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젤란처리된 흙의 구조 및 거동에 관한 연구

Structural and Behavioral Analysis on

Gellan Treated Soils

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The present dissertation has been approved by the dissertation committee as a master's thesis at KAIST

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ABSTRACT

Soil treatment and improvement have been an important field for construction since ancient times, where the use of bitumen or sticky rice mortars have been used for soil strengthening. Since then with the advancement of civilization, the durability and construction materials have improved allowing for further advancements in the field of geotechnical engineering. The main purposes of soil improvement has been the enhancement of one or many engineering characteristics of the soil. Such characteristics include the strength, hydraulic conductivity, durability, and the revitalization of the environment. Among the soil treatment methods, the most widely used and accepted is the use of cement. The use of cement has a long standing history and numerous advantages, such as high strength and durability with an ability to form calcium carbonate crystals under the water table. However, the use of cement has also been associated with various environmental concerns, such as the heavy emission of greenhouse gases, urban runoff and heat, and vegetation growth limitations.

Due to the many environmental hazards associated with cement use, research and development into an environmentally friendly substitute for a soil binder has been researched in recent years. Environmental-friendly and sustainable approaches have recently emerged in the field of geotechnical engineering which involve the use of alternative materials, including geosynthetics, chemical polymers, geopolymers, or biological treatment.

Among such research one possible avenue for an environmentally friendly soil binder is the use of biopolymers. Biopolymers are organic polymers that are synthesized by biological organisms. They consist of monomeric units that are bonded into larger formations. In this study, gellan gum biopolymers are used for soil improvement purposes, and an in-depth study on the structure and behavior of gel type biopolymers has been conducted.

The use of various experiments such as the uniaxial compressive strength, direct shear tests, hydraulic conductivity tests, and oedometer tests have been performed to analyzed the structure and behavior of these gellan treated soils. Specifically with a focus on the presence of clay particles and water molecules. These investigation provided numerous insights into the properties of these gellan treated soils, and the importance of many factors, such as the gellan to clay ratios.

Keywords: gellan gum, sand, kaolinite, strengthening, structural analysis, behavioral analysis, wetting / drying cycles

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Chapter 1. Introduction

1.1 Research Background

Soil treatment and improvement have been an important field for construction since ancient times, where the use of bitumen or sticky rice mortars have been used for soil strengthening [1, 2]. Since then with the advancement of civilization, the durability and construction materials have improved allowing for further advancements in the field of geotechnical engineering. The main purposes of soil improvement has been the enhancement of one or many engineering characteristics of the soil. Such characteristics include the strength, hydraulic conductivity, durability, and the revitalization of the environment [3]. For engineered soils there are two primary methods that are used: mechanical improvement and chemical treatment. Mechanical improvement makes use of physical processes such as compaction, drainage, loading, or other various means to reinforce the strength and behavior of the soil. On the other hand chemical treatment involves the use of chemical reactions such as hydration or pozzolanic reactions to create an artificial binding effect.

Among the chemical treatment methods, the most widely used and accepted is the use of cement. The use of cement has a long standing history and numerous advantages, such as high strength and durability with an ability to form calcium carbonate crystals under the water table [4]. However, the use of cement has also been associated with various environmental concerns.

Environmental Concerns of Cement Use

The use of cement has been most associated with the environmental concerns of high greenhouse gas emissions. When producing cement, 0.4 tons of CO_2 is emitted from calcination and the burning of fossil fuels during production for every 1 ton of cement produced. Additionally, when cement undergoes hydration to form calcium carbonate (*i.e.*, $5CaCO_3 + 2SiO_2 \rightarrow 3CaO \cdot SiO_2 + 2CaO \cdot SiO_2 + 5CO_2$) 0.55 tons of CO_2 are produced for every 1 ton of cement. Therefore, a total of 0.95 tons of CO_2 is produced for every 1 ton of cement [5].

