

Master's Thesis

젤란검으로 처리된 사질토의 지반물성

Geotechnical Properties of Gellan Gum-Treated Sand

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A thesis submitted to the faculty of KAIST in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Civil and Environmental Engineering. The study was conducted in accordance with Code of Research Ethics<sup>1</sup>

06.27.2013

Approved by



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Professor Gye-Chun Cho

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<sup>1</sup> Declaration of Ethical Conduct in Research: I, as a graduate student of KAIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

# Geotechnical Properties of Gellan Gum-treated Sand

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The present dissertation has been approved by the dissertation committee as a  
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### ABSTRACT

Study in ground improvement has been performed since 19<sup>th</sup> century in the history of human civilization. It has been developed following the current technology and human resources to make civil engineering projects all around the world feasible to be constructed. Numerous ground improvement techniques have been developed by engineers for solving problems in the field e.g. inadequate bearing capacity, slope stability, even liquefaction resistance with focusing on the physical and mechanical (i.e. fundamental basis) behavior of soil.

For admixture or grouting type ground improvement method, harmful materials such as cement, epoxy, acrylamide, phenoplasts, and polyurethane are ordinarily used (Karol 2003). Consequently, environmental concerns have been arisen due to the usage of those materials. Due to this circumstance, the study and development of environmentally friendly material for soil improvement are emerging.

In recent development of geotechnical engineering, it is not only physical and mechanical behaviors of soils which are considered, but also chemical and biological effects to soil behavior due to unique phenomena in geotechnical engineering e.g. creep and stress relaxation and clay swelling, which the fundamental basis cannot answer completely. Some researchers and engineers have considered biological and chemical aspects in geotechnical engineering to further explain the soil behavior and solve the field problems.

Some researchers have developed microbial injection soil improvement system or bio-mediated system using bacteria or other biological compounds to increase soil strength.

This method, however, needs a lot of attention in its cultivation condition e.g. nutrient, temperature, pore size, etc., to grow and accumulate the bacteria inside the soil. Therefore, some other researchers started to use ready-made biopolymers for consistent quality control, which is also investigated in this study.

Biopolymer, as environmentally friendly material, has been used as admixture to enhance the strength of soil. However, the durability of the biopolymer-treated soil against water was not discussed and remained uncertain. Therefore, this study also tries to appoint the water problem and proposes a way to solve the problem.

Gellan gum biopolymer with thermal treatment soil mixing method is used in this study. The soil used was joomunjin standard sand. Several experimental procedures were performed: uniaxial compressive strength, direct shear, triaxial compression, and resonant column tests for investigating strengthening behavior; and flexible wall hydraulic conductivity test for investigation clogging effect of biopolymer to the sand.

The results showed that gellan gum biopolymer can increase water durability of soil and enhance the strength by acting as an apparent cohesion. Both direct shear and triaxial compression tests results showed similar result in strengthening effect of gellan gum-treated sand for both saturated and dried specimen conditions. From resonant column test, the result showed insignificant increment in terms of shear modulus, while the damping ratio increases until two times for gellan gum-treated sand. The challenge arose as the strengthening effect is not substantial, possibly due to particle size-molecular length difference between biopolymer and sand. Meanwhile, the gellan gum affects the hydraulic conductivity of sand by decreasing 10,000 times from its original hydraulic conductivity.

Keywords: gellan gum, sand, strengthening, clogging, particle-molecular ratio

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## **Chapter 1. Introduction**

### **1.1. Research Background**

Study in ground improvement has been performed and utilized since 19<sup>th</sup> century in the history of human civilization. With a high demand of population and civil infrastructure, ground improvement techniques become highly reliable for geotechnical engineering projects. It has been developed following the current technology and human resources to make civil engineering projects all around the world, with each unique case, feasible to be constructed in the field.

Most ground improvement techniques are used depends on those specific needs for each project, i.e. to aid stability by increasing the shear strength, to avert too much ground movement by reducing soil compressibility, and to reduce soil hydraulic conductivity (e.g. for earth dams) (Moseley and Kirsch 2004). In certain cases which deal with earthquake problems, soil improvement is also used to minimize failure caused by earthquake (e.g. ground failure, liquefaction) (Schaefer 1997). Those ground improvement techniques which have been developed by engineers are mainly focusing on the physical and mechanical (i.e. fundamental basis) behavior of soil.

For admixture or grouting type ground improvement method, materials such as micro-fine cement, epoxy, acrylamide, phenoplasts, silicates, and polyurethane are ordinarily used (Karol 2003). These materials create environmental concerns for being hazardous, except sodium silicate (Karol 2003). For example, the excessive usage of cement as construction materials has rendered harmful impact on environment and health as cement industry is a large contributor of CO<sub>2</sub> in the worldwide (Worrell et al. 2001), and the material itself causes health problems from its dust and waste (Meo 2004; Mwaiselage et al. 2006) and

also cause skin damage from sustained contact to the skin (Keegan 2001). Due to these causes and factors, the study and development of environmentally friendly material for soil improvement are required.

Moreover, in recent developments of geotechnical engineering and ground improvement study, it is not only physical and mechanical behaviors of soils which are considered, but also chemical and biological effects to soil behavior. Unique phenomena in geotechnical engineering e.g. creep and stress relaxation and clay swelling, need further explanation that fundamental basis cannot answer completely. Thus, the study of biological and chemical roles in geotechnical engineering is emerged and considered important.

Some researchers and engineers have considered biological and chemical aspects in geotechnical engineering to further explain soil properties and behavior. Moreover, studies for using biological material to improve soil properties have also been emerged. These studies are combination of microbiology, ecology, geochemistry, and geotechnical engineering knowledge (Ivanov and Chu 2008). Mitchell and Santamarina (2005) introduced concepts of microbiological with its roles in soils and rocks, and gave examples of utilizing biological material (e.g. bacteria and ready-made biopolymer) into the geotechnical engineering applications. Dejong et.al (2008) showed soil improvement application using bio-mediated system. Moreover, Ivanov and Chu (2008) in their review study discussed the basic and purpose of microorganisms' application to geotechnical engineering in terms of bio-clogging and bio-cementation.

Generally, there are several methods to induce biological effects for soil improvement: (1) microbial injection, (2) bacterial growth and biomass accumulation, (3) microbes growth resulting in biofilms, (4) biopolymer cultivation, and (5) soil-biopolymer mixing (Chang and Cho 2012; Ivanov and Chu 2008; Kamel 2001; Mitchell and Santamarina 2005; Perkins et al. 2000). From those methods, injecting with cultivating bacteria and

microbial have complex parameters to be considered and sensitive to cultivation conditions (Molz et al. 1986). As a result, some researchers used ready-made biopolymer in their study to avoid cultivation sensitivity. For example: Chang and Cho (2012) used ready-made ( $\beta$ -1,3/1,6-glucan) biopolymer to strengthen Korean residual soil (hwangtoh). The investigation had great result in high strength enhancement using biopolymer treatment, and showed that the strength of biopolymer treatment was even greater than cement treatment. However, the durability of the biopolymer-treated soil against water was not discussed and remained uncertain. Therefore, in this study, the durability of biopolymer-treated soil is discussed and confirmed as preliminary study with using proposed ready-made biopolymer (i.e. Gellan gum), while the main study is to investigate the effect of gellan gum biopolymer to the coarse type of soil.

Joomunjin standard sand soil was used in this study. Biopolymer used in this study was gel-type biopolymer: Gellan gum. Certain composition and curing condition for each biopolymer-soil treatment were defined. Preliminary study was performed on Hwangtoh (based on previous study) to investigate the effect of gel-type biopolymer to the strength property and to durability against water. Then, the effect of gel-type biopolymer on joomunjin sand was investigated through standard experimental procedures. Finally, analysis considering micro and macro viewpoint for biopolymer-soil treatment is discussed.

## 1.2. Purpose of study

The purposes of this study are:

1. To investigate durability and strengthening effect of gel-type biopolymer (gellan gum) to silty clay (hwangtoh).
2. To investigate the effect of gellan gum to Joomunjin standard sand on its hydraulic conductivity.

3. To evaluate the influence of gellan gum to Joomunjin standard sand on its static and dynamic (seismic) behavior.

### 1.3. Structure of thesis

This study is organized into four chapters as follows:

Chapter 2 provides description of soil improvement and biopolymers, also reviews several previous studies closely related to this study. The objectives, procedures, and results from those studies are summarized. In the end of this chapter, preliminary study of gellan-treated hwangtoh is presented.

Chapter 3 shows all the experimental procedures performed for this study. Using joomunjin sand as the soil material, flexible wall permeameter test to evaluate hydraulic conductivity property of biopolymer-treated sand and uniaxial compressive test procedure to investigate the compressive strength were described. Also, static and dynamic laboratory testing (i.e. direct shear test, triaxial test, and resonant column test) procedures were explained.

Chapter 4 presents all of the results and analysis of the main study of this thesis. Effects of biopolymer to the soil properties (i.e. strength and permeability) were discussed and the optimum content of gellan gum for the sand mixture of main study was obtained from those two results. The static and dynamic properties of soil obtained from direct shear, triaxial, and resonant column test were shown. Analysis from all the results of biopolymer-treated soil was finally discussed considering macro and micro point of view.

Finally, chapter 5 summarizes the study conclusions, possible field application, and future studies.



## **Chapter 2. Literature Review and Preliminary Study**

### **2.1. Soil improvement**

Commonly used soil improvement techniques are classified into four general categories: compaction, dewatering, reinforcement, and admixture or grouting. Compaction, one of the oldest but also most used method, and dewatering are mainly improving the soil density by decreasing void ratio with compacting soil or removing water from the ground. On the other hand, reinforcement method of soil improvement uses structural ancillary (e.g. piles, ground anchors, etc.) to enhance the soil engineering properties, and admixture or grouting uses additional material to be mixed with soils either by mixing or by filling the voids of soil to modify the original properties of the soil. While compaction and dewatering focus only on the soil, admixture or grouting and reinforcement techniques need to pay attention to the additional materials used in the improvement process.

In admixture and grouting method of soil improvement, usage of hazardous materials such as micro-fine cement, epoxy, acrylamide, phenoplasts, and polyurethane are broad, which can create environmental concerns (Karol 2003). Consequently, environmentally friendly material and method are being studied and developed which in the end are expected to replace the usage of those hazardous materials.

Recently, new studies and opportunities for using biological material to improve soil properties by mixing method have been emerged. These studies are an interdisciplinary research, combining microbiology, ecology, geochemistry, and geotechnical engineering understanding (Ivanov and Chu 2008). Biodegradable polymer called biopolymer, which is ready-made biological material, is used as admixture component for this method of soil improvement. By creating biopolymer solution, it is mixed with soil under controlled

condition (i.e. of water content, biopolymer content, temperature, etc.) to produce soil-biopolymer mixture. The biopolymer have a role of strengthening the soil through its bio-cementation, and reducing the hydraulic conductivity property of soil by its bio-clogging (Ivanov and Chu 2008). Several researchers and engineers have studying this method of soil improvement. It is described in the next section of biopolymer and previous studies.

## 2.2. Biopolymer and its application

A polymer, commonly known as a plastic, represents a structural material comprises of many monomers joining together to form long-chain or network molecule. Biopolymer, on the other hand, is a biodegradable polymer produced by living organisms such as algae, fungus or bacteria, and consists of polysaccharides. Polysaccharides, one type of carbohydrate, are compounds that are formed by monosaccharide with certain position and linkage. It is broadly distributed in nature with the role as structure-forming skeletal substances, assimilative reserve substances, and water-binding substances (Belitz et al. 2009). With its nature behavior, polysaccharides act as thickening agents, stabilizers, sweetening, and gel-forming agents. This is the reason most application utilizing biopolymer are in the field of food production, agricultural, cosmetic, medical and pharmaceutical (Lorenzo et al. 2012; Saha and Bhattacharya 2010; Velde and Kiekens 2002).

Recently, not only in the field of food, medical and pharmaceutical, biopolymer material also has been used in civil engineering applications. In the aim of improving grouting performance, diutan gum and welan gum were used as admixtures in cement-based grout materials as a viscosity modifying agent (Sonebi 2006). Some of researchers have showed utilization of biopolymers in the field of geotechnical engineering in terms of review and experimental study (Cole et al. 2012; Ivanov and Chu 2008; Mitchell and Santamarina 2005). Biopolymer such as xanthan biopolymer has demonstrated good erosion resistance in

dynamic aquatic environments (Knox et al. 2010), increasing in strength, and resistance to liquefaction (Mitchell and Santamarina 2005). Also, latest study has proven that biopolymer (i.e.  $\beta$ -1,3/1,6-glucan) successfully improves mechanical property of soil (Chang and Cho 2012). In that study, biopolymer-treated soil has higher strength compare to cement mixture improvement, with only using lesser amount of biopolymer than cement. Moreover, in terms of economic costs (based on the cost of material and pollution effect), the biopolymer-treated soil has the advantage over the cement-treated soil (Chang and Cho 2012). With this development, study of biopolymer for geotechnical engineering soil improvement need to be conducted even further and deeper, theoretically and experimentally, to obtain the most effective and efficient material and method for each different applications.

#### Gellan gum biopolymer

Gellan gum is a high molecular weight polysaccharides fermented from *Sphingomonas elodea* microbe (formerly known as *Pseudomonas elodea*). The manufacturing process is in aerobic, submerged, and under fermentation process (Kang et al. 1982). Pure *sphingomonas elodea* is injected into a fermentation medium containing a carbon source, a nitrogen source and inorganic salts. The product is strictly controlled in the fermentation conditions such as pH, temperature, aeration and agitation for consistency. After the fermentation broth undergoes pasteurization process, it is treated with alkali to removes the acyl substituents on the gellan gum structure. Finally, the gum is recovered by alcohol precipitation to produce gellan gum with a high degree of purity (Imeson et al. 1997).

Gellan gum structure is a linear anionic polymer composed of four linked monosaccharide: one molecule of rhamnose, one molecule glucuronate, and two molecules of glucose (common sugar) as shown in Figure 2.1 (Morris et al. 2012). It has molecular weight in the range of  $0.5\text{-}2 \times 10^6$  Da (Fraser-Reid et al. 2008; Imeson et al. 1997). In normal

commercial production, gellan gum is modified to become deacylated polymer, which is only partially hydrated in cold deionized water and produces viscous solution. It can be fully hydrated in water at temperature above 90°C and form gels while suitable cations are presented when cooled to gelling temperature (Huang et al. 2007).

Gelation of deacylated gellan is occurred by transformation from disorderly coils to threefold double helices while cooling, and followed by aggregation of double helices by the roles of cations to develop three dimensional networks (Chandrasekaran et al. 1988a; Chandrasekaran et al. 1988b; Morris et al. 2012; Tang et al. 1997; Upstill et al. 1986). With this concept of gelation, adequate gel-promoting cations are needed to produce gel formation (as illustrated in Figure 2.2) and to attain optimal gel strength (Nussinovitch 1997).

Gellan gum has properties of thickening or gelling agent. Since it was approved in Japan, USA, and EU, it is used as a food additive in many countries worldwide. Confections, pie fillings, dairy products, jams and jellies, fabricated foods, icings and frostings are the example of food application using gellan gum (Imeson et al. 1997). Moreover, gellan gum is also used in pharmaceutical industry and biological research (Bajaj et al. 2007).

