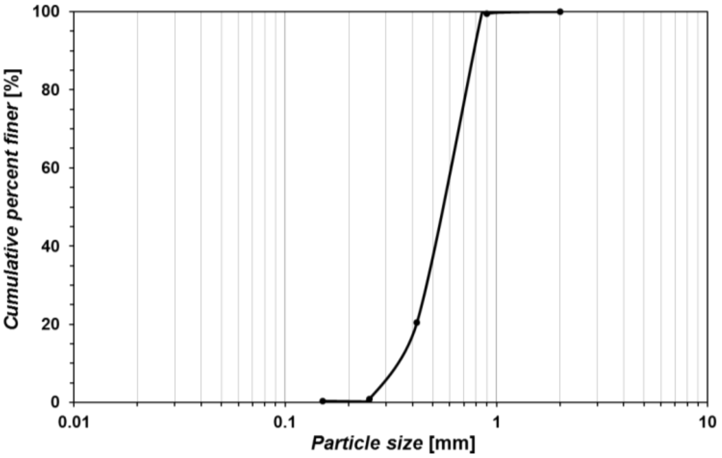

Fig. 1 Particle size distribution of Jumunjin sand

presented when cooled to the gelling temperature (Huang *et al*. 2007). Gellan gum has properties of a thickening or gelling agent. Since it was approved in Japan, the USA, and the EU, it has been used as a food additive in many countries worldwide.

One major property of gellan gum is its thermo-gelation characteristic. At normal room temperature, gellan gum is only partially hydrated in deionized water; however, when the water is heated to temperature above 90℃, gellan gum becomes easily dispersed. After the solution is heated, when it cools back down to room temperature, the gellan gum monomers reform with suitable cations, which allows for stronger links between the particles and results in the formation of a stiff hydrogel (Huang *et al*. 2007).

The gelation of deacylated gellan gum occurs by transformation from disorderly coils to threefold double helices while cooling, followed by aggregation of double helices by the roles of cations to develop three dimensional networks (Chandrasekaran and Radha 1995, Morris *et al*. 2012, Tang *et al*. 1997, Upstill *et al*. 1986).

2.3 Xangthan gum biopolymer

Xanthan gum (CAS No.11138-66-2) has been used to as a high molecular chain type, gel (gum) - forming type biopolymer. Xanthan gum is a polysaccharide commonly used as a food additive and a rheology modifier; it is produced by the fermentation of glucose or sucrose by the *Xanthomonas campestris* bacterium (Davidson 1980, Rosalam and England 2006).

The most well-known characteristic of xanthan gum is its pseudo plasticity (i.e., viscosity degradation depending on the increase of the shear rate) (Casas *et al*. 2000). The xanthan gum structure consists of repeated units formed by five sugar residues: two glucose, two mannose, and one glucuronic acid (Jansson *et al*. 1975, Melton *et al*. 1976). In static conditions, a small amount of xanthan gum (in most foods, 0.5%) induces a large increase in the viscosity of a liquid. Moreover, unlike other gums, xanthan gum shows high stability under a wide range of temperature and pH (Sun and Gunasekaran 2009, Zohuriaan and Shokrolahi 2004). Moreover, its anionic and hydrophilic surface characteristics facilitate interactions with cations (Bergmann *et al*. 2008, Nolte *et al*. 1992) and other polysaccharides, inducing stronger gel structures (Laneuville *et al*. 2006)

For its high ability of increasing viscosity and thickening as well as its anti-salt and anti-pollution properties, xanthan gum has been used in the oil drilling industry (Comba and Sethi 2009). It is also applied as an additive in concrete to increase viscosity and prevent washouts (Plank 2004).

3. Experimental program

3.1 Sample preparation

3.1.1 Gellan gum biopolymer-treated sand

In order to fully exploit the hydro-gelation property of gellan gum, the specimens were prepared with temperature control. A gellan gum solution was prepared by dissolving gellan gum into heated deionized water at 90℃ with a magnetic stirrer to provide homogeneity. After the solution was prepared, it was mixed directly with sand heated in an oven. Sand-gellan gum solution mixing was performed to set the gellan gum to sand ratio in mass as 1% and 2% with 30% initial water content. After mixing, the mixtures were poured into cylindrical molds immediately before cooling. The final dimensions of the gellan gum-treated sand specimens are 50 mm in diameter and 100 mm in height.

The molds were then cooled to room temperature for 24 hours under a thin plastic film seal to prevent moisture loss during cooling. After cooling, the mixture was removed from the mold. The condition of the soils immediately after being removed from the mold represents the initial condition. Once removed from the mold, half of the specimens were dried at room temperature (20±1℃) for 14 days to represent a dry condition, while the remaining half were tested immediately at the initial condition. Due to the change in the dry densities of the gellan treated samples with drying, when the samples were made, the dry densities were controlled so that the dry conditions had a similar dry density as the untreated samples (approximately 1450 kg/m^3), resulting in the initial samples having a lower dry density at 1300 kg/m^3.

3.1.2 Xanthan gum biopolymer-treated sand

Xanthan gum biopolymer was first mixed with deionized water to form a uniform hydrocolloid solution at room temperature (20±1℃) before mixing with sand. Since the most economical and efficient concentration of xanthan gum for soil treatment is approximately 1-1.5% (Chang *et al*. 2015a), 1% xanthan gum content to the mass of sand was used in this study. As sand-xanthan gum mixtures were mixed with 30% initial water content, and the xanthan gum solution was prepared with a 3.3% concentration.