With such a high ratio of CO_2 emissions with the production and use of cement, the use of cement has been a major contributor to global greenhouse gas emissions. In 1995, there was a global

production of 1453 M·tons of cement, which contributed to approximately 5% of the global annual CO_2 emissions for that year [6]. In addition, the global cement production has only increased since 1995, which in turn has increased the CO_2 emissions from cement [7, 8]. By the year 2003, the global CO_2 emission from cement production had increased to 7% of the global annual CO_2 emissions, and by 2010 this figure had increased to 9% [9]. The CO_2 emissions from cement through the years can be seen in *Fig. 1.1*.
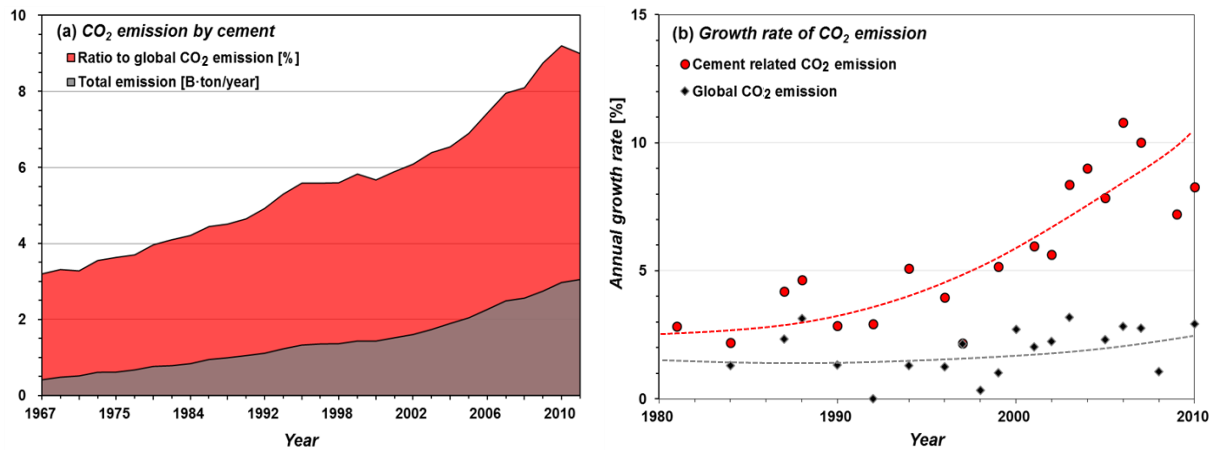
Fig. 1.1 CO_2 emissions of cement throughout the years (based off Oss 2014 (a) and Rapier 2012 (b))

In addition to greenhouse gas emissions, cement has been known to cause several other environmental problems. When mixed into the soil the process of hydration releases alkaline hydroxide (OH-) ions which significantly increases the pH of the soil up to 12-13 [10], and this increase in pH can cause many detrimental effects to the organisms and ecosystem in that area [11].

Widespread use of cement is also related to several urban environmental issues, such as urban runoffs, heat islands, and prevention of vegetation growth. Along with such urban problems, due to the irreversible effects of cement hydration demolition and waste problems occur [12].

Urban runoff is known to be amplified due to the massive use of impervious cement-based concrete with increasing urbanization. The absence of ground infiltration and severe surface runoff can produce floods, and is strongly related to economic and ecological losses such as residential or infrastructural damage [13, 14]. Moreover, surface runoff also degrades overall water quality by flushing various pollutants and contaminants into waterways from urban sources [15, 16].

Urban heat island effect is mainly caused by concrete or asphalt materials, whose specific heats are lower than that of soil [17], to increase the temperature around urban areas. Urban heat islands can have a number of environmental impacts such as affecting local wind patterns, humidity, the development of urban smog, and localized heavy precipitation [18, 19].