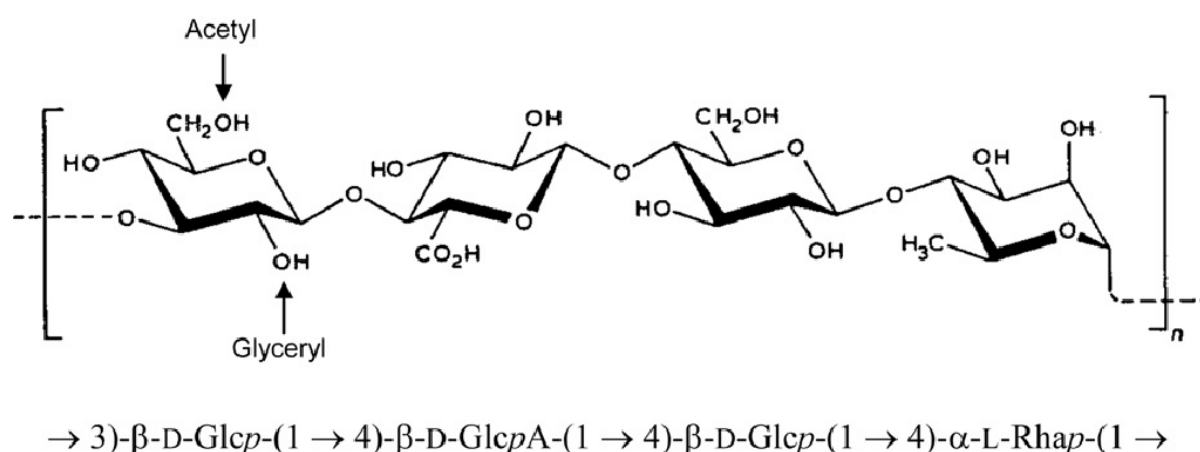


Figure 2.1. Chemical structure and composition of gellan gum (Morris et al. 2012)

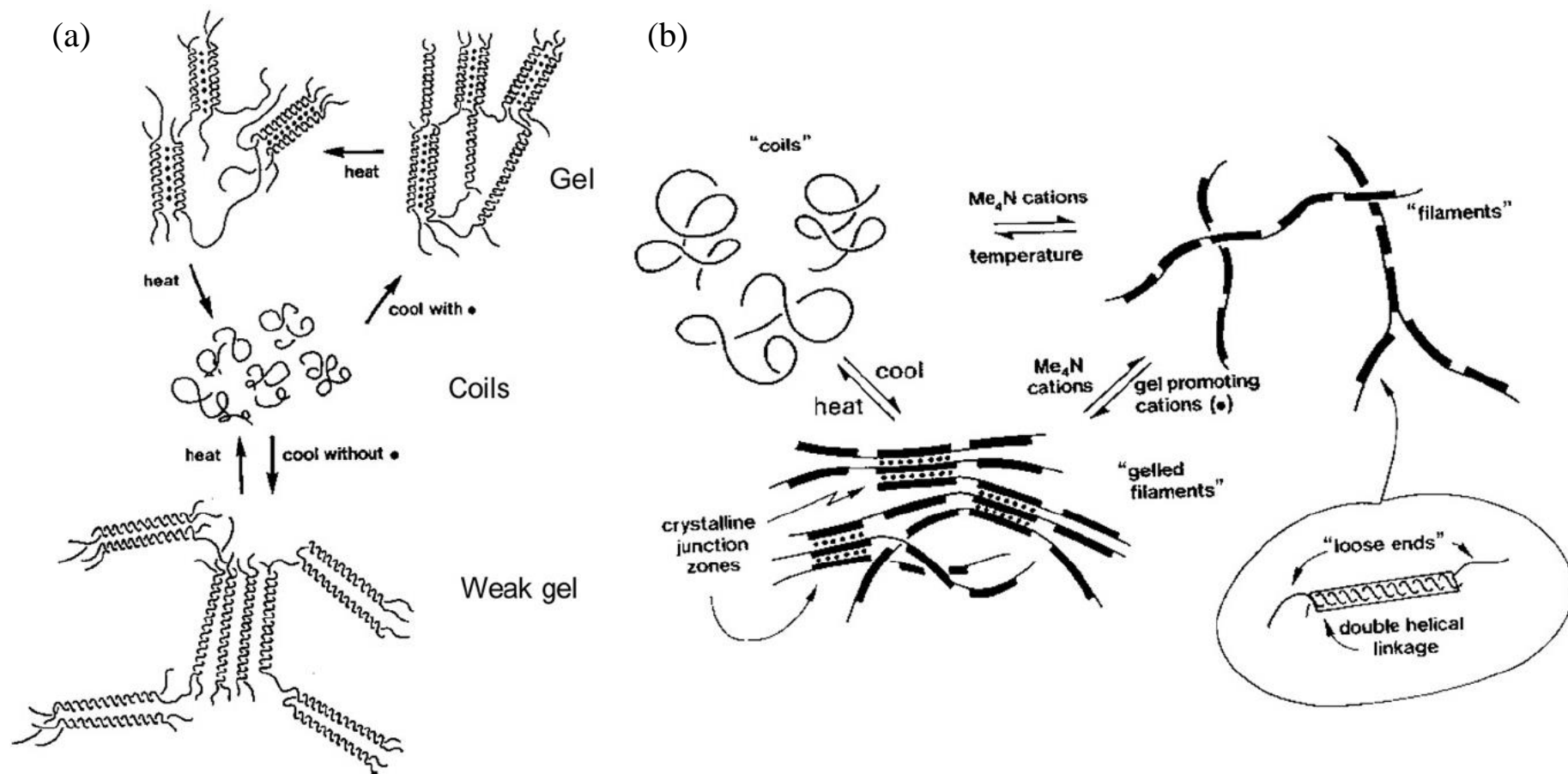


Figure 2.2 Models for gelation of gellan by (a) Robinson et al. (1991) and (b) Gunning and Morris (1990)

### 2.3. Literature review

This chapter presents an idea from previous studies regarding biopolymer applications in the field of geotechnical engineering. Although there are many applications of biopolymer to geotechnical engineering, this chapter only summarizes two potential applications for supporting this study: biocementation for soil strength and bioclogging for soil hydraulic conductivity.

#### Soil strength

Biopolymer strengthening or biocementation is one promising application of biopolymer to improve the strength and stiffness of soil. Chang and Cho (2012) used biopolymer named Polycan™ ( $\beta$ -1,3/1,6-glucan) to investigate the strength improvement of Korean residual soil called hwangtoh. Purchased ready-made Polycan™ biopolymer was used and mixed with the soil to make the cubic shape specimens. The parameters considered were biopolymer content, and curing temperature. Based on ASTM D 1633, uniaxial compressive tests were performed using universal testing machine (UTM) to acquire the compressive strength of biopolymer-treated hwangtoh (see Figure 2.3). The strength of biopolymer-treated hwangtoh was compared not only with natural hwangtoh, but also with cement (ordinary Portland cement, OPC)-treated hwangtoh as shown in Figure 2.4. Moreover, the strengthening mechanism of biopolymer-treated hwangtoh was described in terms of electrical interactions between polymer and soil, and summarized by showing schematic view of particle-polymer bonding (see Figure 2.5).

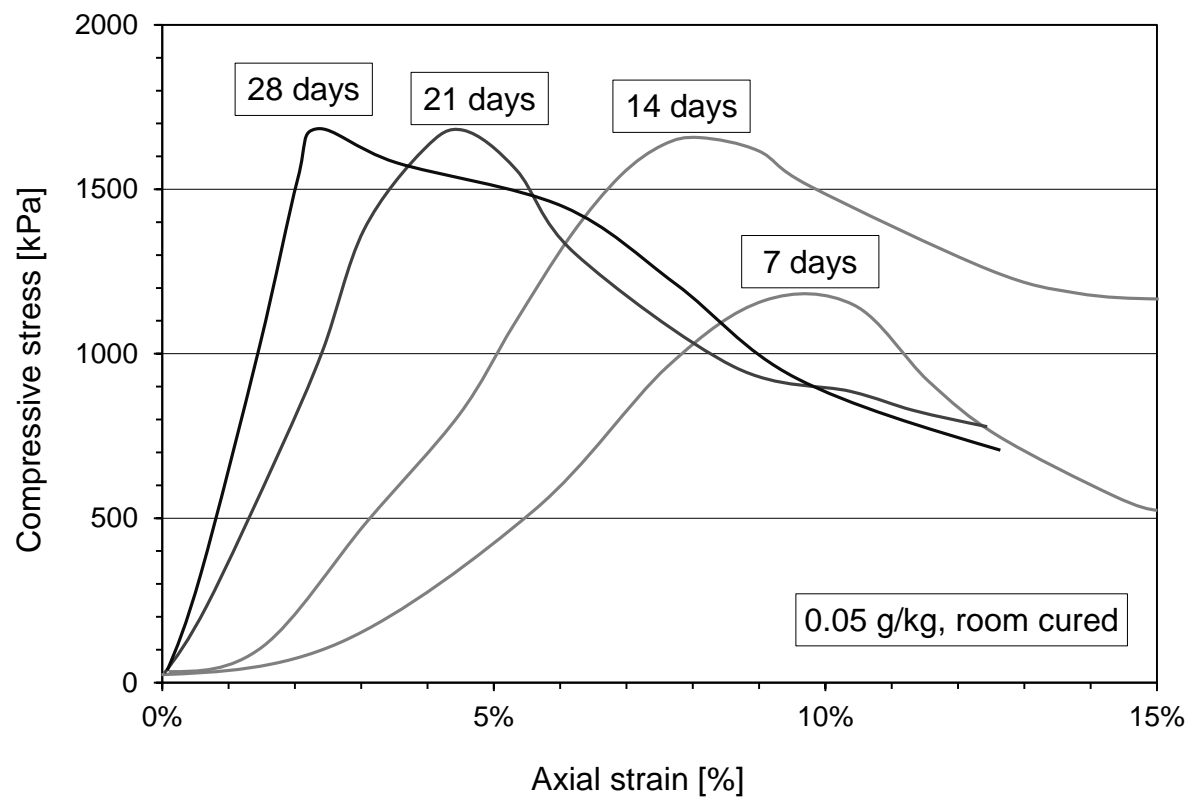


Figure 2.3. Result of unconfined compressive test of  $\beta$ -1,3/1,6-glucan treated hwangtoh with time (Chang and Cho 2012)

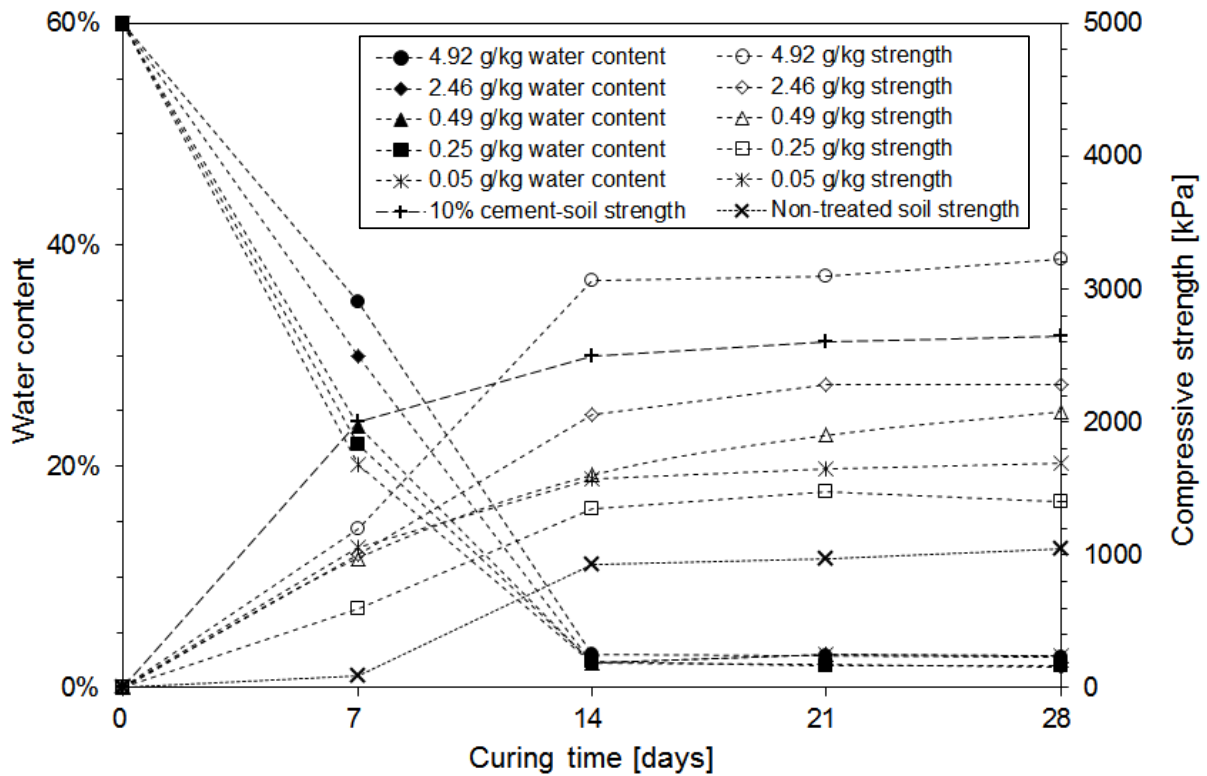


Figure 2.4. Strengthening and water content vs curing time for natural hwangtoh, cement-treated hwangtoh and  $\beta$ -1,3/1,6-glucan treated hwangtoh (Chang and Cho 2012)

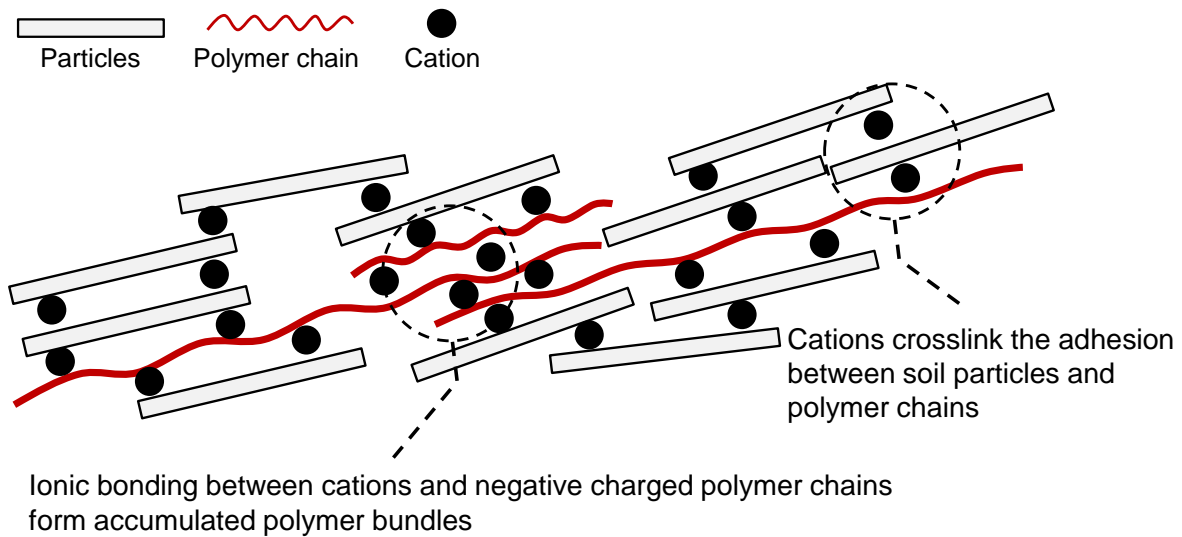


Figure 2.5. Schematic view of particle-biopolymer bonding (Chang and Cho 2012)



### Hydraulic conductivity

Biopolymer clogging or bioclogging is a promising application of biopolymer to reduce hydraulic conductivity of soil which is useful several applications e.g. to reduce erosion, to reduce migration of pollutants by forming grout, and to prevent piping (Ivanov and Chu 2008). Khachatoorian et al. (2003), with concern in usage of biopolymers for barriers and enhancement of oil recovery, used several biopolymers (i.e. xanthan, polyhydroxybutyrate (PHB), guar gum, polyglutamic acid (PGA) and chitosan) to investigate bioclogging phenomena on Ottawa sand. Purchased ready-made biopolymers were used in that study for experimental study using laboratory-pressurized pumping flow system. Water flow rate was measured and hydraulic conductivity ratio of each biopolymer was compared. It was analyzed that the reduction of sand hydraulic conductivity was occurred due to the plugging effects of biopolymer. The best plugging effects was obtained from PHB biopolymer, with more than billion-fold hydraulic conductivity reduction, followed by chitosan and PGA, with million-fold reduction. In the end, it is stated that the plugging effect is influenced by biopolymer structure. Similarity in biopolymer structure will lead to similar plugging effects.