Once 1% xanthan gum-sand mixtures were prepared, the sand-xanthan gum mixture was poured and compacted into five layers inside cylindrical molds having dimensions of 50 mm diameter and 100 mm height. All specimens were dried in an oven at 30°C for 14 days until reaching the constant mass. All samples were prepared at equal dry density of 1450 kg/m^3.

3.2 Experimental procedure

3.2.1 Resonant column (RC) test

Resonant column (RC) tests (Kim and Stokoe 1994) were performed to observe the nonlinear dynamic properties (e.g., shear stiffness and damping) of the cement-treated clay in small-to-intermediate shear strain ranges. The testing apparatus was connected to a computer for detailed measurements and automated calculations. The specimens were attached to the testing pedestal on the top and bottom caps through the use of gypsum for firm attachment between the samples and the apparatus. Confining pressures were applied to the gellan gum-treated specimens at confinements of 25, 50, 100, 200, and 400 kPa. After applying the confining pressures, the specimens were then left to fully consolidate before shearing was applied. The basic operational principle is based on vibrating the cylindrical specimen in first-mode torsional motion. Applying power from 0.05 to 40 mV, the frequency of excitation was increased from a low value until the resonant frequency of the specimen was obtained. The obtained results were used to calculate the shear wave velocity (V_s), shear modulus (G), shear strain (γ), and damping ratio (D) with equipment characteristics and size of the specimen (Drnevich *et al*. 1978). The testing apparatus of the resonant column test is illustrated in Fig. 2.

3.2.2 Scanning electron microscope (SEM) imaging

SEM images were taken to observe the micro-scale direct interactions between sand particles and gel-type biopolymers. Undisturbed (at rest) and disturbed (after RC testing) 1% gellan gum treated sand samples were considered by collecting 0.5 cm^3 bulk cubic samples from 1% gellan gum-sand specimens on a SEM mount (diameter 25 mm) using carbon conductive tabs. Carbon paint was applied on sample edges and bottoms to provide sufficient grounding. Specimens were

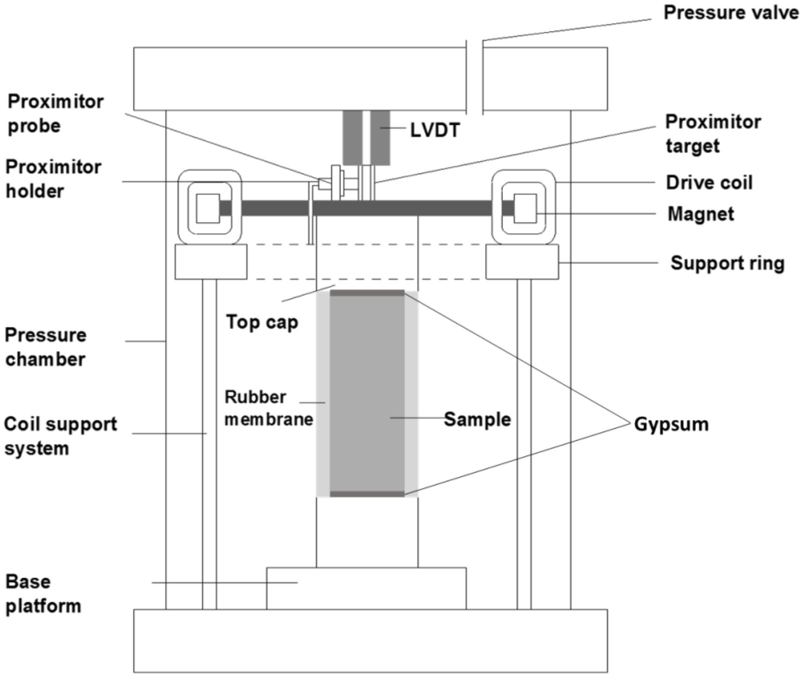

Fig. 2 Resonant column testing apparatus

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 (Magellan400) was used to observe the sample surfaces.

4. Results and analysis

4.1 Dynamic behavior of gellan gum-treated sands

4.1.1 G/G_{max} behavior of gellan gum biopolymer-treated sand

The maximum shear moduli ($G_{\max}$) of gellan gum-treated (dried and initial) and untreated sands obtained from RC tests are summarized in Table 1. With an increase in confinement the $G_{\max}$ of sands gradually increases regardless of the biopolymer treatment conditions. However, the $G_{\max}$ values of gellan gum-treated sands are mostly lower than the $G_{\max}$ of untreated sand except for at the dried 2% gellan gum-treated condition. For the 1% gellan gum-treated sands, the $G_{\max}$ of the 25 kPa confinement shows an increase, but at higher confinements the $G_{\max}$ values of the 1% gellan gum-treated sands are lower than those of the untreated sand. This indicates that at 1% the effects of confinement on the samples were lower than for the untreated samples as a result of resisting the compaction from the confining pressure. Additionally, the binding effects of the gellan gum may be broken at higher confinements, resulting in overall reduced stiffness. For the gellan gum-treated sands at the initial (wet) condition, significantly lower $G_{\max}$ values than those of untreated soils are obtained, regardless of the gellan gum content. This is most likely due to the difference in the dry density between the untreated sands (1450 kg/m^3) and the initial treated sands

Table 1 Shear modulus ($G_{\max}$) values of untreated and gellan gum-treated sands with different confinement

Cell confinement [kPa]	$G_{\max}$ of untreated sand [MPa]	$G_{\max}$ of Gellan gum-treated sand [MPa]			
		Initial		Dried	
		1%	2%	1%	2%
25	50.1	43.6	47.6	53.1	60.5
50	68.5	48.8	49.3	54.7	67.5
100	94.9	57.0	44.7	59.0	75.2
200	127.2	64.2	70.8	80.5	116.0
400	166.2	76.2	86.2	103.5	203.4

(1300 kg/m^3). Moreover, $G_{\max}$ value differences between 1% and 2% gellan gum treatment are almost negligible for the initial state.