Moreover, the presence of cementitious covers also prevents the growth of surface vegetation. Vegetation such as trees and grass can lower the surrounding temperature via evapotranspiration and by providing shade. Thus, vegetation can reduce peak summer temperatures in urban areas by 1-5℃, and can also be used to mitigate urban heat islands [20]. In addition, the presence of vegetation has other benefits, including increasing the efficiency of cooling systems, enhancing rainwater management and water quality by absorbing and filtering precipitation, and improving air quality [21].

Cement demolition waste and its management by disposal or recycling has become a significant environmental concern at the end of the life cycle of cement-based concrete structures [22]. Moreover, cement used for geotechnical purposes such as deep mixing or grouting is difficult to remove from the ground.

Concrete dust can be released into the air through various pathways such as concrete structure demolition or natural disasters (*e.g.*, earthquakes), and can induce lung diseases [23]. For example, high concentrations of concrete dust, 150 μg/m^3, were monitored after the Great Hanshin earthquake in Japan in 2015, where the alkaline component of the concrete dust in the air was equivalent to an amount sufficient to neutralize the annual acid rainfall in Japan [24].

Due to such environmental hazards associated with many chemical soil treatments, such as cement use, research and development into an environmentally friendly substitute for a soil binder has been researched in recent years.

1.2 Related Research Trends

Geosynthetics and Geopolymers

While the use of cement creates a number of environmental problems, as mentioned in the previous section, the construction industry also accounts for approximately 40% of global energy consumption [25]. In response, environmental-friendly and sustainable approaches have recently emerged in the field of geotechnical engineering which involve the use of alternative materials, including geosynthetics, chemical polymers, geopolymers, or biological treatment.

Geosynthetics are artificial polymeric products, including geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners, geofoam, geocells, and geocomposites, which are implanted into the soil to strengthen or enhance the soil's geotechnical engineering properties. Geosynthetics have high tensile strength, flexibility, and impervious characteristics, and are therefore, generally used for soil separation, filtering, reinforcement, and drainage purposes across a large range of applications. [26-28]. While such materials can provide higher strength, specifically tensile strength, the strengthening is almost completely dependent on the material itself and not the soil, making them undesirable for various engineering practices.

In the late 20th century, geotechnical engineers began introducing chemically synthesized polymers as soil conditioners to replace the use of conventional binders, such as lime and cement, for geotechnical engineering and agricultural purposes. Polyacrylamide (PAM) [29] is a simple linear- or cross-linked polymer synthesized by acrylamide (*i.e.*, $CH_2CHCONH_2$) subunits, which are non-toxic and hydrophilic [30]. Anionic polyacrylamide (PAM) has negative charge density and induces electrostatic bonding with clay particles [31, 32], which results in reduced soil erosion and runoff control [33]. PAM consequently has been used in various fields such as agriculture, construction, and military applications (*e.g.*, temporary helicopter landing fields) as a soil erosion reduction agent [33, 34]. Sodium silicate ($Na_2(SiO_2)_nO$) and other chemicals, including acrylics, lignosulfonates and phenolasts, have been widely implemented in soil grouting practices, especially for sandy soils. However, chemically synthesized polymers and solutions have raised concerns about toxicity and water pollution problems [35], which has restricted the usage of chemical solutions near water conservation regions in particular.

Meanwhile, electroosmotic chemical treatment (ECT) has been attempted in several studies to improve the strength of soft soils [36, 37]. However, the ECT method requires the massive injection of chemical solutions to produce an increase in osmotic pressure, and has not yet been accepted for practical implementation [38].

Geopolymers are polymers synthesized from either organic or inorganic, such as silicon-based, origins [39, 40]. The geopolymerization process involves initial mixing in an alkaline solution, which dissolves silicon and aluminum ions (*i.e.*, alkali-activation) from soil or industrial byproducts such as fly ash or blast furnace slag. Hydroxyl ions ($2OH^-$) remaining in the alkaline solution then react to form one free water molecule (H_2O) and an oxide ion (O^{2-}) [41]. The released oxygens then form

monomers with the dissolved silicon and aluminum ions, which undergo condensation. Geopolymers require isolated heating (above 60℃) for proper geopolymerization (hardening) [42, 43], which can limit site application for geotechnical engineering purposes. Studies have shown that geopolymers are highly susceptible to water and show significant degradation in strength when saturated in water, especially in acid solutions, due to depolymerization of aluminosilicate polymers and removal of silicic acid [44].