Another attempt in bioclogging comes from Bouazza et al. (2009) by investigating several biopolymers (i.e. guar gum, xanthan gum, and sodium alginate) effects on pore plugging of high permeable silty sand soil. The biopolymers used were commercially available (ready-made biopolymer) in a powder form. Biopolymers and soil were mixed in dry condition, with several different contents, before adding the water. The specimens were sealed to prevent moisture loss and left to equilibrate for 7 days. The experiment was conducted according to ASTM D 5084. The results show that hydraulic conductivity reduction occurs due to the pore plugging effect by biopolymer. The hydraulic conductivity keeps reducing as biopolymer content inside the specimen increases.

Both of these studies show a potential application for using biopolymers to reduce the hydraulic conductivity.

#### 2.4. Preliminary Study

Studies in engineered soil utilizing biological matters especially ready-made biopolymer have been arisen. The biopolymer successfully gives significant effect to soil properties. However, from the studies regarding biopolymer-treatment, there is no explanation or discussion regarding the effect of water (e.g. soil water content, submerged condition, etc) to the strength of biopolymer-treated soil. Most of the studies are investigating the properties (i.e. strength) of cured-based biopolymer-treated soil, which are in dry condition, whereas the real condition of soil in the field is influenced by water (e.g. ground water table, rain, surface run-off, etc).

There are some biopolymers which cannot bind and strengthen the soil particles after they exposed to water, such as Polycan™. This type of biopolymer is fiber type (Chang and Cho 2012). It can increase soil strength, particularly fine-type soil, until three to four times compare to untreated soil after it's cured for 7 days. However, when Polycan™ treated soil is exposed to water, it starts to collapse and loses its strength. Figure 2.6 shows Polycan™ - treated hwangtoh (Korean residual soil) specimen, after cured for 28 days, when exposed to water. The soil started to crumble down and fail after just a short exposure time. When the specimen was exposed to water, both soil and biopolymer absorbed the water because both materials are hydrophilic (because of montmorillonite inside hwangtoh and the hydrophilic attribute of Polycan™ biopolymer). With this challenge, another type of biopolymer with different method of mixing is introduced and investigated in this study. The biopolymer is gellan gum with thermal treatment mixing method.

The unique property of gellan gum biopolymer is that it has to undergo thermal treatment of heating and cooling to become gel after mixed with soil in order to have durability against water. To make gellan gum solution, gellan gum has to be dissolved in boiled water ( $> 90^{\circ}\text{C}$ ). If gellan gum is poured and mixed into the cold water, it will only partially dissolved and produce high viscosity solution. The viscosity is decreased as the solution gets heated and increased again when cooled (shown in Figure 2.7). After it is cooled and form chemical structure as described in previous section (see Figure 2.2), the solution becomes gel-structured material which have its own strength. With this property, it was expected to increase the durability of soil against water when it is mixed together, which is investigated by this preliminary study.



Figure 2.6. 28 days cured Polycan™ treated hwangtoh after exposed to water

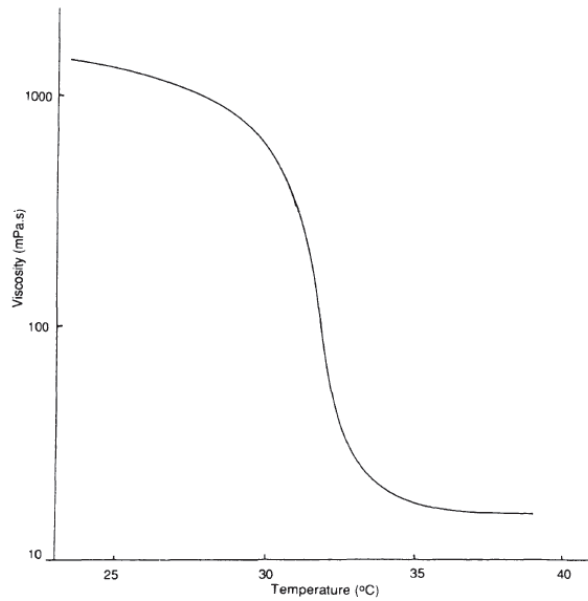


Figure 2.7. Temperature effect on viscosity of 1% gellan gum solution (Imeson et al. 1997)

To see the effect of this material and mixing method to the soil durability against water, preliminary study has been performed for hwangtoh-gellan gum mixture. Gellan gum content of 1% and 3% (of soil mass) have been used. With thermal treatment, gellan gum was dissolved into boiled distilled water and mixed with hwangtoh. Immediately after mixing, the hwangtoh-gellan gum mixture was poured into cubic mold (see Figure 2.8) and let it be cooled for 1 hour. The specimen then extracted from its mold and submerged into water for 28 days. For each 7 days, three specimens were taken out and tested its strength by uniaxial compressive test. The result is shown in Figure 2.9.

Compare to Polycan™ treated hwangtoh and natural hwangtoh, which are not water-durable, the gellan gum-hwangtoh mixture has water durability and strength despite has been fully submerged. The strength was not changed from 7 days testing to 28 days testing. This is due to the high and constant water content (see Figure 2.10) which governs the strength and behavior of gellan gum-hwangtoh mixture. The gellan gum biopolymer inside hwangtoh has managed to increase the durability and strength of soil even after exposed to water.

By this preliminary study, it was confirmed that gellan gum with thermal mixing method can increase the durability of soil against water. Therefore, gellan gum biopolymer and thermal treatment were used to investigate the strengthening of sand.



(a)



(b)

Figure 2.8. Pictures showing (a) 4 cm cubic mold and (b) molded gellan gum-treated hwangtoh

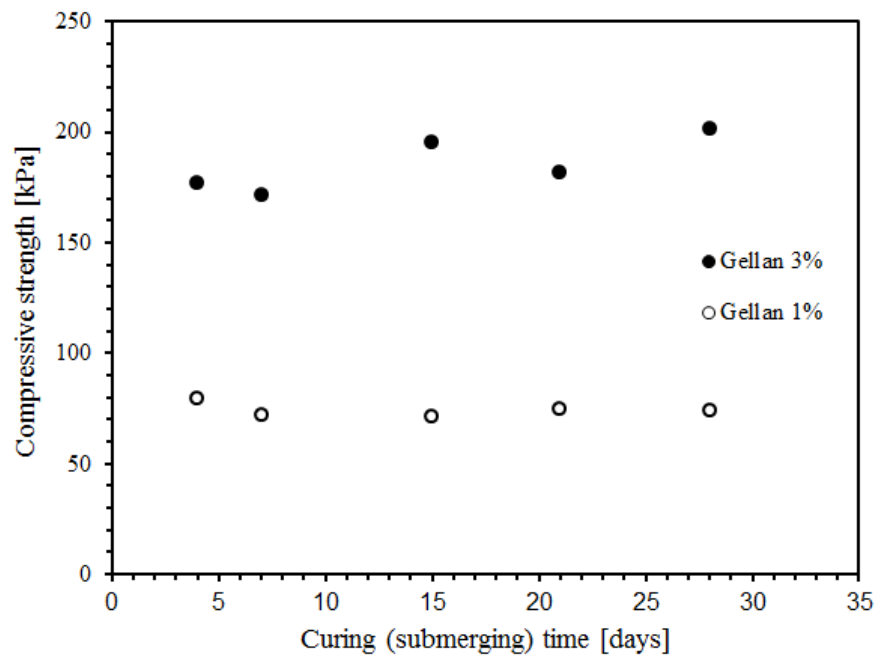


Figure 2.9. Compressive strength of gellan gum-treated hwangtoh (1% and 3% content) for different curing (submerging) time

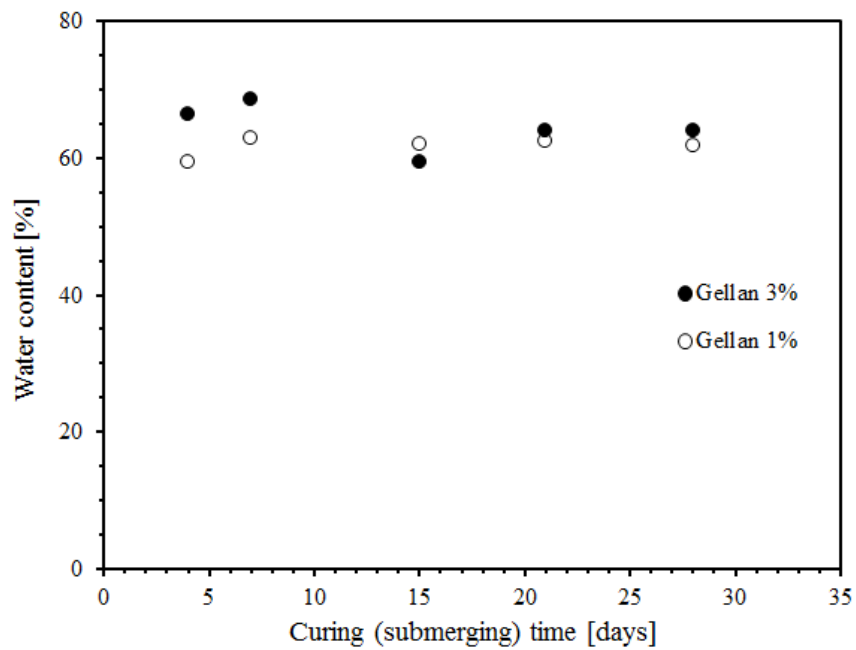


Figure 2.10. Water content of gellan gum-treated hwangtoh (1% and 3% content) for different curing (submerging) time

## Chapter 3. Experimental Tests

This chapter contains about the experimental preparation and procedure which were performed. It contains explanation about materials used in the experiments, and experimental step, parameter, and condition for this study.

### 3.1. Materials

The materials used for experiments in this study were standard joomunjin sand and gellan gum biopolymer.

#### Joomunjin sand

Joomunjin sand is a Korean standard sand soil. It has been used by scholars for research and study in the field of geotechnical engineering and environmental engineering. The geotechnical properties of joomunjin sand were obtained from standard laboratory procedures: soil classification from ASTM D 2487-06, specific gravity ( $G_s$ ) from ASTM D 854-06, and particle size distribution from ASTM D 422-63.

Joomunjin sand is classified as poorly graded sand. The particle-size distribution curve is shown in Figure 3.1. It has  $C_u$  (uniformity coefficient) 1.936 and  $C_c$  (coefficient of gradation) 1.087, specific gravity ( $G_s$ ) 2.65 also maximum and minimum void ratio ( $e$ ) 0.927 and 0.608 respectively. This type of soil represents coarse soil and used as the main study investigating effect of biopolymer to coarse soil.

Table 3.1. Geotechnical properties of joomunjin sand

Soil	Classification	Specific gravity ( $G_s$ )	Particle size distribution [mm]		Void ratio, $e$	
			$D_{60}$	$D_{10}$	$e_{max}$	$e_{min}$
Joomunjin sand	Poorly graded sand	2.65	0.6	0.31	0.927	0.608

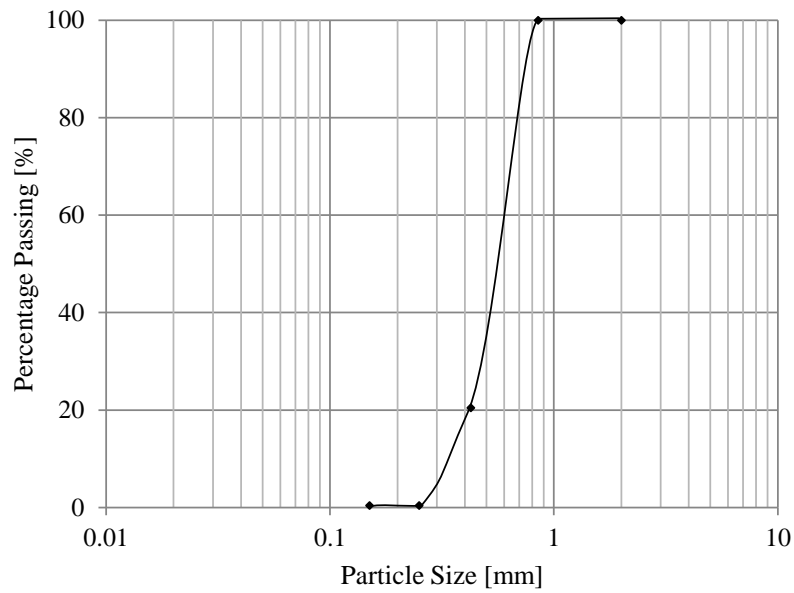


Figure 3.1. Particle-size distribution of Joomunjin sand

### Biopolymer

Gellan gum is a high molecular weight polysaccharides fermented from *Sphingomonas elodea* microbe (formerly known as *Pseudomonas elodea*). In this study, deacylated gellan gum polymer was used which purchased from Sigma Aldrich with CAS No: 71010-52-1. This deacylated type of gellan gum is only partially hydrated in cold deionized water and produces viscous solution. It can be fully hydrated in water at temperature above 90°C and form gels while suitable cations presented when cooled to gelling temperature (Huang et al. 2007).



### 3.2. Sample preparation and experimental procedure

Generally, the specimens for all experiments were prepared under same procedure. The differences were the mold type, initial water content for mixing soil and biopolymer, and curing condition. Soil and biopolymer solution were mixed to make biopolymer treated-soil specimen. Initial water content was decided considering the mixing workability of soil-biopolymer to obtain the required void packing and density of the soil-biopolymer mixture for each experiment condition. Gellan gum biopolymer solution was prepared by dissolving gellan gum powder into boiled distilled water (temperature 100°C). The gellan gum powder was poured inside the boiled distilled water and stirred constantly until it was fully dissolved (Figure 3.2). On the other hand, soil was dried and heated in the oven with temperature of 100°C. Soil and biopolymer solution were then mixed in high temperature condition and molded into the required mold for each experiment. Vibration is applied using vibrator (Figure 3.3) to help achieving the target void ratio of specimen for certain experiment, and spatulas were used to flatten and smooth the surface. Finally, the specimen was cured according to each experiment and target condition. All the parameter and condition described in this section are comprised in Table 3.2.

Table 3.2. Parameter and condition of experiments

Test	Biopolymer content [% of soil weight]	Target void ratio	Dimension [mm]	Curing condition	Test condition
Uniaxial compressive	0.5, 1.0, 2.0	Initial water content 30%	40 × 40 × 40	<ul style="list-style-type: none"> <li>• Air-dried (room temperature, 20±1 °C);</li> <li>• Submerged</li> </ul>	Strain rate: 0.4 mm/min (1% of soil height)
Hydraulic conductivity	0.5, 1.0, 2.0	0.82 – 0.87	70 (diameter)	Cooled, sealed, settled for 7 days	Hydraulic gradient less than 20
Direct shear	1.0	0.74 – 0.80	60 (diameter) 20 (height)	<ul style="list-style-type: none"> <li>• 7 days air-dried (room temperature, 20±1 °C)</li> <li>• Cured while saturation and loaded</li> </ul>	Normal stress: 50, 100, 200, 400 kPa; Strain rate: 1.2 mm/min; <ul style="list-style-type: none"> <li>• Dry test condition</li> <li>• Saturated test condition</li> </ul>
Triaxial	1.0	0.74 – 0.80	50 (diameter) 100 (height)	<ul style="list-style-type: none"> <li>• 1 day cooled followed by 13 days air-dried (room temperature, 20±1 °C)</li> <li>• 1 day cooled followed by 1 day submersion</li> </ul>	Confining pressure: 50, 100, 200 kPa; Strain rate: 1% (of height) mm/min
Resonant column	1.0	0.74 – 0.80	50 (diameter) 100 (height)	<ul style="list-style-type: none"> <li>• 1 day cooled followed by 13 days air-dried (room temperature, 20±1 °C)</li> <li>• 1 day cooled followed by 1 day submersion</li> </ul>	Confining pressure: 25, 50, 100, 200, 400 kPa;



Figure 3.2. Dissolving gellan gum powder in boiled distilled water



Figure 3.3. Vibrator

### 3.2.1. Hydraulic conductivity test

Initial water content for soil-biopolymer mixing was set to produce void ratio within the range of: 0.82 – 0.87. The gellan gum biopolymer content used for this test was 0.5%, 1%, and 2% of soil mass. Soil-biopolymer mixtures were molded into cylindrical mold having diameter of 7 cm. The mold then sealed, while the specimen was settling and cooling, to prevent any loss of water inside the mixture, and left for 7 days. Then, the specimen was extracted from the mold and tested with standard test method for hydraulic conductivity measurement using flexible wall permeameter as shown in Figure 3.4 (ASTM D 5084).