At the initial state, the existence of hydrogels inside inter-granular pores appears to have negative effects on inter-particle interactions (e.g., interlocking) due to the swelling characteristic of the gellan gum hydrogels (Lee *et al*. 2004). Meanwhile, the $G_{\max}$ values of gellan gum-treated sands gradually increase with drying, which implies the phase transfer of gellan gum from water adsorbed hydrogels to dried biofilms. Thus, drying of gellan gum is expected to induce rigid inter-particle bonding between sand grains, which results in increment of shear stiffness as well as inter-particle cohesion (Chang *et al*. 2016a). Shear strain dependent $G/G_{\max}$ curves of gellan gum-treated and untreated sands are displayed in Fig. 3. Compared to untreated sand, gellan gum-treated sands show an earlier shear modulus reduction at lower strain levels. At a low confinement condition (Fig. 3(a)), the shear stiffness deterioration behavior of gellan gum-treated sand appears to follow a single trace, regardless of the gellan gum content and the moisture condition. However, with higher confinements (Figs. 3(b) and (c)), the shear modulus reduction of gellan gum-treated sand at the initial state is larger than that in dried conditions. The remarkable $G/G_{\max}$ reduction of the wet (initial) gellan gum hydrogel containing sand implies weak inter-particle interactions of sand grains due to the swelling pressure of inelastic hydrogels in inter-granular pores.

4.1.2 Damping behavior of gellan gum biopolymer-treated sand

The shear strain dependent damping ratios (D) of gellan gum-treated and untreated sands are shown in Fig. 4. First, the damping ratios of the gellan gum treated sands follow the general trend of an increasing damping ratio with higher shear strains. However, the gellan-gum treated sands show significantly higher damping than that of untreated sand, regardless of the gellan gum content, moisture condition, and confinement level. Although the presence of gellan gum matrices between sand particles (especially dried gellan gum films) enhances both the shear modulus and the shear strength of cohesionless sands, the damping ratio increase appears to be the most significant function induced by gellan gum biopolymer treatment.

The microstructure of gellan gum-treated sand is known to have fibrous gellan gum matrices covering (coating) individual particles and enhancing inter-particle contact via contact point cementation and the creation of connection bridges between distinct particles, which results in remarkable increases of the unconfined compressive strength and shear strength properties of soils (Chang and Cho 2014, Chang *et al*. 2016a, 2015a, c). However, although inter-particle contact is enhanced, the intensity and phase differences between rigid sand grains and ductile gellan gum

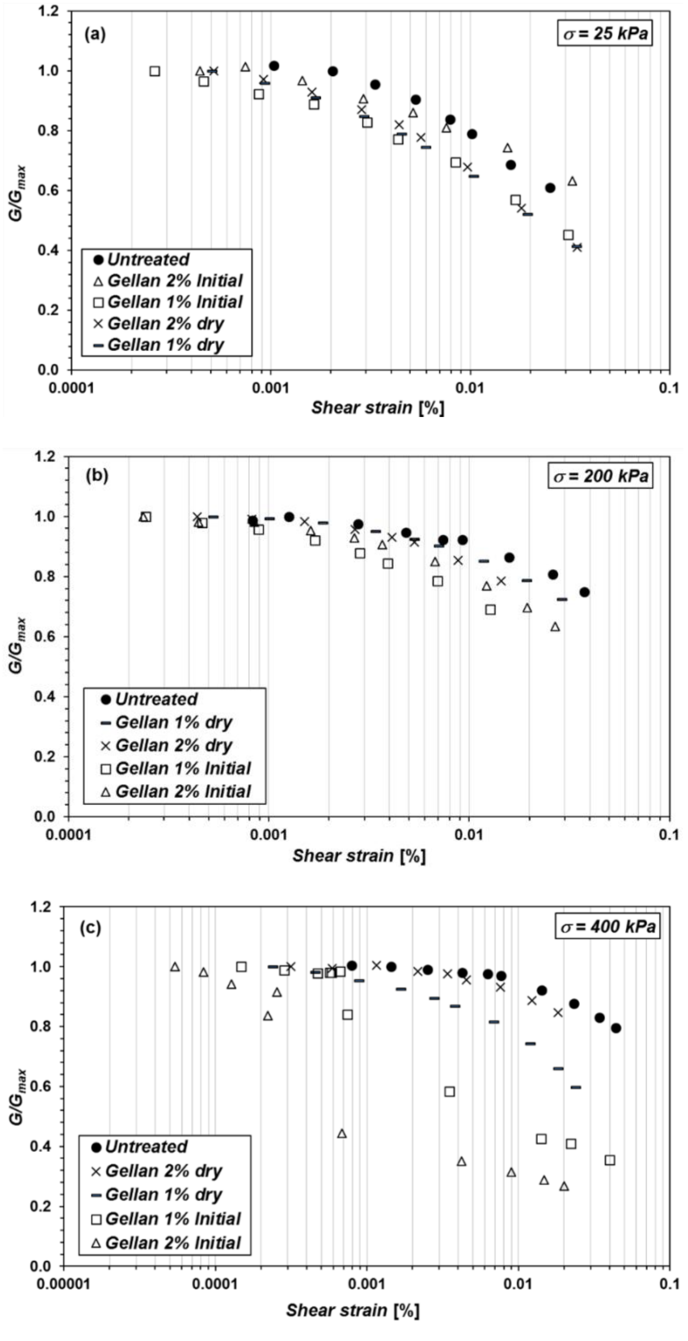

Fig. 3 $G/G_{\max}$ curves of untreated and gellan treated soils: (a) 25 kPa confinement pressure; (b) 200 kPa confinement pressure; (c) 400 kPa confinement pressure

gels appear to render significant seismic energy dissipation at the gellan gum-sand interfaces and gellan gum hydrogels (García *et al*. 2011, van den Berg *et al*. 2008).