Bio-mineralization

Since the beginning of the 21st century researchers have been seeking more biogenic alternatives to existing strengthening agents. Recently, environment-friendly approaches have emerged that involve the use of biological materials such as microbes and enzymes, in attempts to improve the mechanical properties of soil. The most common approach is bio-mineralization, which entails mineral precipitation in soil pores via biological organisms [45]. Another approach, based on biofilm formation, starts with a weak attraction force between microorganisms that later develops into a larger attachment which is irreversible [46].

Among bio-mineralization strategies, the most recognized soil treatment method is microbial induced calcite precipitation (MICP). MICP employs microorganisms including *Sporosarcina pasteurii* and *Bacillus pasteurii* to precipitate calcium carbonate crystals in soil voids, to provide interparticle bonding [47, 48]. MICP occurs through urea hydrolysis, which primes the soil for calcium carbonate precipitation when calcium is present [49]. Ureolytic bacteria are used to convert urea to ammonium and carbonate. Calcium carbonate precipitates are then formed from the carbonate and calcium ions [50]. The calcium carbonate precipitates bind with the soil grains to increase the strength and stiffness of the soil [51].

Several studies have been performed to increase the strength and stiffness of soils using urease positive microorganisms [48, 52]. In those studies, the microorganism *Sporosarcina pasteurii* was injected directly into the soil to allow for calcite precipitation by the microorganisms themselves.

The use of urea, $CaCl_2$, and urease will precipitate calcite through enzymatic processes without microbial activities, which is suitable for soil strengthening and increasing stiffness [53]. MICP has also been found to be applicable in various other fields, including the remediation of heavy metals [54], CO_2 sequestration [55], and the repair of concrete [56, 57].

Although MICP is a more environment-friendly substitute to conventional methods of soil treatment, it has several shortcomings when implemented in the field. MICP is most applicable to coarse sediments, and encounters difficulties when used with fine grained soils due to infiltration problems: the pore sizes of fine grained sediments provide an unsuitable environment for bacteria growth. It has been speculated that clay particles may provide better nucleation sites for the calcium carbonate precipitates [58]. Moreover, the transport, cultivation, and fixation performance of bacteria is not consistent. Thus, recent studies have adopted the use of urease enzyme instead of using bacteria to promote the hydrolysis of urea, for the chemical precipitation of calcite [59].

The application of MICP leaves ammonia as a byproduct in the soil, which increases the pH and affects the local soil ecosystem. Another limitation of MICP is that the microorganisms have difficulty penetrating the soil, which causes heterogeneous cementation of the soil layer. The most important factor for attaining uniform calcium carbonate precipitation is the effective distribution of microbes [60]. Furthermore, the use of MICP results in a highly concentrated ammonium chloride byproduct, which needs to be removed and treated, generally in the form of soil flushing [61].

Even though the limitations of MICP are problematic, the bio-soil method has been shown to have several promising features, including high strengthening, low environmental impact, self-proliferation, and biodegradation. A number of researchers have thus focused on the direct use of biogenic excrement (*i.e.* biopolymers) instead of attempting to cultivate the microorganisms in the soil.

Biopolymers

Biopolymers are organic polymers that are synthesized by biological organisms. They consist of monomeric units that are bonded into larger formations. The use of biopolymers is, in fact, not an entirely new development in geotechnical engineering. Organic polymers such as natural bitumen, straws and sticky rice have been used in ancient civilizations and can also be classified as biopolymers in a broad sense. In ancient Chinese civilization, sticky rice mortar was used as a binder. Sticky rice soup mixed with *Actinidia chinensis* cane juice, lime, loess, and river sand produced a mortar with good strength, high toughness, and water resistance [62].