The tests were conducted under room temperature ( $20 \pm 1^\circ\text{C}$ ) with effective confining pressure less than 30 kPa. The cell pressure, influent and effluent flows were controlled by pressure controllers and monitored in pressure panels (Humboldt FlexPanels). During the saturation process by back pressure, change of volume was minimized by applying low increment in cell, influent, and effluent pressures. Saturation was verified using Skempton B-value of more than 95%. After reached saturation, falling-head test was performed with hydraulic gradient less than 20. The permeation was conducted to obtain at least five hydraulic conductivity measurements under steady condition with the ratio of outflow to inflow rate was  $1 \pm 0.25$ . The average of last three hydraulic conductivity measurements which fell within  $\pm 0.3$  of those values were taken and reported.



Figure 3.4. Flexible wall permeameter apparatus with using Humboldt FlexPanels

### 3.2.2. Uniaxial compressive test

Considering workability, initial water content was set 30% for joomunjin sand. The gellan gum biopolymer content was 0.5%, 1%, and 2% (of soil mass) for joomunjin-gellan gum mixture. Soil-biopolymer mixtures were molded into 4 cm cubic mold. After settled and cooled for 1 hour, the specimens were taken out from the mold and cured.

The specimens were cured in air-dried condition under room temperature ( $20 \pm 1^\circ\text{C}$ )

and tested by uniaxial compressive test after 1, 3, 7, and 28 days of curing. After 28 days of testing, the specimens were submerged for 3 hours before tested its strength by uniaxial compressive test.

Cubic specimens were tested its compressive strength by uniaxial compressive test using Universal Testing Machine Instron 5583 (Figure 3.5) with strain rate of 0.4 mm/min (1% of soil height). Three specimens were tested for each set condition (i.e. curing condition, type and amount of each biopolymer) and taken the average to represent strength of biopolymer-treated soil. Load and deformation behavior were obtained from each of the test.



Figure 3.5. Uniaxial compression test machine

### 3.2.3. Direct shear test

Initial water content for soil-biopolymer mixing was set to produce void ratio within the range of: 0.74 – 0.80. The gellan gum biopolymer content used for this test was 1% of soil mass. Two different curing conditions were applied: cured in air-dried (room temperature,  $20\pm1^{\circ}\text{C}$ ) for 7 days and cured while saturation and loaded inside the direct shear apparatus prior to testing.

For air-dried curing, the soil-biopolymer mixture was poured into the mold (6 cm diameter with 2 cm height), waited to be cooled and stabilized for 30 minutes, and then extracted from the mold to be cured. After 7 days of curing, the specimen was ready to be tested.

For the other curing condition, the soil-gellan gum mixture was poured into the shear box (6 cm diameter) followed by setting of the direct shear test and filling water into the shear box. After the setup was finished, the specimen was directly loaded for 12 hours by applying a certain confining pressure whilst the mixture settled and cured inside the shear box.

The specimens from both curing condition were tested under consolidated drained condition (ASTM D 3080). Four confining pressures were applied: 50, 100, 200, and 400 kPa. After consolidation stage finished, shear was applied with the shear rate of 1.2 mm/min. The measurement systems for load, vertical and horizontal displacement were connected to a computer for automatic and detailed monitoring. When the reading indicated failure stage, the test was stopped and the specimen was taken out from the shear box. The specimen was dried in the oven to obtain the final dry weight of the specimen. The overall setting of direct shear apparatus can be seen in Figure 3.6.



Figure 3.6. Direct shear test apparatus

#### 3.2.4. Triaxial test

Initial water content for soil-biopolymer mixing was set to produce void ratio within the range of: 0.74 – 0.80. With biopolymer content of 1% (of soil mass), the soil-biopolymer mixtures were poured into cylindrical mold having diameter 5 cm and height 10 cm. After settled and cooled for 1 day, the specimens were extracted from its mold and cured under room temperature ( $20 \pm 1^\circ\text{C}$ ) for 13 days for dry test condition and submersion for 1 day for saturated test condition.

The test was performed under consolidated drained condition, with four different confining pressures: 50, 100, 200, and 400 kPa. The load, axial displacement, and all pressure transducer monitoring systems were connected to a computer. After applying confining pressure to the specimen and waiting for 30 minutes to stabilize and consolidate, the axial loading was applied with strain rate 1% of specimen height. When the test reached the failure stage, the test was stop and the specimen was taken out from the apparatus followed by





Figure 3.7. Triaxial test equipment

drying in the oven to get final dry weight of the specimen. The load and displacement data were received from the triaxial reading and analyzed to obtain pressure (deviatoric stress)-displacement relationship and Mohr-coulomb criteria. The overall setting of triaxial apparatus can be seen in Figure 3.7.

#### 3.2.5. Resonant Column (RC) test

Initial water content was set to produce void ratio within the range of: 0.74 – 0.80. The gellan gum biopolymer content used for this test was 1% of soil mass. Mixing procedure and curing condition were same as triaxial test.

The equipment of RC test was connected to computer for detailed measurement and automated calculation. The test was performed on specimen in both dry and saturated condition. The specimen was attached to the pedestal and top cap by using gypsum. It was ascertained that the gypsum attachment was rigid and strong to avoid the effect of attachment to the experiment. The confining pressures applied in this experiment were 25, 50, 100, 200, and 400 kPa. The specimen was given a certain confining pressure, and given 30 minutes for the specimen to get stabilized before the shearing applied. After the shearing was applied, the confining pressure was increase to the next stage and same procedure was performed. When the test finished, the specimen was taken out from the apparatus and measured its water content. The overall setting of RC apparatus can be seen in Figure 3.8.

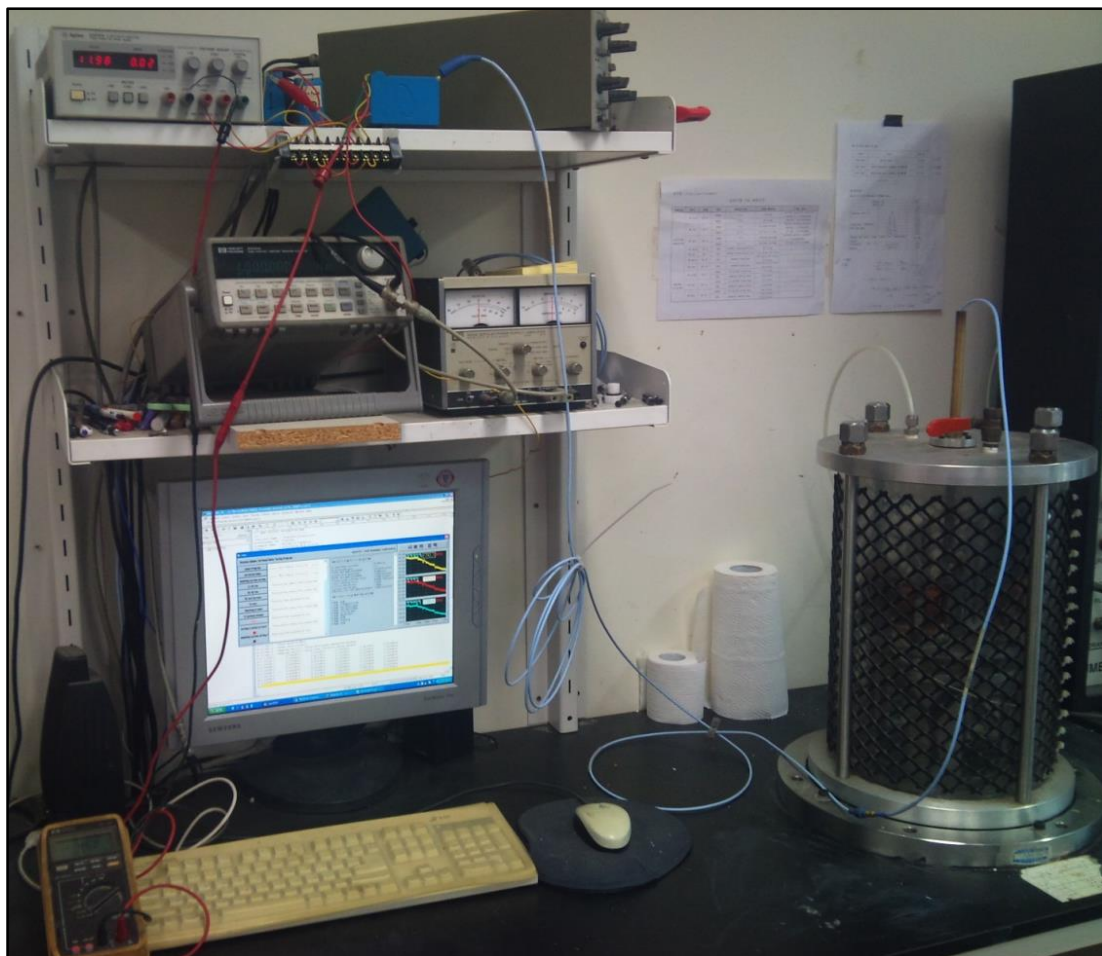


Figure 3.8. Resonant Column test instrumentation

## Chapter 4. Results and Discussion

With all experiment parameter and condition described in chapter 3, the results were obtained and presented in this chapter. The effects of biopolymer (i.e. gellan gum) to the joomunjin sand are shown with analysis based on the data and facts gathered from the experiments results. Discussion is presented at the end of this chapter to extract and discover more the possible phenomenon happened by gellan gum biopolymer to the soil.

### 4.1. Hydraulic conductivity

Falling head hydraulic conductivity tests were performed using flexible wall permeameter method. This test is to investigate the bio-clogging effect (in reducing hydraulic conductivity) of gellan gum-treated joomunjin sand. Joomunjin sand is coarse-type of soil which has high hydraulic conductivity value. The general hydraulic conductivity value of sand is around  $10^{-5} - 10^{-1}$  cm/s (Das 2008). Also, the void ratio was set to be in the range of 0.82 – 0.87 with relative density ( $I_D$ ) of 18% - 34%. According to Skempton (1986),  $I_D$  value of 18% - 34% categorized as loose density state. With this condition, the effect of gellan gum to the hydraulic conductivity of sand (bio-clogging phenomena) can be clearly seen by the data obtained from the hydraulic conductivity measurement.

Figure 4.1 shows the hydraulic conductivity data obtained from the experiment with different gellan gum content. It can be seen from the figure that the gellan gum biopolymer really affects the hydraulic conductivity of the soil. Hydraulic conductivity value of non-treated joomunjin sand is  $2.11 \times 10^{-4}$  cm/s. With 1% content of gellan gum, the hydraulic conductivity is reduced 10,000 times to  $2.64 \times 10^{-8}$  cm/s. It indicates the role of gellan gum biopolymer in decreasing the hydraulic conductivity (i.e. clogging phenomena). The clogging

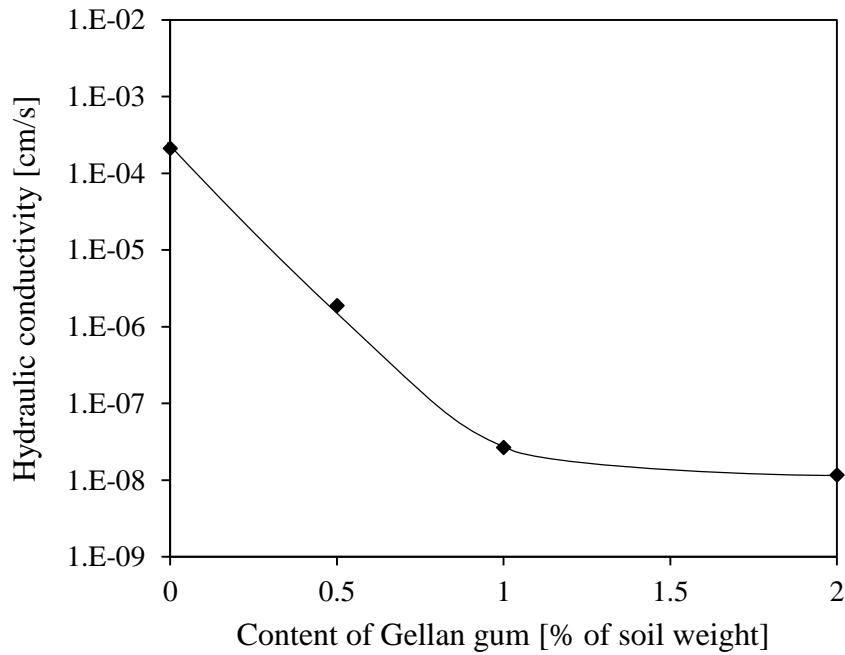


Figure 4.1. Hydraulic conductivity value of gellan gum-treated joomunjin sand with different gellan gum content

effect increases in the same manner of gellan gum content, resulting in hydraulic conductivity reduction even further. When the gellan gum content increases, the layer and matrix of gellan gum gel between soil particles become thicker. This designates further clogging of soil.

However, from above 1% gellan gum content, the hydraulic conductivity just slightly decreases. This is due to the maximum void filling that can be done by gellan gum. At 1% gellan gum content, it can be inferred that the void inside the soil almost filled in completely with gel. Even though the gellan gum filling inside the soil became thicker as the gellan gum content increased to 2%, however, as the void of soil already filled in with 1% gellan gum content, the increasing of gellan gum content became insignificant to change the hydraulic conductivity. It can be concluded that the clogging at 1% gellan gum content is the most effective content for reducing hydraulic conductivity of sand.

## 4.2. Uniaxial compressive strength

Joomunjin sand was mixed with gellan gum solution to make gellan gum-treated joomunjin specimen. Uniaxial (unconfined) compressive tests were performed on the specimen. The compressive strength of gellan gum-treated joomunjin was investigated in terms of curing time (air-dried curing) and biopolymer content.

As in chapter 2 already described, the important parameter which defines the strength of gellan gum-treated soil is water content, not the curing time. Figure 4.2 shows the strengthening tendency of gellan gum-treated joomunjin with water content and different biopolymer content. It can be assumed that the unconfined compressive strength of natural joomunjin sand is 0. The strengthening is increasing as water content decreases whilst biopolymer content increases. The specimens were also tested its durability against water. After dried in room temperature ( $20\pm 1^{\circ}\text{C}$ ) for 28 days, the specimens were submerged and tested its compressive strength. With having a large amount of water content, the specimen could still stand by itself and has strength compared to non-treated joomunjin sand.

Comparison between the gellan gum content was established from the strength and hydraulic conductivity result, also from workability of gellan gum-sand mixing and market price. Table 4.1 comprises all the comparison between all the gellan gum content used in gellan gum-sand mixture. From this comparison, it is shown that 1% gellan gum content is the optimal value. Therefore,decided that 1% gellan gum content (of soil mass) is used in the geotechnical study of gellan gum-treated joomunjin sand.