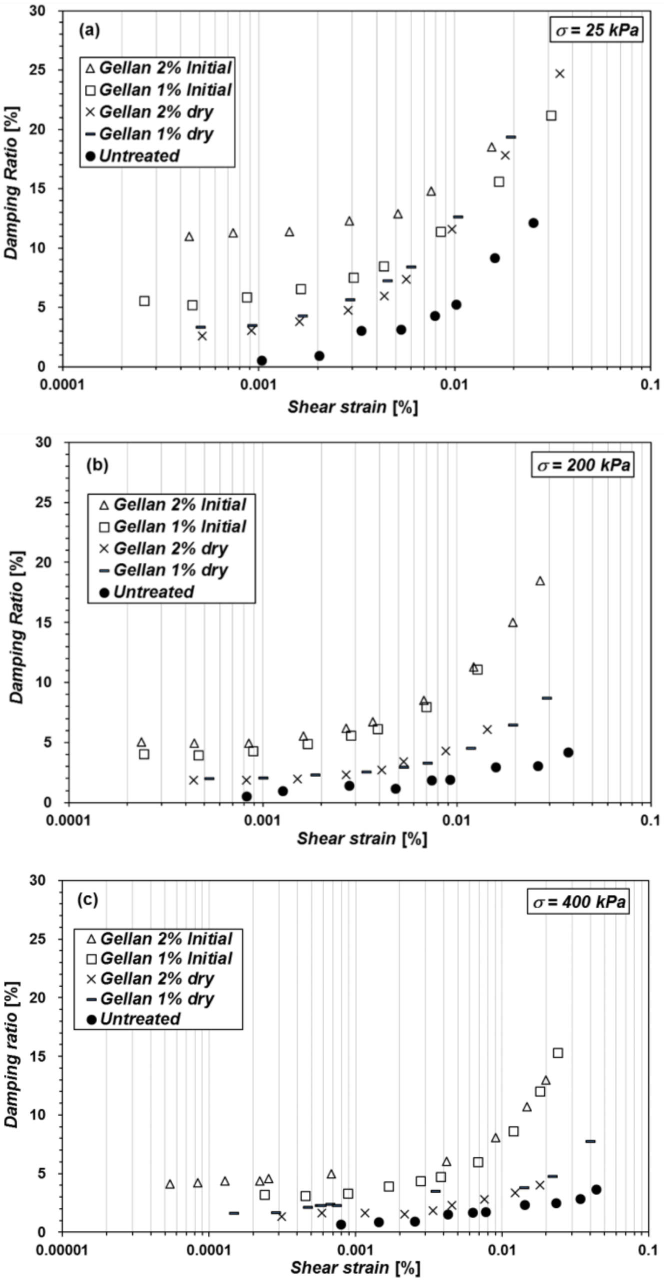

Fig. 4 Damping ratio curves of untreated and gellan treated soils: (a) 25 kPa confinement pressure; (b) 200 kPa confinement pressure; (c) 400 kPa confinement pressure

4.2 Xanthan Gum treated sands

From Table 2 it is seen that both xanthan gum and gellan gum biopolymers show an increase in $G_{\max}$ at lower confinements; however, unlike the gellan gum, the xanthan gum treated sand show a constant increase in $G_{\max}$ even at higher confinements.

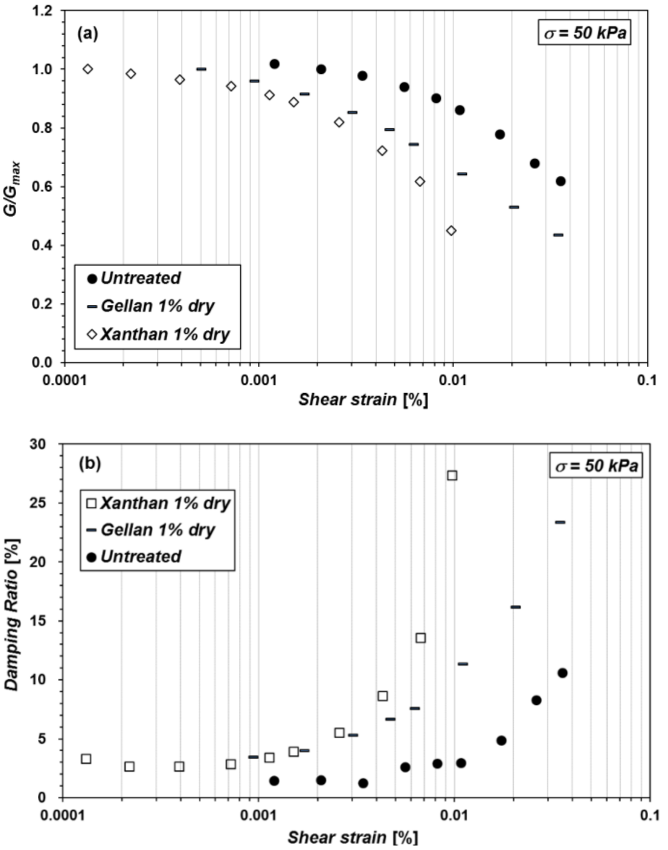

Fig. 5 Dynamic properties of gel-type biopolymer-treated sands: (a) G/G_{max}; (b) Damping ratio