Among the three typical types of biopolymers – polynucleotides (*e.g.*, RNA, DNA), polypeptides (*e.g.*, composed of amino acids), and polysaccharides – polysaccharides have been the most common contemporary biopolymer type to be applied in various practices [63, 64].

Polysaccharides are polymeric carbohydrate chains composed of monosaccharide units. Polysaccharides are widely found in nature because they are employed in key biological roles, as substances forming skeletal structures, assimilative reserve substances, and water binding substances [65]. The properties of polysaccharides have led to their widespread use as thickening agents, stabilizers, sweeteners, and gel forming agents in the fields of food production, agriculture, cosmetics, medical treatment, and pharmaceuticals [66-68].

Biopolymers mixed with soil, such as sticky rice mortar, promote strengthening of the soil, including increased cohesion and strength, resistance to erosion, reduced permeability, etc., by acting as a binder. The direct use of biopolymers in soil has several benefits over pre-existing biological soil treatment methods [69]. The direct application of biopolymers to soils circumvents many of the shortcomings of other approaches, such as microbial injection, time required for cultivation and precipitation, and the uncertain quality of the soil treatment. Moreover, since biopolymers are readily found in nature and many are known to be harmless and edible, biopolymers can be considered eco-friendly substitutes for soil treatment. Several polysaccharide group biopolymers have been examined recently for use in geotechnical engineering. The characteristics of common biopolymers are summarized in *Table 1.1*, and the following sections review their notable case studies in geotechnical engineering.

The enhancement capabilities of biopolymer treated soils in geotechnical engineering has been shown to have significant strengthening efficiencies from previous studies [70, 71]. In general, biopolymers have high specific surfaces with electrical charges, which enable direct interactions between the biopolymers and fine soil particles, thereby providing firm biopolymer-soil matrices with high strength. Additionally, the use of biopolymers in soil have shown various behaviors and properties with the presence of clayey soils and water [71, 72]. Therefore, the use of biopolymers has shown promise as a possible alternative for an environmentally friendly soil binder.

Table 1.1 Characteristics of common biopolymers (Adibkia et al., 2007; Barrére et al., 1986; Chang et al., 2006; Daniel et al., 1994; Harada et al., 1968; Hassan, 2005; Kulicke et al., 1982; Wan et al., 2004).

Biopolymer	Composition	Characteristics
Cellulose	*β-(1→4)-D-glucose* linkages	- Hydrophilic
		- Properties depend on the chain length
Starch	*D-glucose residues* linked by *α-(1, 4) glucosidic bonds*	- Soluble in heated water
		- Viscous, gelatinization
Chitosan	*P-(1,4)-2-amino-2-deoxy-D-glucose*	- Soluble in acidic solvents
		- Bioadhesive for (-) charged surfaces
		- Biodegradable
Xanthan	$C_{35}H_{49}O_{29}$	- High viscous rheology
Curdlan	$(C_6H_{10}O_5)_n$	- Gel formation via heating in aqueous solutions
Beta-Glucan	D-glucose monomers linked by *β*-glycosidic bonds	- Capable of immune activation in humans
		- Cholesterol absorption capabilities
Polyacrylamide	$(C_3H_5NO)_n$	- Water absorbent, gel formation
		- Thickener

1.3 Research Purpose

Among previously studied biopolymers the use of thermally treatable gel type biopolymer gellan gum has shown the largest increases in strength and stability [72]. However, research on such biopolymers till now have only focused on the strengthening efficiencies and not the behavior and mechanisms behind such biopolymer treated soils. As such the purpose of this research was to provide an in depth study on the structure and behavior of gel type biopolymers, using gellan gum as a basis, and the various parameters that effect the properties of these biopolymer treated soils.