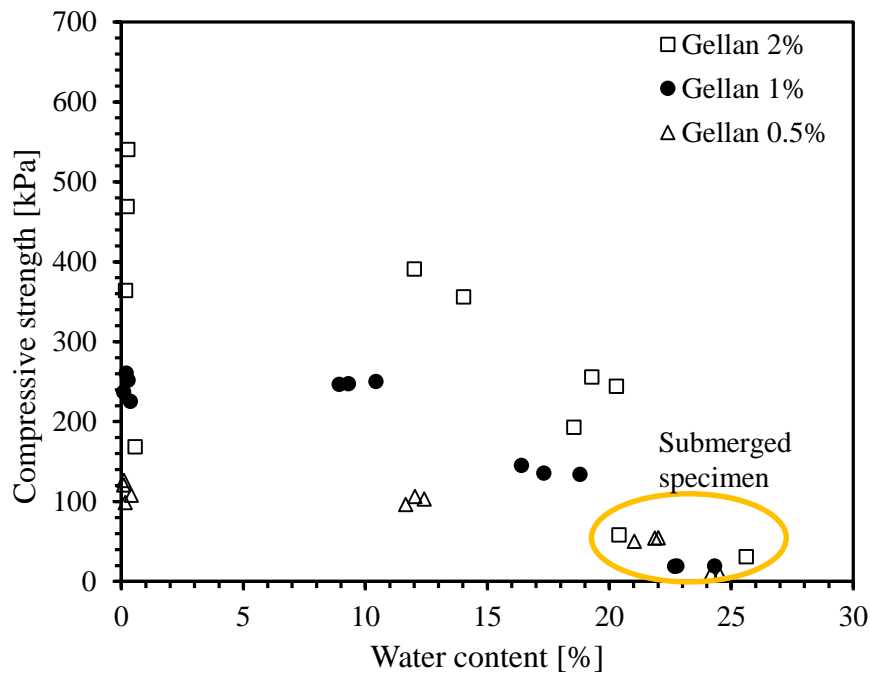


Figure 4.2. Compressive strength of gellan gum-treated joomunjin sand (gellan gum content: 0.5%, 1% and 2% of soil weight) with water content

Table 4.1. Comparison between 0.5%, 1.0%, and 2.0% gellan gum content in soil mixture in terms of strength, hydraulic conductivity, workability, and market price

Parameter	Gellan gum content (of soil weight)		
	0.5%	1.0%	2.0%
Average strength, dried [kPa]	113.6	243.7	434.5
Average strength, submerged [kPa]	9.3	19.2	44.7
Hydraulic conductivity [cm/s]	$1.88 \times 10^{-6}$	$2.64 \times 10^{-8}$	$1.16 \times 10^{-8}$
Workability <sup>1</sup>	Very high	High	Low
Cost for 1 kg soil mixing [US\$] <sup>2</sup>	1.94	3.87	7.74

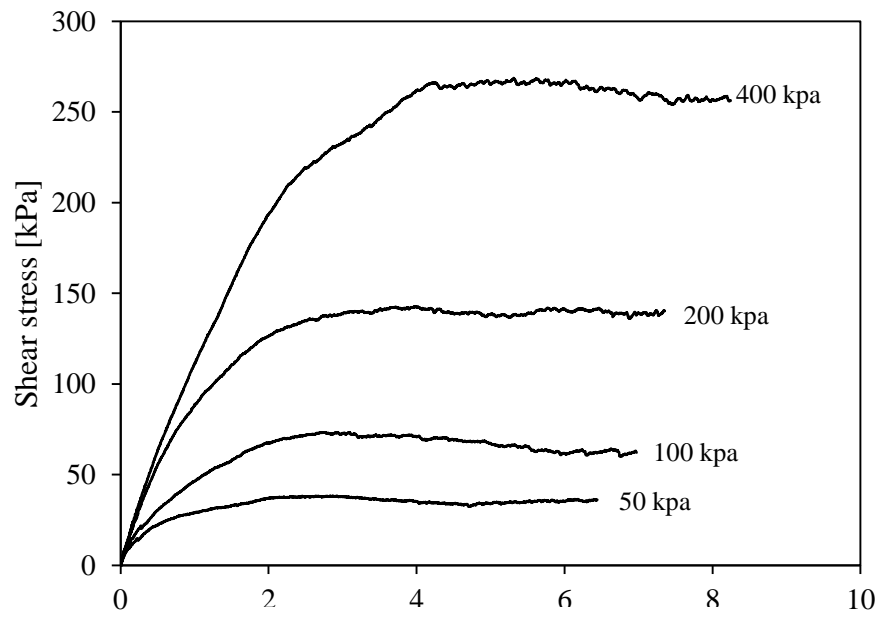
<sup>1</sup>workability in mixing with same water content (30%)

<sup>2</sup>Cost is based on the price from Sigma Aldrich (<http://www.sigmaaldrich.com/>) with the price: US\$ 387 for 1 kg gellan gum

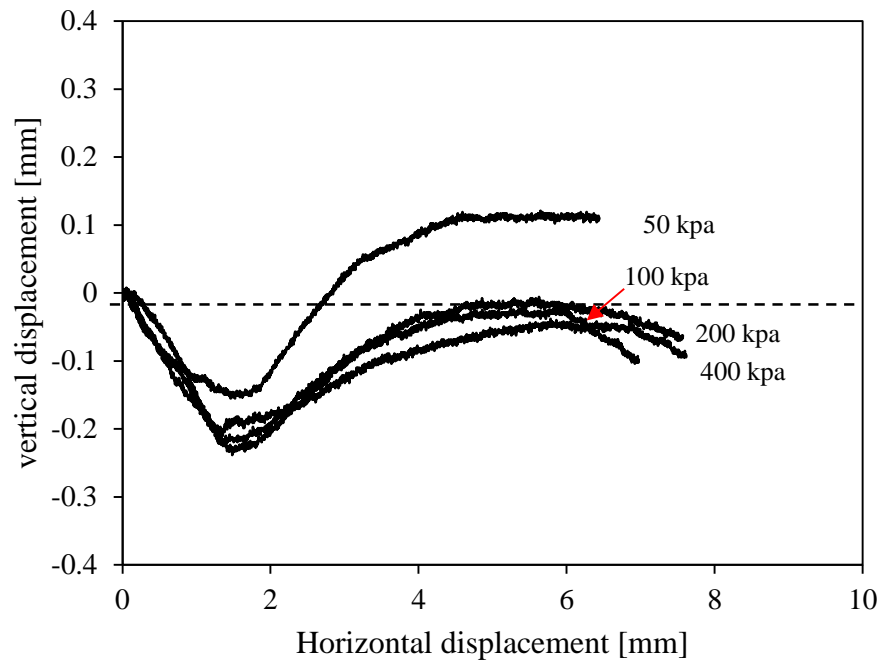
### 4.3. Direct shear strength

Figure 4.3 shows the stress-displacement and vertical displacement-horizontal displacement behavior of non-treated joomunjin sand with different confining pressure (normal stress) for void ratio condition of 0.74 – 0.80 (relative density,  $I_D$ , of 40% - 58%). According to Skempton (1986),  $I_D$  value of 40% - 58% categorized as medium density state.

It can be seen that it follows general tendency in terms of confining pressure. As confining pressure increases, the shear stress increases and shear strain at peak stress shifts. The shear stress reached peak first and then decreased until constant value. The vertical displacement went through contraction until around 1.8 mm horizontal displacement followed by dilation. The horizontal displacement at peak stress shift from 2 to 4 mm with increasing in confining pressure.



(a)



(b)

Figure 4.3. (a) Shear stress and (b) vertical displacement vs horizontal displacement of non-treated joomunjin sand for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%; medium state) with different confining pressure



For gellan gum-treated joomunjin sand, two different specimen conditions were tested: dry condition and curing while saturating and loaded. The stress-displacement and vertical-horizontal displacement can be seen at Figure 4.4. Void ratio (density) condition was conditioned to be same as non-treated joomunjin sand:  $0.74 - 0.80$  ( $I_D = 40\% - 58\%$ , medium state).

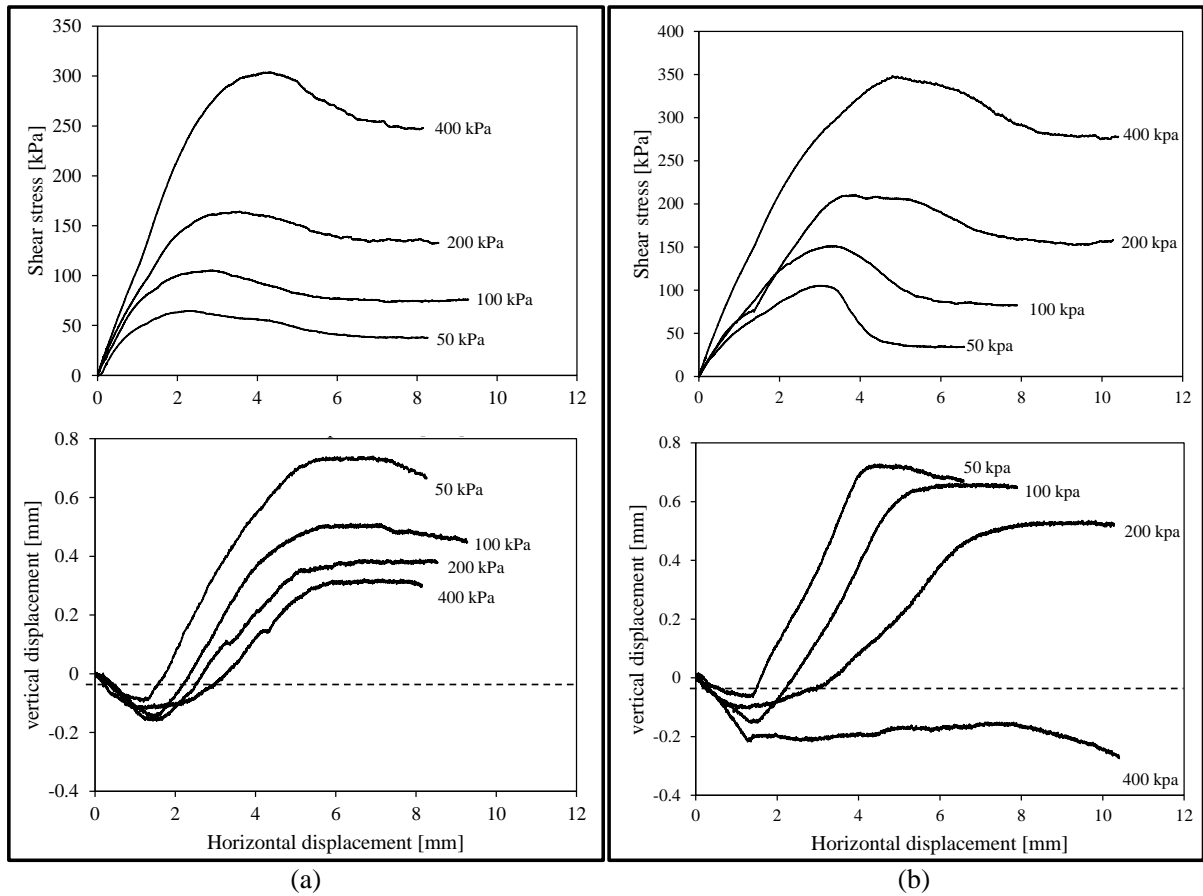


Figure 4.4. Shear stress and vertical displacement vs. horizontal displacement results of gellan gum 1%-treated sand for void ratio of  $0.74 - 0.80$  ( $I_D: 40\% - 58\%$ ) with different confining pressure of: (a) saturated condition test; and (b) dry condition test

Interesting occurrences can be seen from the stress-strain relationship of gellan gum-treated specimen. The stress greatly increased to peak value, especially for dry condition, before decreasing until constant value (ultimate stress). The vertical displacement also showed clear alteration of contraction at the beginning and dilation at the end of test. When non-treated and treated sand are compared, difference can be seen in terms of both stress and vertical displacement.

The stress reached peak for treated specimen due to gellan gum matrix inside the specimen. The gellan gum matrix hold specimen together and add strength to it when the specimen sheared until it fails, i.e. reaching peak stress. Then, the stress was decreased gradually until constant value (ultimate stress). This ultimate stress of submerged specimen appears to be similar as the stress of non-treated specimen at the end of the test for the same void ratio/density condition (see Figure 4.5). The treated saturated specimen ultimate stress converged into similar value as non-treated specimen because the gellan gum matrix already failed and the behavior of the soil returned back to its original state (i.e. governed by sand). For treated dry specimen, it still has more resistance after the failure point which makes the ultimate stress slightly higher than non-treated specimen.

Dilation occurred in gellan gum-treated specimen (dry and saturated condition) is bigger than non-treated specimen. It might be due to cementation effect of gellan gum inside soil particles. The gellan gum coated sand particle and created denser packing condition (total density) even though the dry density was same with non-treated specimen. This makes large dilation for gellan gum-treated specimen as the shear proceed.

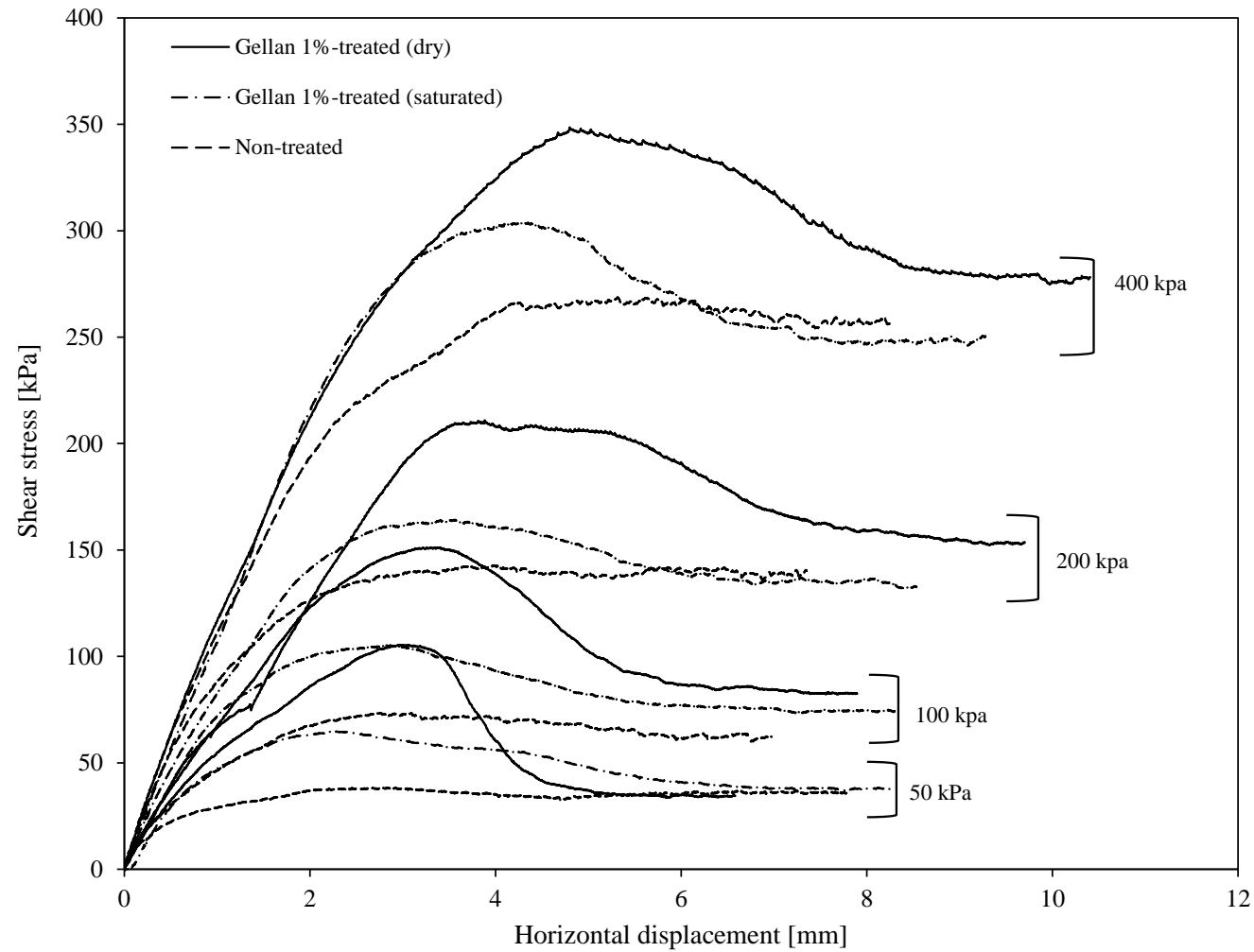


Figure 4.5. Comparison between gellan gum 1%-treated joomunjin sand (saturated and dry test condition) with non-treated joomunjin sand for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%) with different confining pressure

The data of shear stress and confining pressure can be plotted as Coulomb envelope to obtain friction angle and cohesion value. It is shown in Figure 4.6 that gellan gum improves the cohesion of joomunjin sand. The cohesion increases to 25.6 kPa for saturated specimen and 71.8 kPa for dry specimen. The friction angle of non-treated sand is 34.3°, while for gellan gum 1% treated sand is 34.9° and 34.2° for dry and saturated condition, respectively.