Table 2 Shear modulus (G_{max}) values of untreated, 1% gellan gum-treated sands, and 1% xanthan gum-treated sands with different confinement

Cell confinement [kPa]	G_{max} of untreated sand [MPa]	G_{max} of gellan gum-treated sand [MPa]	G_{max} of Xanthan gum-treated sand [MPa]
		Dried	Dried
		1%	1%
25	50.1	53.1	56.2
50	68.5	54.7	70.1
100	94.9	59.0	110.3
200	127.2	80.5	152.9
400	166.2	103.5	215.4

Fig. 5 presents the strain dependent dynamic properties of dried 1% xanthan gum-treated sand with a comparison to dried 1% gellan gum-treated and untreated sands. Similar to the gellan gum-treated condition, the shear modulus of xanthan gum-treated sand shows deterioration at lower strain levels compared to untreated sand. However, the shear modulus reduction of xanthan gum-treated sand becomes more rapid than that of gellan gum-treated sand. This appears to be an effect of the gel strength and the stiffness difference between gellan gum and xanthan gum at a dried condition, reflecting higher plasticity of xanthan gum relative to gellan gum. Moreover, the higher damping ratios of xanthan gum-treated sand (Fig. 6(b)) indicate the possibility of severer structural disturbance of xanthan gum-sand interfaces, which results in higher seismic energy dissipation compared to high viscous gellan gum gels.

4.3 Scanning Electron Microscope (*SEM*) *Images of gel-type biopolymer-treated sands*

SEM images of dried gel-type biopolymer-treated sands are displayed in Fig. 6. Gellan gum (Fig. 6(a)) and xanthan gum (Fig. 6(b)) treated sands at rest show a similar inter-particle structure with continuous thin biofilms encompassing sand particles. The continuous biopolymer matrix formation inside inter-granular pores (Fig. 6(c)) has been shown to increase the inter-particle cohesion in previous studies (Ayeldeen *et al*. 2016, Chang *et al*. 2016a, Smitha and Sachan 2016). Meanwhile, for xanthan gum-treated sands, the xanthan gum matrix shows a structural composition of fibrils and discrete films (Fig. 6(b)), while the gellan gum matrix shows higher continuity (Fig. 6(a)). This difference is ascribed to different gelation mechanisms, where gellan gum forms a firm gel structure via thermo-gelation.

Although gel type biopolymer-treated sands show a higher $G_{\max}$ than untreated sand at the lower confinements, the rapid $G/G_{\max}$ reduction with shear strain can be understood from Fig. 6(d). Fig. 6(a), gellan gum biofilms in Fig. 6(d) show gellan gum fragments that are disturbed

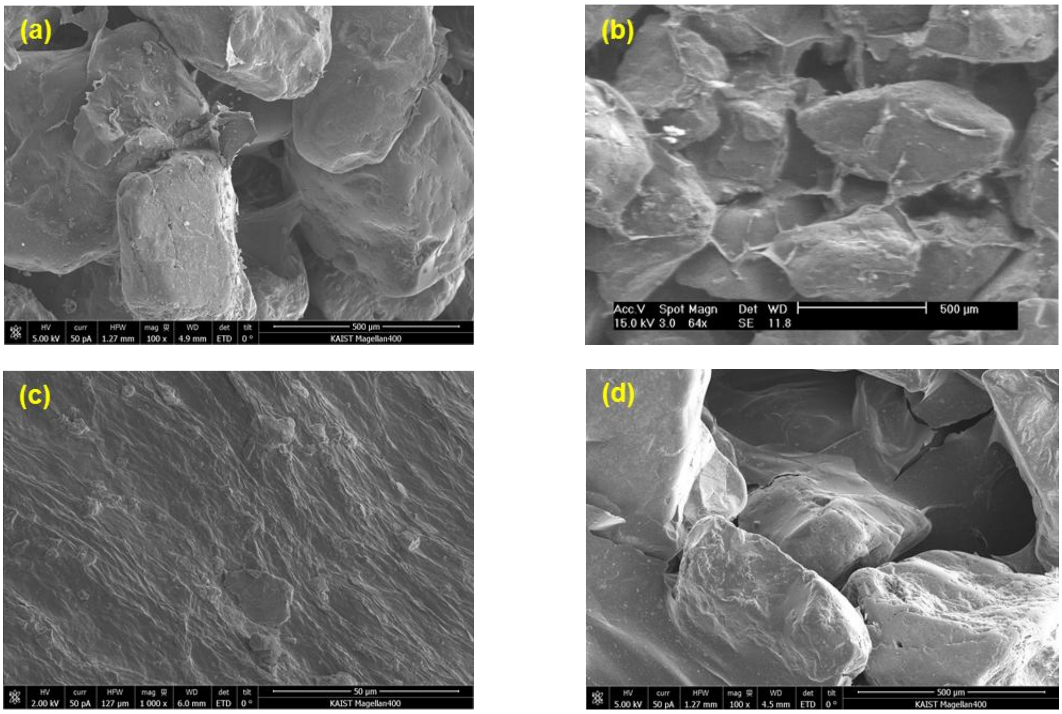

Fig. 6 SEM images of biopolymer-treated sands: (a) Gellan gum-treated at rest; (b) Xanthan gum-treated at rest (courtesy by Chang *et al*. 2015a); (c) Pure gellan gum biofilm; (d) Gellan gum-treated after shearing

(cracking) Fig. 6(d) shows SEM images of dried 1% gellan gum-treated sand after RC testing. Compared to during torsional shearing. This shows that, with sufficient strain, failure of the gellan gum films mainly occurs through tensile failures. For larger macro-strain conditions, disturbance of the gellan gum films becomes severe, and more detached and even torn fragments in pore spaces are observed (Chang *et al*. 2016a).