Chapter 2. Materials and Procedure

2.1 Materials

Gellan Gum Biopolymer

Gellan gum was chosen as the biopolymer binding agent for this study due to its high strength and stability. Gellan gum is a high molecular weight polysaccharide that is fermented from *Sphingomonas elodea* microbes. Low acyl gellan gum biopolymer produced by Sigma Aldrich (CAS No: 71010-52-1) was used in this study. Low acyl gellan gum partially hydrates in cold water, and fully dissolves at temperatures above 90 ℃, forming a hydrocolloid solution. The viscosity of a gellan gum solution increases with declining temperature and finally forms a highly viscous hydrogel below 40℃ (*i.e.*, thermo-gelation). Thus, hydrogel formation is expected to naturally occur during the mixing process with soil via decreasing temperature.

Jumunjin Sand

Jumunjin sand is a typical standard sand in Korea that has been widely used in various studies [73-75]. In the USCS classification Jumunjin sand is classified as a poorly graded sand (*SP*) with a particle size distribution as shown in Fig. 1. The coefficient of uniformity (C_u) and the coefficient of gradation (C_c) are 1.94 and 1.09, respectively. It has particulate structures between a minimum void ratio of 0.64 and a maximum void ratio of 0.89; its specific gravity (G_s) is 2.65.

Kaolinite

To compare with Jumunjin sand, kaolinite was chosen to represent the fine soils for this study. *Bintang* kaolin (Belitung island, Indonesia), a commercially available white kaolin powder, was used for this study. *Bintang* kaolin is a highly plastic clay (*CH*) having material properties of $PL = 24$, $LL = 56$, $G_s = 2.65$, and $D_{50} = 44$ μm.

2.1 Experimental Procedure

2.1.1 Sample Preparation

All gellan gum-sand samples were prepared by following the same sample preparation method. First, a gellan solution was prepared by dissolving pure gellan gum into heated (*i.e.*, to 100 ℃) distilled water according to the target concentration (*i.e.*, 0.5, 1.0, 1.5, 2.0, and 5.0 % of gellan gum to

the mass of soil) of the gellan gum-soil mixtures. Once the gellan was fully dissolved into the solution, the solution was directly mixed with the soil. The soils used were a combination of sand and kaolinite at various concentrations to observe the behavioral properties for fine and coarse soils. The solution's water content was set so that the desired water content and gellan concentration was mixing into the soil. Once the mixture was thoroughly mixed, the mixture was set into a mold and allowed to set while reaching room temperature (24 ℃). Once the samples reached room temperature, the samples were removed from the mold and cured with either air drying (dry condition) or submerged in water (wet condition).

2.1.1 Experimental Setup

Unconfined uniaxial compression test

Cube (50 mm × 50 mm × 50 mm) shaped gellan gum-soil \ samples were prepared at various gellan concentrations. Unconfined uniaxial compressive testing was performed using a UTM (Universal Testing Machine; Instron 5583) device. The axial strain rate was controlled at 0.5 mm/min (*i.e.*, 1 % strain / min). The maximum strength and the stress-strain behaviors were obtained by averaging three different measurements for a single condition. The experimental setup can be seen in *Fig. 2.1*.
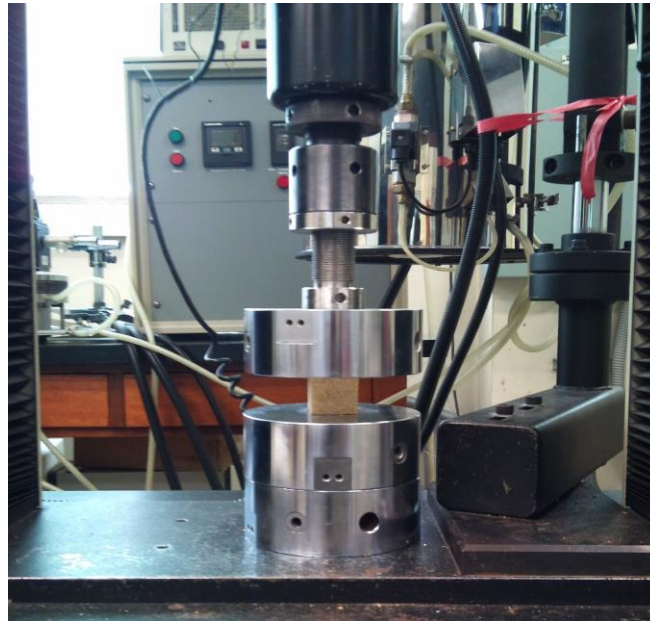