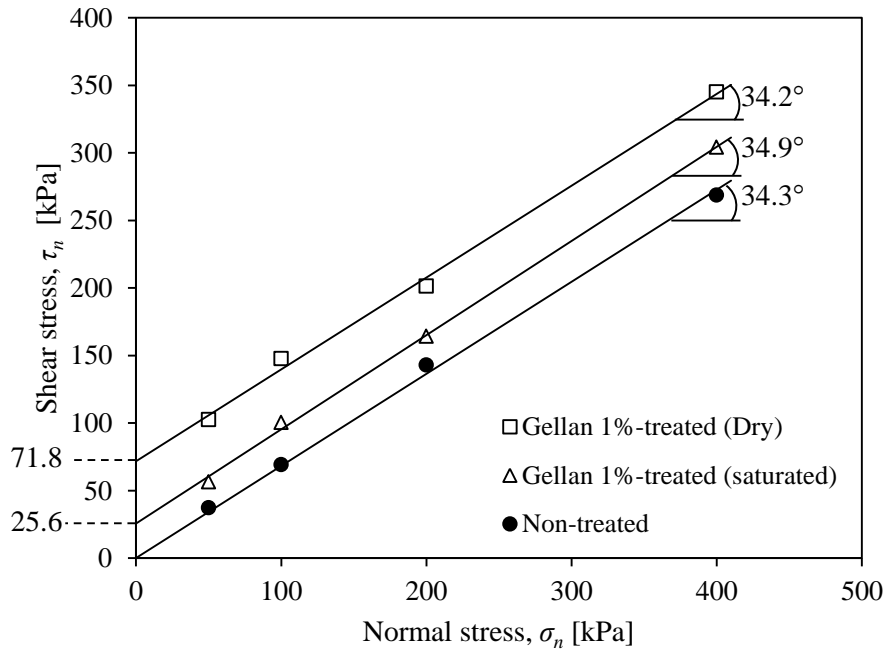


Figure 4.6. Coulomb envelope of non-treated and gellan gum 1%-treated joomunjin sand (dry test and saturated test condition) for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%)

#### 4.4. Triaxial shear strength

Figure 4.7 and 4.8 show the stress-strain behavior of both non-treated and gellan gum 1%-treated joomunjin specimen in dry and saturated condition for void ratio condition of 0.74 – 0.80 ( $I_D = 40\% - 58\%$ , medium state) under different confining pressure (i.e. 50, 100, 200 kPa). For non-treated specimen, the stress reached peak and slightly reduced for further strain. For gellan gum 1%-treated specimen, both dry and saturated specimens, they also experienced peak deviator stress at certain shear strain. This peak point was considered as a failure point. After reached peak stress, the stress decreased. .

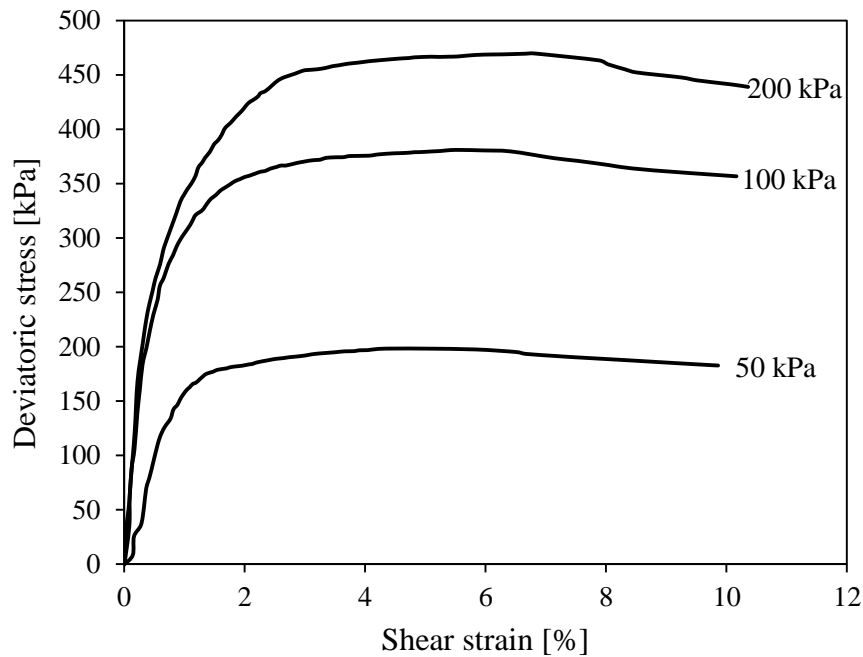


Figure 4.7. Stress – strain behavior of non-treated joomunjin sand with void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%) under 50 kPa, 100 kPa, and 200 kPa confining pressure

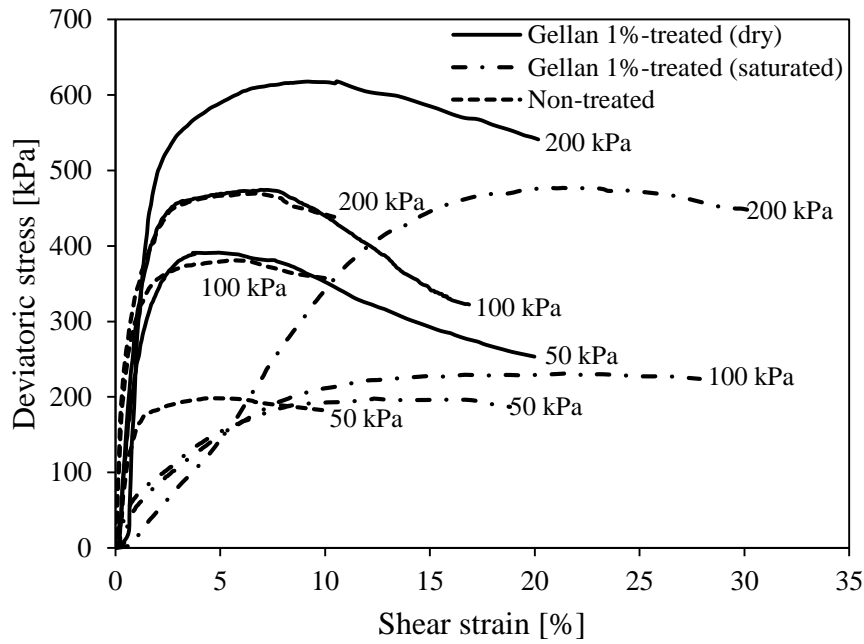


Figure 4.8. Stress – strain behavior of gellan gum 1%-treated joomunjin sand in dry and saturated condition with void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%) under 50 kPa and 100 kPa confining pressure

The differences from those specimens (non-treated, gellan gum 1%-treated in dry and saturated condition) are the stress and strain at which it reached the peak point, and the behavior after failure (i.e. after peak point). For non-treated and saturated gellan gum treated specimen, the decrement of stress after peak point is narrow, while the gellan gum 1%-treated specimen (dry) decreases until half of its peak stress. The strain range at which the stress reached peak is 4.5% to 6.8% for non-treated specimen, 12.3% to 20.5% for saturated gellan gum-treated specimen and 1.83% to 6.95% for dry gellan gum-treated specimen. It indicates that the saturated gellan gum-treated specimen is softer and behaves very ductile compare to both non-treated and dry gellan gum-treated specimen.

Gellan gum matrix inside the specimen resists until certain value of stress and strain before it failed. This resistance from gellan gum matrix is acting as cohesion-like to the specimen, giving strength to the sand specimen by inter-particle bonding. After failure, the

gellan gum matrix loses its strength which makes the stress reduces far below the peak stress for dry treated specimen.

Figure 4.9 shows the comparison of  $q$ - $p$  behavior of non-treated and gellan gum 1%-treated (saturated and dry) joomunjin sand for void ratio condition of 0.74 – 0.80 ( $I_D = 40\%$  - 58%, medium state) under different confining pressure (i.e. 50, 100, 200 kPa). The strengthening effect is clearly seen for gellan gum 1%-treated specimen in dry condition, with the cohesion increasing by 100.6 kPa. For saturated gellan gum-treated specimen, the cohesion also increases by 20.3 kPa. However, for both condition, as the friction angle are lower than non-treated specimen, the strengthening effect of gellan gum is decreasing with confining stress increases and nullified after reach certain confining pressure.

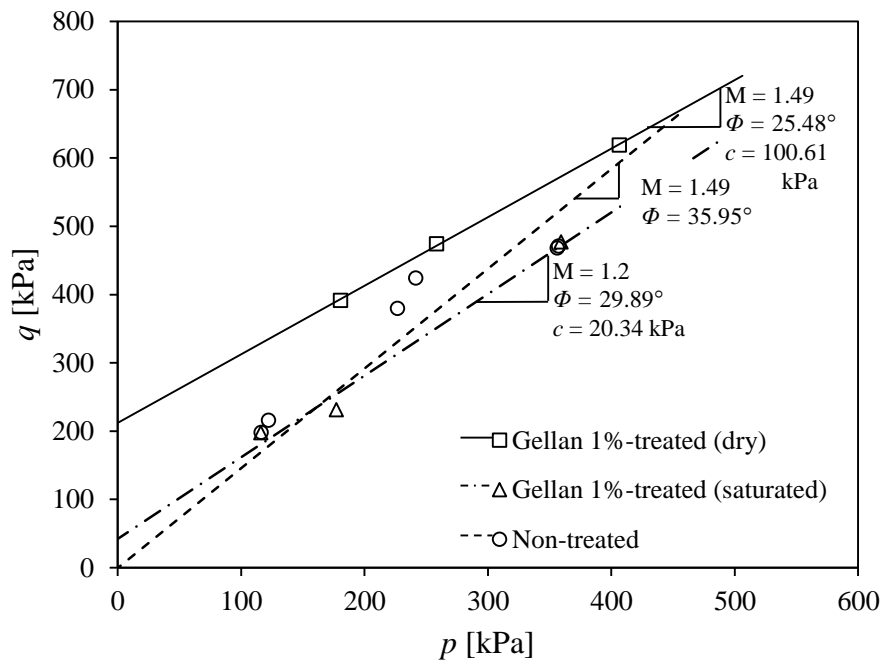


Figure 4.9.  $q$ - $p$  behavior of non-treated and gellan gum 1%-treated joomunjin sand (dry and saturated condition) with void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%) under 50, 100, and 200 kPa confining pressure

#### 4.5. Resonant Column (RC) – Shear modulus and damping ratio

##### Shear Modulus

Figure 4.10 a and b show shear modulus-strain curve of non-treated and gellan gum-treated joomunjin sand (dry condition) for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%, medium density condition) under different confining pressure (25, 50, 100, 200, 400 kPa). It can be seen from that both specimens have the general behavior of modulus-strain: strain level and confining pressure affects the shear modulus. Shear modulus decreases as strain level increases, whilst increases with confining pressure. For normalized value ( $G/G_{max}$ ), it is

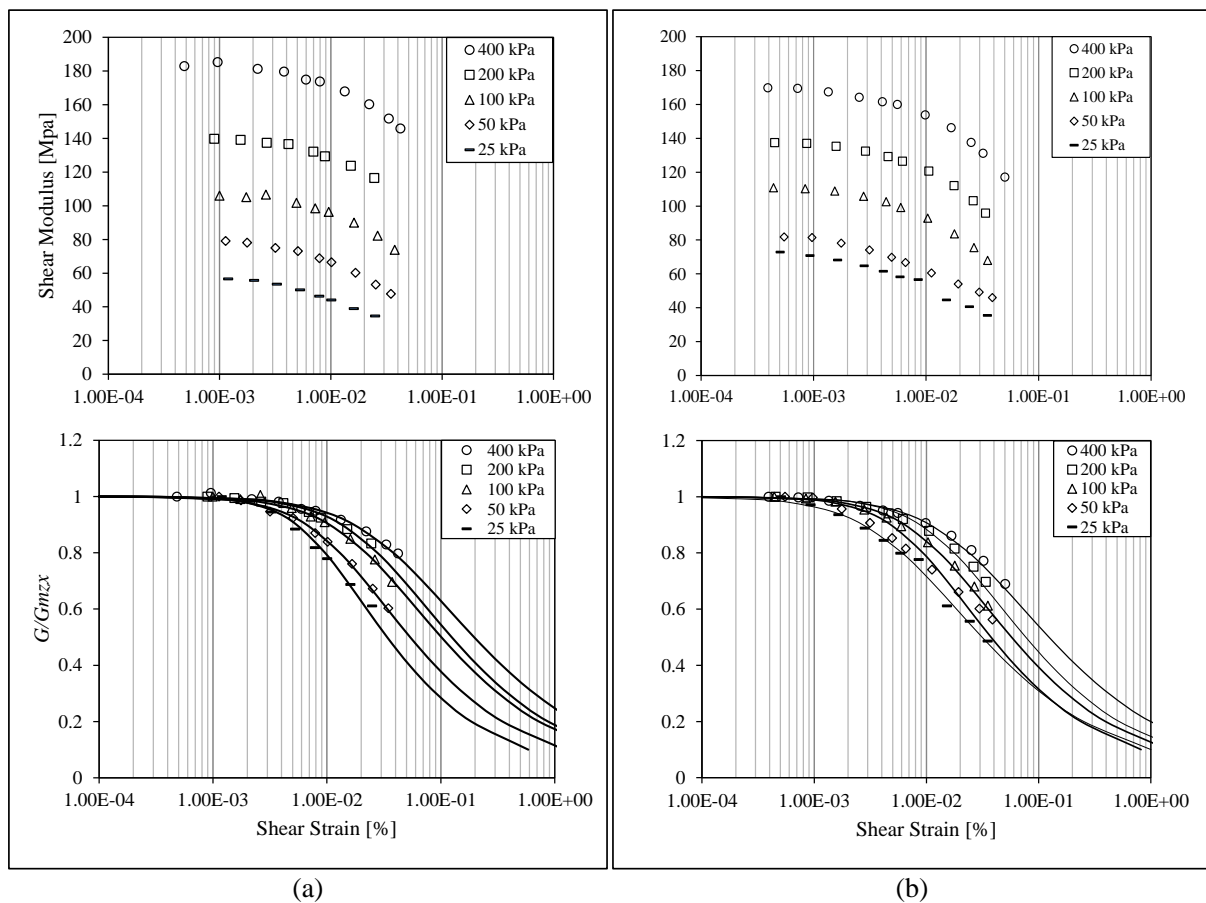


Figure 4.10. Shear modulus – strain and normalized shear modulus ( $G/G_{max}$ ) – strain of (a) non-treated and (b) gellan gum 1%-treated joomunjin sand (dry condition), for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%), under different confining pressure



influenced by confining pressure: in intermediate strain ( $\gamma = 10^{-3} - 10^{-1}$ ) where the specimen undergoes plastic behavior, the  $G/G_{max}$  curve becomes shallower as confining pressure increases.