4.4 Suggested dynamic behavioral model of gel-type biopolymer-treated sands

As already mentioned in previous sections, the presence of the gel-type biopolymer improves the overall inter-particle interaction of sand particles, especially at the lower confinements, with an increase of the damping ratio. Generally, cemented soil that accompanies significant strengthening shows a reduction of the damping ratio due to the structural variation becoming more brittle (Acar and El-Tahir 1986, Delfosse-Ribay *et al*. 2004). However, gel-type biopolymer-treated sands show higher damping ratios than that of untreated sand, regardless of biopolymer type, content, and gel phase (water content). This unique damping characteristic appears to be governed by the interactions between rigid sand particles and biopolymer hydrogels having different phases.

Fig. 7 presents a hypothetic model of the dynamic behavior of gel-type biopolymer-treated sands. Without the presence of biopolymers, sand particles form direct contact with each other, where granular interlocking provides proper propagation of seismic energy. Moreover, due to the high stiffness of single phase (solid) sand particles, the seismic energy propagation between sand particles undergoes less dissipation via physical friction at particle contact.

For sand with water adsorbed gel-type biopolymer hydrogels in pore spaces, swelled and viscous biopolymer hydrogels fill inter-granular pore spaces. A previous study showed that only 1% gellan gum content is sufficient to fully fill the voids of granular soils via bio-clogging (Chang *et al*. 2016a). The whole soil medium then becomes a multi-phase body with rigid solid particles and viscous hydrogels. Therefore, the significant intensity difference at sand particle-gel interfaces renders reflections and refractions, which attenuate seismic energy via micro-vibration of sand grains as well as material and geometric attenuation through biopolymer hydrogels. With a higher intensity difference between sand grains and pore hydrogels, seismic energy attenuation is expected to render higher damping ratios.

Meanwhile, when biopolymer hydrogels dry to form thin biofilms on particle surfaces and inter-particle contact, the damping ratio should decrease due to the enhanced inter-particle inter-

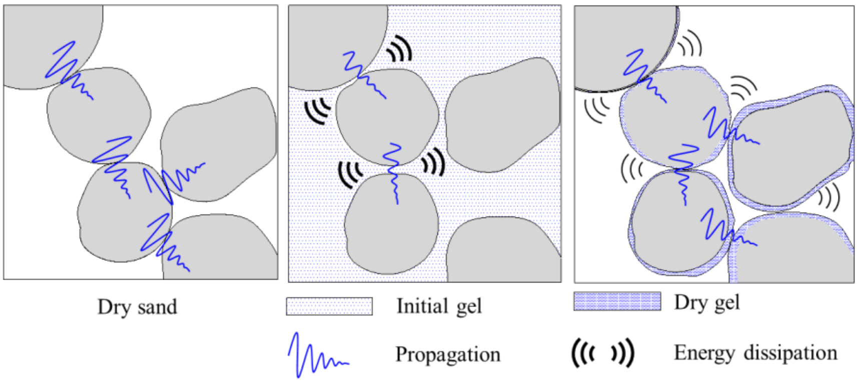

Fig. 7 Schematic model of the dynamic behavior of gel-type biopolymer-treated sands

action. However, experimental results show an increase of the damping ratio for dried gel-type biopolymer-treated sands (Figs. 4 and 5(b)), which indicates the phase difference between solid grains and surrounding ductile biopolymer biofilms. Moreover, the lower damping in the dried condition is expected to be affected by the lower intensity difference between dried biopolymers and sand grains relative to water adsorbed biopolymer hydrogels and solid sand particles.

In comparison, xanthan gum-treated sands show higher damping than that of gellan gum-treated sands (Fig. 5(b)), and this appears to be altered by the rheology and strength difference between xanthan gum gels and thermo-gelated gellan gum gels. Without the distinctive thermo-gelation property, xanthan gum gels are naturally looser and weaker than gellan gum gels, resulting in higher damping behavior than gellan gum-treated sand.

5. Conclusions

In this study, a series of resonant column tests was conducted on xanthan gum and gellan gum treated sand. Depending on the thermo–gelation characteristics of gellan gum, thermal treatment was applied to gellan gum-treated sand during the specimen preparation process. It is concluded that the existence of a biopolymer within sand pores affected the dynamic properties of the sand.

- Experimental results showed that gellan gum treatment of sand led to an increase in the shear modulus at low confinement. However, at higher confinements, the effect of confinement on the shear modulus is greatly reduced with gellan gum treatment. Additionally, it was seen that, due to the gellan gum fibrous structures within the sand pores, the energy dissipation was greatly enhanced, allowing for a larger damping ratio than the untreated sands.
- Changes in the shear modulus and damping ratio of dried specimens with 1% biopolymer treatment of xanthan gum and gellan gum under 50 kPa of confinement pressure were compared. Because of the stronger fibrous structure, the shear modulus reduction rate of gellan treated sand is slower than that of xanthan gum treated sand. Furthermore, the xanthan gum matrix showed greater improvement in energy dissipation in comparison with the gellan gum biopolymer.
- The increase in the damping even with increased particle contact is believed to be directly related to the phase change between the sand particles, specifically with the difference in the stiffness of the materials. With a much higher stiffness than the gel-type biopolymers, the wave propagation from the sand particles to the biopolymers is attenuated, resulting in higher stiffness.
- From these results, although their effects may be limited to shallow depths, the use of gel-type biopolymers for soil treatment may be effective in preventing liquefaction in sandy soils.

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References

Acar, Y.B. and El-Tahir, E.-T.A. (1986), "Low strain dynamic properties of artificially cemented sand", *J. Geotech. Eng.*, **112**(11), 1001-1015.

Ardeshiri-Lajimi, S., Yazdani, M. and Assadi Langroudi, A. (2016), "A Study on the liquefaction risk in seismic design of foundations", *Geomech. Eng.*, *Int. J.*, **11**(6), 805-820.

Ayeldeen, M.K., Negm, A.M. and El Sawwaf, M.A. (2016), "Evaluating the physical characteristics of biopolymer/soil mixtures", *Arab. J. Geosci.*, **9**(5), 1-13.

Bajaj, I.B., Survase, S.A., Saudagar, P.S. and Singhal, R.S. (2007), "Gellan gum: Fermentative production, downstream processing and applications", *Food Technol. Biotechnol.*, **45**(4), 341.

Bergmann, D., Furth, G. and Mayer, C. (2008), "Binding of bivalent cations by xanthan in aqueous solution", *Int. J. Biol. Macromol.*, **43**(3), 245-251.

Bouazza, A., Gates, W. and Ranjith, P. (2009), "Hydraulic conductivity of biopolymer-treated silty sand", *Géotechnique*, **59**(1), 71-72.

Casas, J.A., Santos, V.E. and García-Ochoa, F. (2000), "Xanthan gum production under several operational conditions: molecular structure and rheological properties☆", *Enzyme Microb. Tech.*, **26**(2-4), 282-291.

Chae, Y.S. and Au, W.-C. (1978), "Dynamic shear modulus and damping in additive - Treated expansive soils I II".

Chae, Y. and Chiang, Y. (1973), "Dynamic behavior of weak soils treated with additives", *Proceedings of the 5th World Conference on Earthquake Engineering*, Rome, Italy, June, pp. 1606-1610.

Chandrasekaran, R. and Radha, A. (1995), "Molecular architectures and functional properties of gellan gum and related polysaccharides", *Trends Food Sci. Tech.*, **6**(5), 143-148.

Chang, I. and Cho, G.-C. (2012), "Strengthening of Korean residual soil with β-1,3/1,6-glucan biopolymer", *Constr. Build. Mater.*, **30**, 30-35.

Chang, I. and Cho, G.-C. (2014), "Geotechnical behavior of a β-1,3/1,6-glucan biopolymer-treated residual soil", *Geomech. Eng.*, *Int. J.*, **7**(6), 633-647.

Chang, I., Im, J., Prasidhi, A.K. and Cho, G.-C. (2015a), "Effects of Xanthan gum biopolymer on soil strengthening", *Constr. Build. Mater.*, **74**, 65-72.

Chang, I., Jeon, M. and Cho, G.-C. (2015b), "Application of microbial biopolymers as an alternative construction binder for earth buildings in underdeveloped countries", *Int. J. Polym. Sci.*, **9**.

Chang, I., Prasidhi, A.K., Im, J. and Cho, G.-C. (2015c), "Soil strengthening using thermo-gelation biopolymers", *Constr. Build. Mater.*, **77**, 430-438.

Chang, I., Prasidhi, A.K., Im, J., Shin, H.-D. and Cho, G.-C. (2015d), "Soil treatment using microbial biopolymers for anti-desertification purposes", *Geoderma*, **253-254**, 39-47.

Chang, I., Im, J. and Cho, G.-C. (2016a), "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", *Can. Geotech. J.*, **53**(10), 1658-1670.

Chang, I., Im, J. and Cho, G.-C. (2016b), "Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering", *Sustainability*, **8**(3), 251.

Chen, R., Lee, I. and Zhang, L. (2014), "Biopolymer stabilization of mine tailings for dust control", *J. Geotech. Geoenviron. Eng.*, **141**(2), 04014100.

Comba, S. and Sethi, R. (2009), "Stabilization of highly concentrated suspensions of iron nanoparticles using shear-thinning gels of xanthan gum", *Water Res.*, **43**(15), 3717-3726.

Davidson, R.L. (1980), *Handbook of Water-Soluble Gums and Resins*, McGraw-Hill, New York; London.

Delfosse-Ribay, E., Djeran-Maigre, I., Cabrillac, R. and Gouvenot, D. (2004), "Shear modulus and damping ratio of grouted sand", *Soil Dyn. Earthq. Eng.*, **24**(6), 461-471.

Drnevich, V., Hardin, B. and Shippy, D. (1978), "Modulus and damping of soils by the resonant-column method", *Dyn. Geotech. Test.*, ASTM International.

EarthquakeTrack (2016), Recent earthquakes near South Korea; Earthquake Track. Retrieved October 11, 2016. Accessible at: http://earthquaketrack.com/p/south-korea/recent

García, M.C., Alfaro, M.C., Calero, N. and Muñoz, J. (2011), "Influence of gellan gum concentration on the dynamic viscoelasticity and transient flow of fluid gels", *Biochem. Eng. J.*, **55**(2), 73-81.

Grasdalen, H. and Smidsr, O. (1987), "Gelation of gellan gum", *Carbohyd. Polym.*, **7**(5), 371-393.

Ha, I.-S., Olson, S.M., Seo, M.-W. and Kim, M.-M. (2011), "Evaluation of reliquefaction resistance using shaking table tests", *Soil Dyn. Earthq. Eng.*, **31**(4), 682-691.

Huang, M., Kennedy, J.F., Li, B., Xu, X. and Xie, B.J. (2007), "Characters of rice starch gel modified by gellan, carrageenan, and glucomannan: A texture profile analysis study", *Carbohyd. Polym.*, **69**(3), 411-418.