Figure 4.11 provide the comparison between non-treated and gellan gum-treated sand for different confining pressure. It can be seen that at the low confining pressure (i.e. 25 kPa); shear modulus of gellan gum-treated sand is higher than non-treated sand. However, as confining pressure increases, the effect of gellan gum to the sand becomes null. Also, from  $G/G_{max}$  curve in Figure 4.12, it can be seen that the elastic threshold for gellan gum-treated sand is smaller than that of non-treated sand. The elastic thresholds for gellan gum-treated sand in dry condition shift from about  $3.3 \times 10^{-4} \%$  in 25 kPa confining pressure to  $1.3 \times 10^{-3} \%$  in 400 kPa confining pressure and for saturated condition is around  $2.0 \times 10^{-4} \%$  to  $7.0 \times 10^{-4} \%$ . Meanwhile, for non-treated sand, the elastic thresholds remain constant above  $10^{-3} \%$  (i.e.  $1.3 \times 10^{-3} \%$  in 25 kPa to  $2.1 \times 10^{-3} \%$  in 400 kPa). It indicates that as strain increases, the treated specimen (both in dry and saturated condition) undergoes plastic behavior earlier than non-treated specimen. It can be concluded in this stage that in term of shear modulus, the effect of gellan gum to the sand apparent only in low confining pressure (i.e. shallow depth).

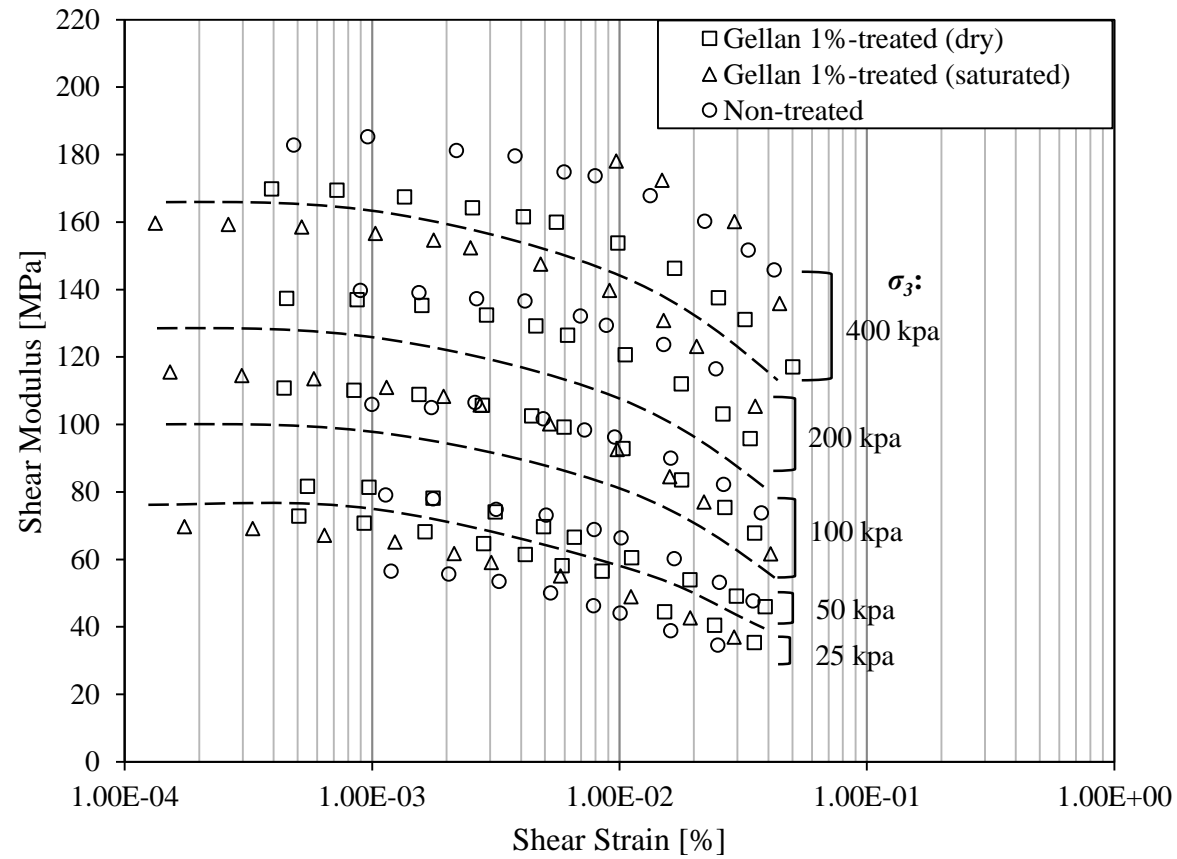


Figure 4.11. Comparison in shear modulus-strain between non-treated and gellan gum 1%-treated joomunjin sand for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%), under 25, 50, 100, 200, and 400 kPa confining pressure

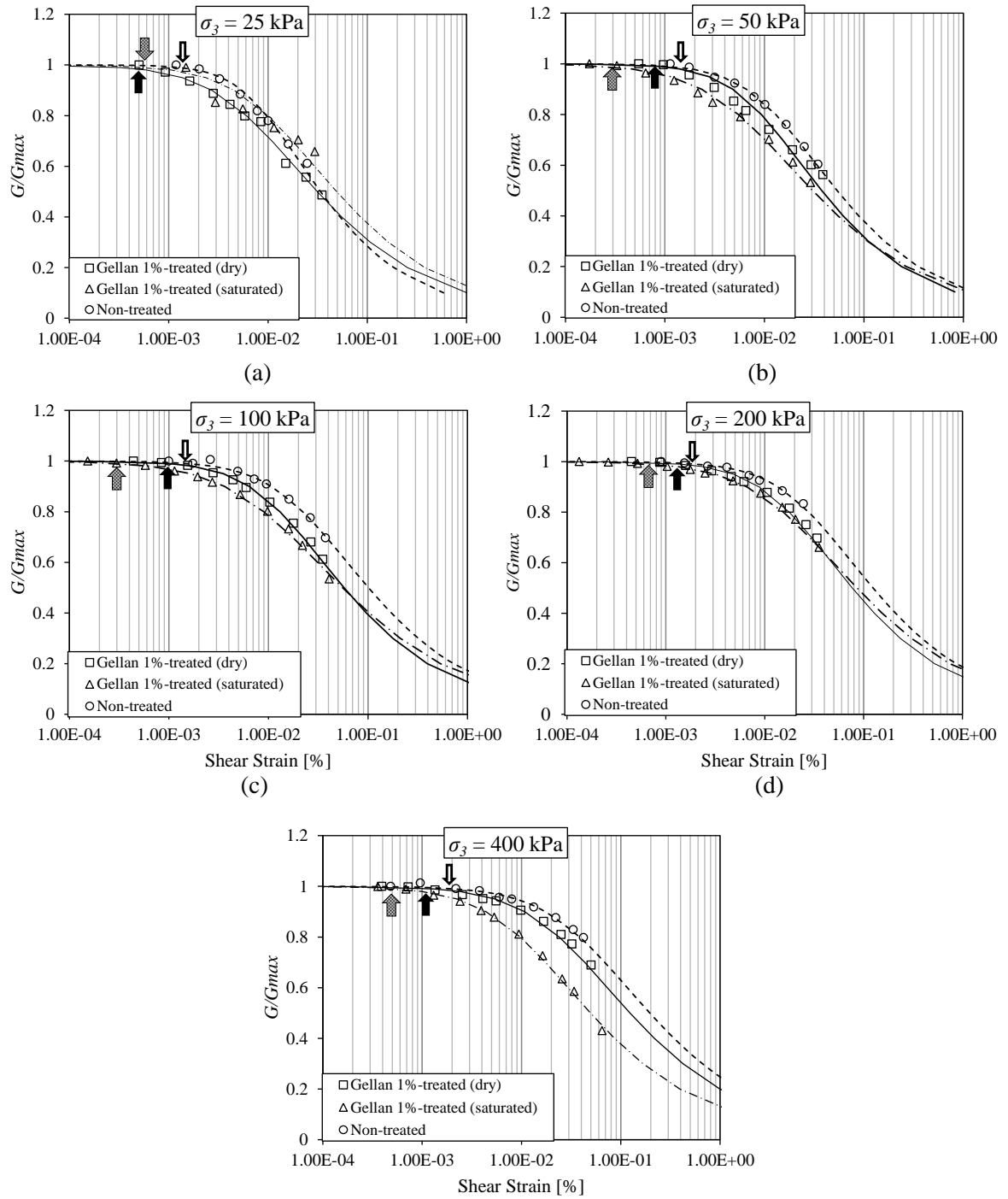


Figure 4.12. Comparison in  $G/G_{max}$  curve between non-treated and gellan gum 1%-treated joomunjin sand for void ratio of 0.74 – 0.80 ( $I_D$ : 40% – 58%), under (a) 25 kPa, (b) 50 kPa, (c) 100 kPa, (d) 200 kPa, (e) 400 kPa confining pressure. Black arrow, shaded arrow, and white arrow indicates elastic threshold for gellan gum 1%-treated sand in dry condition and saturated condition, and non-treated sand, respectively

### Damping Ratio

On the contrary, while it is not satisfying for the shear modulus result of gellan gum-treated sand, damping ratio shows substantial results. Figure 4.13 provide the comparison of damping ratio between non-treated and gellan gum-treated sand in different confining pressure. In all confining pressure condition (25, 50, 100, 200, 400 kPa), it is clearly shown that the damping ratio of gellan gum-treated sand are consistently higher than non-treated sand in all range of shear strain. Even in dry condition, the gellan gum is possible to absorb the wave propagation which makes the damping ratio higher than pure sand (non-treated specimen). Overall, the damping ratio increases at least two times for dry gellan gum-treated specimen, and five to ten times for saturated gellan gum-treated specimen.

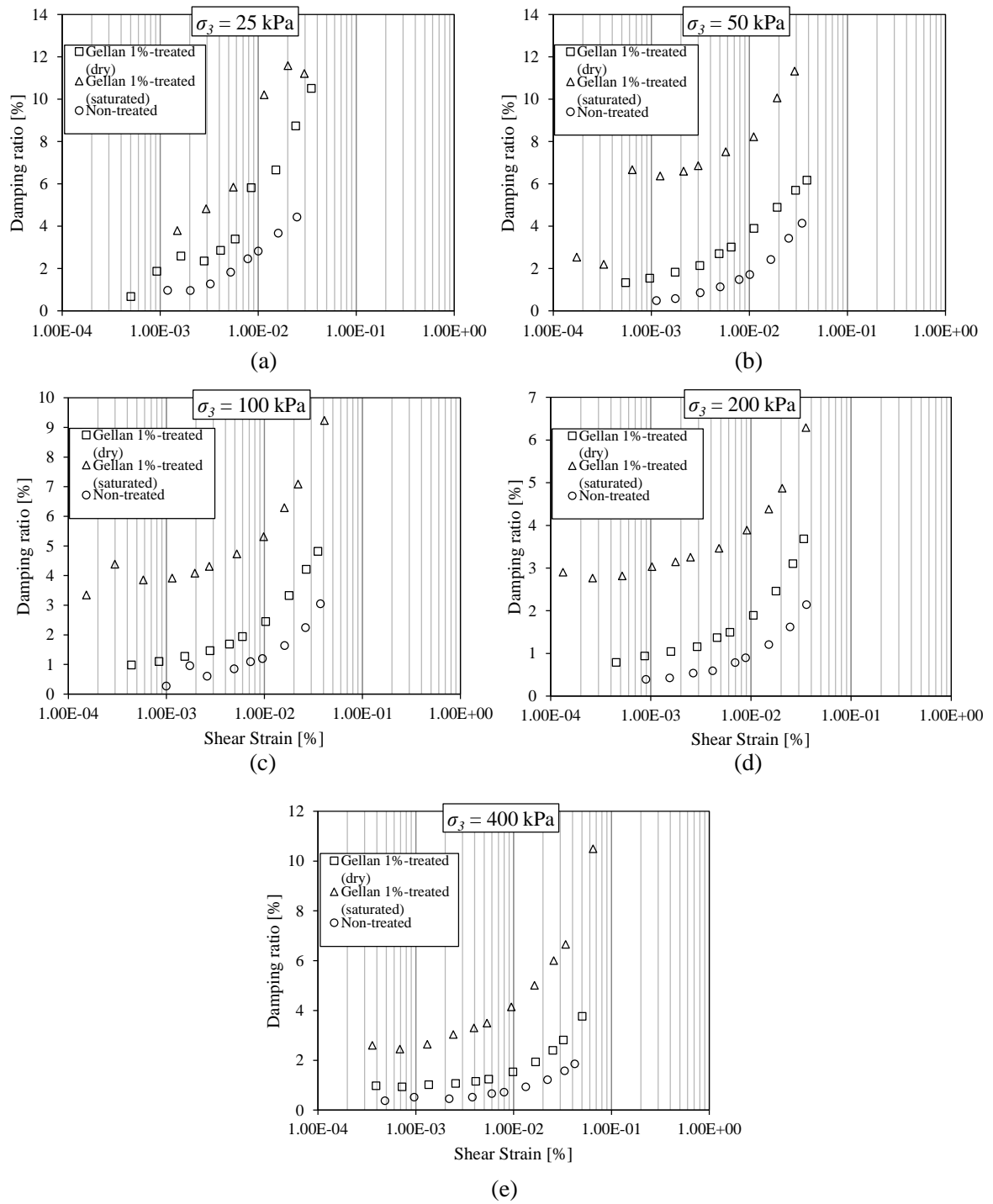


Figure 4.13. Comparison in damping ratio between non-treated and gellan gum 1%-treated joomunjin sand for void ratio of 0.74 – 0.80, under (a) 25 kPa, (b) 50 kPa, (c) 100 kPa, (d) 200 kPa, (e) 400 kPa confining pressure.

#### 4.6. Discussion

Based on the results and analyses of all experiments, it can be seen that generally gellan gum enhance the strength of sand by acting as apparent cohesion. Also, from the hydraulic conductivity result, it is shown that gellan gum decreases the hydraulic conductivity value by clogging (i.e. filling the void between particles) the sand. With these results, gellan gum has potential to be applied in the real field to improve the properties of sand soil.

However, it is also shown that the enhancement from gellan gum to joomunjin sand is not significant. From the result of direct shear test, gellan gum increases the cohesion for sand to 25.6 kPa under saturated condition and 71.8 kPa under dry condition, while from triaxial test increased by 20.3 kPa under saturated condition and 100.6 under dry condition. Moreover, from the result of resonant column test for seismic behavior, gellan gum only increases the stiffness under low confining pressure while it shows no effect under high confining pressure, although the results of damping ratio are substantial. This could be one major challenge of gellan gum application to the sand.

In the study of Polycan™ treated hwangtoh (Chang and Cho 2012), the micro point of view of Polycan™ strengthening effect to hwangtoh was analyzed. It can be seen from Figure 4.14 that hwangtoh particles are attached to the Polycan™ bundles (Chang and Cho 2012). Also, the study mentioned in terms of molecular weight/length by comparing both Polycan™ polymer and hwangtoh particle. It is stated that beta glucan biopolymer is estimated to have 1.4-16.7  $\mu\text{m}$ , which is larger than single hwangtoh particle ( $d < 1 \mu\text{m}$ ).

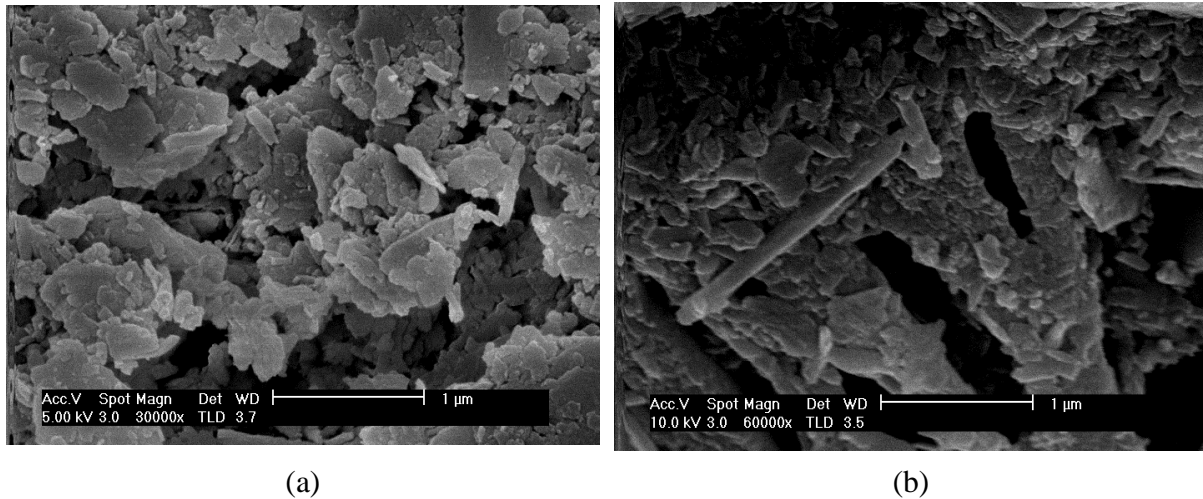


Figure 4.14. SEM images of: (a) natural hwangtoh (oven dried at 110°C) and (b) 0.05% of  $\beta$ -1,3/1,6-glucan polymer-treated *hwangtoh* (cured at 20°C; 28 days) (Chang and Cho 2012)

To have similar comparison with this study, SEM images of gellan-treated hwangtoh have been captured, as shown in Figure 4.15. It is shown that the ratio or proportion of biopolymer to the soil (hwangtoh) is even smaller than the previous study by Chang and Cho (2012) of Polycan™ treated hwangtoh. It is reported that gellan gum has molecular weight ( $M_w$ ) of  $0.5-2 \times 10^6$  Da. With a single glucose molecule length ( $M_w = 180$  Da) is about 1 nm, gellan gum is estimated to have 2.8 – 11.2  $\mu$ m molecule length. It is bigger than hwangtoh particle ( $d < 1 \mu$ m), which explains the hwangtoh-gellan gum interparticle connection. The gellan gum forms matrix/web-like structure and bonds hwangtoh particle together.

When it is compared to Figure 4.16 of SEM images of gellan-treated sand, it shows big differences. According to particle size, joomujin has the size of 0.425 mm and less. The size is more than hundred times larger than gellan gum molecular length. The difference of particle size – molecular length between sand and gellan gum is too big which makes the gellan can only bundles to form coating to the sand and bridges between the sand. This phenomenon can be one possible explanation of low strengthening effect by gellan to sand.

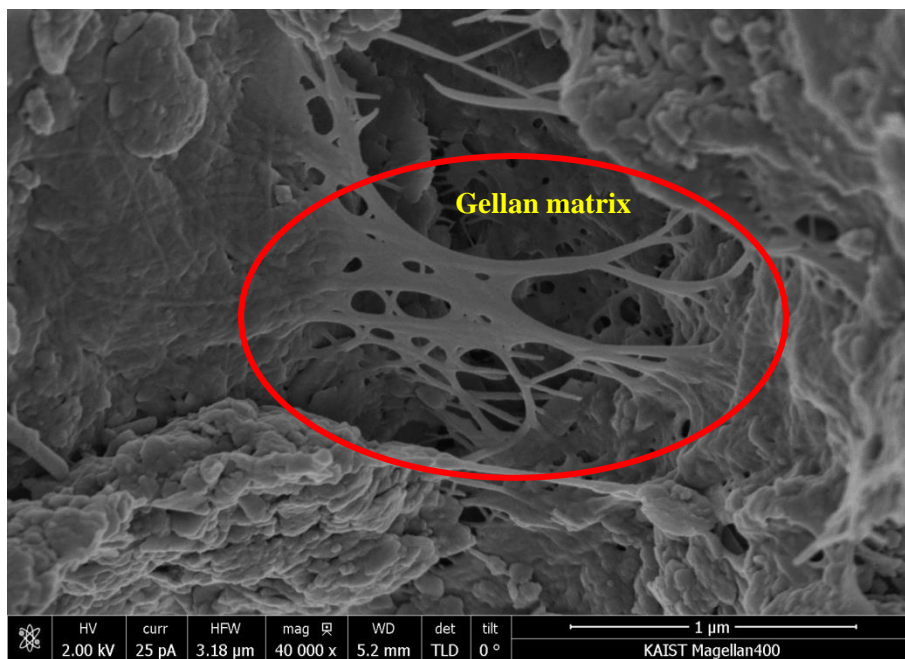


Figure 4.15. SEM images of gellan 1%-treated hwangtoh



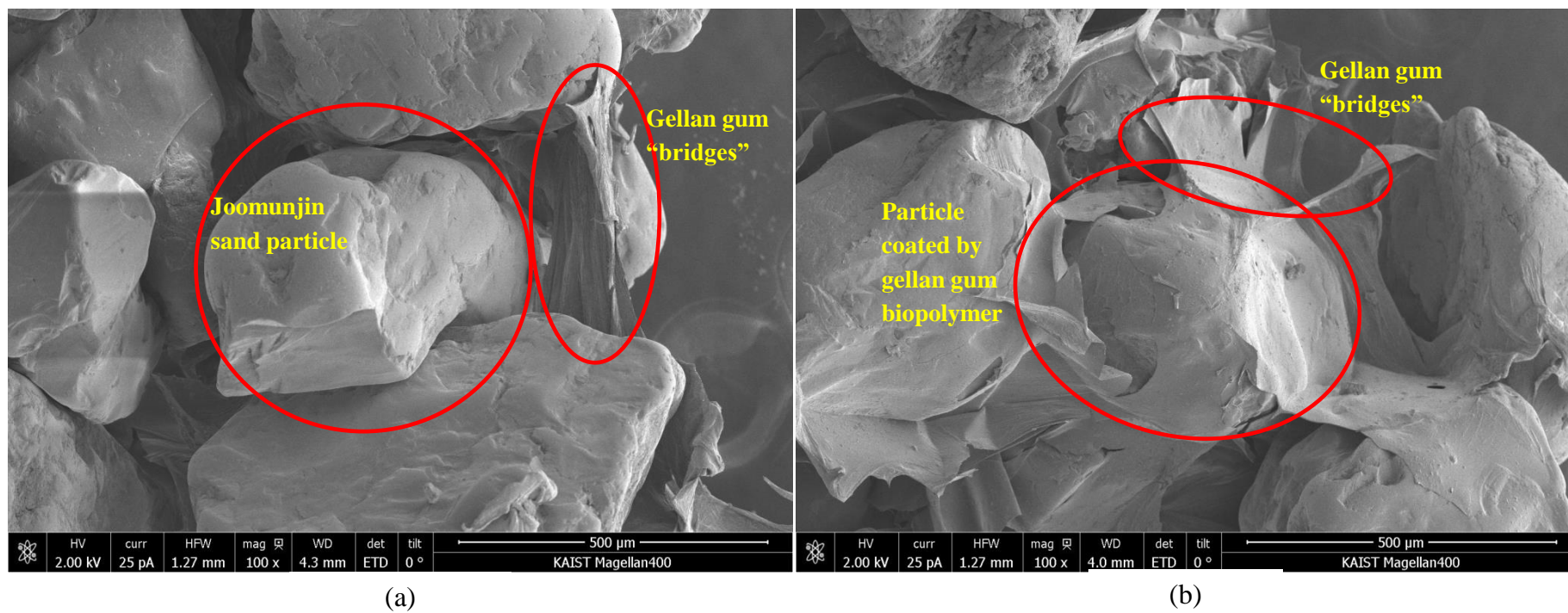


Figure 4.16. SEM images of gellan gum-treated sand. Gellan gum bundles to coat sand particle and to make bridges between sand particles

## **Chapter 5. Conclusion and Further Study**

### **5.1. Conclusion**

This study investigates the strengthening effect of gellan gum biopolymer to sand-type soil (i.e. joomunjin sand). Refer to studies which haven't discussed the effect of water to biopolymer-treated soil, this study tried to discuss about it and solve the problems of durability against water by using gellan gum biopolymer with thermal-treated mixing. The gellan gum biopolymer with thermal treatment successfully increases the durability of soil against water.

Several experiments have been performed to see the strengthening (by performing uniaxial compressive, direct shear, triaxial, and resonant column tests) and clogging effect (by performing falling head hydraulic conductivity tests) of gellan gum biopolymer to joomunjin sand. The facts have shown that gellan gum successfully decreases its hydraulic conductivity and increases the strength of joomunjin sand by giving cohesion, although the strengthening effect is not significant.

Based on the data and analysis presented, it can be concluded that:

- Thermal treatment is able to modify the gellan gum biopolymer to become gel material. The gel material of gellan gum is possible to make the soil durable against water and increase the soil strength.
- Biopolymer can serve as bioclogging to the soil by filling in the void, decreasing hydraulic conductivity of coarse-type soil up to 10,000 times lower than its original hydraulic conductivity.
- Biopolymer can increase the strength of sand, serve as particle binding matrix inside the soil and act as apparent cohesion to the soil.

- The limitation of strengthening of gellan gum to sand soil is probably due to the molecular length – particle size difference between biopolymer and soil. This difference affects in how the gellan gum biopolymer forms bonding in/between the soil particle.

## 5.2. Further study

It has to be noted that this study is far from its end. Study of the biopolymer material itself is one of important thing to be done because it is the main material which used in this type of study. Many researchers in the field of polymer, food technology, and all related application have studied the basic properties of biopolymers (i.e. rheology, textural, strength, chemical structure, etc) and also the behavior of combination between biopolymers or biopolymer with other organic compounds. What is left to be investigated by geotechnical engineers/researchers in this step are the biopolymer molecule-soil particle connection, in terms of physical, chemical, and electrical behavior. It is one of the key point in order to select and use the type of biopolymer that matches well to the soil properties, so that the soil improvement can have more effective and efficient results.

This study reflects the challenge faced by biopolymer treated sand (mainly in strengthening effect) which must be solved. One solution for this challenge is to perform cross-linking between biopolymers or biopolymer-organic compounds. It must be investigated further to find the correct cross-linking between two compounds to have stronger gelation effect and significant strengthening result on the soil.

To have a full understanding in the behavior of gellan gum-treated soil, further investigation in geotechnical engineering must be performed, such as loading-rate effect to the strength-stiffness behavior. As gellan gum is a viscous material with temperature dependence, it might be affected by loading rate to its strength-stiffness behavior (Rodriguez et al. 2008) and also to the elastic threshold strain range. This concept must be studied to

achieve deeper and more comprehensive understanding.

Finally, field application should be performed to confirm the usefulness and also to measure the practicability of biopolymer-treated soil study. Practical applications which possible to apply gellan gum biopolymer with thermal treatment, for example, are grouting and deep soil mixing. By applying heat to the gellan gum (producing gellan gum solution), stream it to the grout or deep mixing, and waited for the solution to be cooled and settled, it can bind the soil particle to enhance the strength or to reduce the hydraulic conductivity of soil, creating a clog to prevent piping or barrier for hazardous material encapsulation. This idea should be investigated further for real application in the field.

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## 요약문

### 젤란검으로 처리된 사질토의 지반물성

19세기 이후의 산업혁명과 인류 문명의 급속한 발전과 더불어 자연상태의 토양을 개량 또는 보강하여 재해를 줄이거나, 사회의 근간이 되는 각종 구조물 시공을 위한 토대를 제공하기 위한 다양한 시도들이 이루어져 왔다. 특히, 지반의 지지력을 증진시키거나, 비탈면의 안정성을 향상 시키고, 나아가 지진에 대한 내진성능 향상이 지반 보강의 주요 골자라 할 수 있다. 이를 위해 인류는 다양한 물리적, 화학적 처리 기술과, 수치해석 기법들을 발전시켜 왔다.

지반 처리 및 개량을 위한 가장 보편적 방법은 시멘트, 에폭시, 아크릴아미드 계열, 페놀 계열, 또는 폴리우레탄 계열 수지 등을 이용하여 지반과 혼합하거나 직접 주입 (즉, 약액주입) 하는 방법으로 크게 분류된다. 하지만, 기존의 지반 처리/개량 방법들에서 사용되고 있는 재료들은 최근 환경 유해성 문제 등이 제기되어 점차 그 사용이 제한될 전망이다. 따라서 새로운 친환경 재료를 이용한 지반 처리/기술 개발의 필요성이 점차 증대되고 있다.

최근의 지반공학 기술은 흙의 물리적, 역학적 거동뿐만 아니라, 흙의 화학적, 생물학적 거동에 대한 고려로 발전하고 있다. 하지만, 흙 속의 화학적, 생물학적 상호거동으로 인해 유발되는 크리프(장기침하), 응력이완, 그리고 팽창 (swelling) 등에 대한 기초적이고 이론적인 이해가 크게 부족한 상황이다. 따라서 이러한 흙의 화학적, 생물학적 거동 특성은 지반공학 분야의 미해결 난제로 남아



있는 상황이다.

최근 몇몇 연구들을 통해 흙 속에 미생물을 직접 주입시키거나, 흙 속에 자연적으로 존재하는 미생물을 활성화 시키는 방법으로, 흙의 강도를 증진시키고자 하는 시도들이 있었다. 하지만 미생물을 이용한 흙의 강도 증진은 미생물의 배양 환경 즉, 영양분, 온도, 공극률 등에 따라 민감하게 차이를 보여 신뢰성과 반복성이 높은 결과를 제공하지 못하는 단점이 있다. 따라서 최근에는 미생물의 배설물을 직접 이용하여 흙을 처리/개량하는 시도들이 이루어지고 있다.

바이오폴리머는 친환경적인 미생물 배설물로써, 이를 이용한 흙의 강도 증진 및 침식 억제에 관한 연구들이 수행되고 있다. 하지만, 바이오폴리머 처리토의 내구성, 특히 물에 수침/포화 된 조건에 대한 고려가 부족한 실정이다. 따라서 본 연구에서는 함수 조건에 따른 바이오폴리머 처리토의 거동을 심도있게 분석하고자 하였다.

본 연구에서는 열적젤화(thermo-gelation) 바이오폴리머의 일종인 젤란검을 대표 사질토인 주문진표준사와 혼합하여 각종 지반공학적 거동인자들을 분석하였다 다양한 실내 실험들 - 일축압축강도시험, 직접전단시험, 삼축압축시험, 공진주시험 등이 공인된 시험표준을 바탕으로 수행이 되어 바이오폴리머 처리토의 역학적 거동을 분석하였으며, 투수시험과 전자주사현미경 관찰은 바이오폴리머 처리토의 미세 거동, 특히 흙 입자 - 공극 - 바이오폴리머 젤 간 상관 관계를 분석하는데 활용되었다.

결과에 의하면 젤란검 바이오폴리머는 흙의 점착력(cohesion)을 증진시킴으로써 전체적으로 흙의 강도를 높이는 효과를 유발함을 확인할 수 있었다. 직접

전단시험과 삼축압축시험에서 도출된 응력 - 변위 상관 관계는 상호 유사한 거동을 보였으며, 특히 건조된 시료와 포화된 시료 간 거동 차이를 명확하게 제시해주었다. 공진주 시험결과에 의하면, 젤란검 바이오폴리머 처리는 흙의 최대전단탄성계수 증진에는 큰 효과가 없으나, 흙의 감쇠비(damping ratio)를 크게 향상시키는 효과가 있음을 확인할 수 있었다. 또한, 흙의 투수성은 바이오폴리머 처리 조건이 흙의 투수성은 10,000 배 감소시킴을 확인하였다. 본 연구 결과들과 선행 연구들을 비교해본 결과, 바이오폴리머 처리토의 강도 증진은 상호거동을 하는 바이오폴리머 입자와 흙 입자간 상대적 크기에서 기인함을 모델을 통해 제시하였다.

주요어: 젤란검, 모래, 강도증진, 막힘, 입자-분자 간 상관관계

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