Imeson, A. (2010), *Food Stabilisers, Thickeners and Gelling Agents*, Wiley-Blackwell Publication, Chichester, UK; Ames, IA, USA.

Jansson, P.-e., Kenne, L. and Lindberg, B. (1975), "Structure of the extracellular polysaccharide from Xanthomonas campestris", *Carbohyd. Res.*, **45**(1), 275-282.

Khachatoorian, R., Petrisor, I.G., Kwan, C.-C. and Yen, T.F. (2003), "Biopolymer plugging effect: Laboratory-pressurized pumping flow studies", *J. Petrol. Sci. Eng.*, **38**(1-2), 13-21.

Kim, S. and Park, K. (2008), "Proposal of liquefaction potential assessment procedure using real earthquake loading", *KSCE J. Civil Eng.*, **12**(1), 15-24.

Kim, D.-S. and Stokoe, K.H. (1994), "Torsional Motion Monitoring System for Small-Strain (10− 5 to 10−3%) Soil Testing", *Geotech. Test. J.*, **17**(1), 17-26.

Laneuville, S.I., Turgeon, S.L., Sanchez, C. and Paquin, P. (2006), "Gelation of native beta-lactoglobulin induced by electrostatic attractive interaction with xanthan gum", *Langmuir*, **22**(17), 7351-7357.

Lee, K.Y., Shim, J. and Lee, H.G. (2004), "Mechanical properties of gellan and gelatin composite films", *Carbohyd. Polym.*, **56**(2), 251-254.

Melton, L.D., Mindt, L. and Rees, D.A. (1976), "Covalent structure of the extracellular polysaccharide from Xanthomonas campestris: Evidence from partial hydrolysis studies", *Carbohyd. Res.*, **46**(2), 245-257.

Mitchell, J. and Santamarina, J. (2005), "Biological considerations in geotechnical engineering", *J. Geotech. Geoenviron. Eng.*, **131**(10), 1222-1233.

Morris, E.R., Nishinari, K. and Rinaudo, M. (2012), "Gelation of gellan – A review", *Food Hydrocolloids*, **28**(2), 373-411.

Nolte, H., John, S., Smidsrød, O. and Stokke, B.T. (1992), "Gelation of xanthan with trivalent metal ions", *Carbohyd. Polym.*, **18**(4), 243-251.

Nugent, R.A., Zhang, G.P. and Gambrell, R.P. (2009), "Effect of exopolymers on the liquid limit of clays and its engineering implications", *Transp. Res. Record*, **2101**, 34-43.

Park, L.K., Suneel, M. and Chul, I.J. (2008), "Shear strength of jumunjin sand according to relative density", *Mar. Georesour. Geotech.*, **26**(2), 101-110.

Peng, X., Hallett, P.D., Zhang, B. and Horn, R. (2011), "Physical response of rigid and non-rigid soils to analogues of biological exudates", *Eur. J. Soil Sci.*, **62**(5), 676-684.

Plank, J. (2004), "Applications of biopolymers and other biotechnological products in building materials", *Appl. Microbiol. Biotech.*, **66**(1), 1-9.

Rosalam, S. and England, R. (2006), "Review of xanthan gum production from unmodified starches by Xanthomonas comprestris sp", *Enzyme Microb. Tech.*, **39**(2), 197-207.

Sidik, W.S., Canakci, H., Kilic, I.H. and Celik, F. (2014), "Applicability of biocementation for organic soil and its effect on permeability", *Geomech. Eng., Int. J.*, **7**(6), 649-663.

Smitha, S. and Sachan, A. (2016), "Use of agar biopolymer to improve the shear strength behavior of sabarmati sand", *Int. J. Geotech. Eng.*, **10**(4), 387-400.

Sun, C. and Gunasekaran, S. (2009), "Effects of protein concentration and oil-phase volume fraction on the stability and rheology of menhaden oil-in-water emulsions stabilized by whey protein isolate with xanthan gum", *Food Hydrocolloids*, **23**(1), 165-174.

Tang, J., Tung, M.A. and Zeng, Y. (1997), "Gelling properties of gellan solutions containing monovalent and divalent cations", *J. Food Sci*., **62**(4), 688-692.

Tsai, P.-H. and Ni, S.-H. (2012), "Effects of types of additives on dynamic properties of cement stabilized soils", *Int. J. Appl. Sci. Eng*., **10**(2), 131-144.

Upstill, C., Atkins, E.D.T. and Attwool, P.T. (1986), "Helical conformations of gellan gum", *Int. J. Biol. Macromol*., **8**(5), 275-288.

USGS (2016), Earthquake Statistics; USGS - Earthquake Harzards Program. Earthquake Lists, Maps & Statistics; Retrieved October 11, 2016.
Accessible at: https://earthquake.usgs.gov/earthquakes/browse/stats.php

van den Berg, L., Carolas, A.L., van Vliet, T., van der Linden, E., van Boekel, M.A.J.S. and van de Velde, F. (2008), "Energy storage controls crumbly perception in whey proteins/polysaccharide mixed gels", *Food Hydrocolloids*, **22**(7), 1404-1417.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe II,K.H. (2001), "Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils", *J. Geotech Geoenviron. Eng*., **127**(10), 817-833.

Zemmouri, H., Drouiche, M., Sayeh, A., Lounici, H. and Mameri, N. (2013), "Chitosan application for treatment of Beni-Amrane's water dam", *Energy Procedia*, **36**, 558-564.

Zohuriaan, M.J. and Shokrolahi, F. (2004), "Thermal studies on natural and modified gums", *Polym. Test*., **23**(5), 575-579.