Fig. 2.1 Unconfined uniaxial compression test setup

Direct shear test

Disk shape (D 60 mm × H 20 mm) gellan gum-soil samples were placed into a direct shear apparatus (Humboldt HM-2560A) with porous stones placed above and beneath, and confined at 50, 100, 200, and 400 kPa respectively via a pneumatic actuator for 24 hours before applying horizontal

shear. The samples saturated in water by filling the inside of the shear box with water before applying vertical confinement. Horizontal shear (*i.e.*, shear rate = 2 % strain / min) was applied under a consolidated-drained condition following the instructions of the ASTM D 3080 standard [76], with confining pressures of 50, 100, 200, and 400 kPa, respectively. Horizontal shear was applied for 500 seconds to finally induce 10 mm (= 1.2 mm/min × 500 secs) horizontal displacement. Horizontal load, vertical strain, and horizontal displacements were obtained automatically via load cell (HM-2300.020) and LVDT (HM-14368, HM-14180) measurements. The direct shear experimental setup is shown in *Fig. 2.2*.
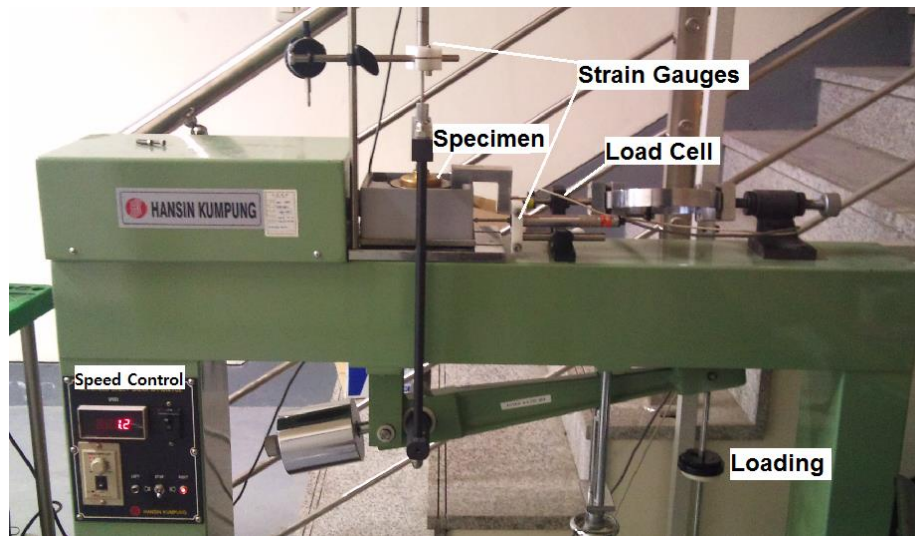
Fig. 2.2 Direct shear test setup

Hydraulic Conductivity

A variation of the constant head permeability test was performed, where the permeability was observed with varying confining pressures and pore water pressures. The general setup for the experiment can be seen in *Fig. 2.3*. As shown a pneumatic air compressor was used to apply a confining load onto the sample while a water inflow and outflow allowed for the control in pore pressure. An applied pressure of 100, 200, and 400 kPa onto the soil was implemented for this study in the drained condition and the hydraulic conductivity was observed after no more settlement was observed. Once confined the top cap was fixed to prevent any additional vertical movement of the top cap. The pore pressures were continually increased until a dramatic increase in the permeability (i.e. the breakdown pressure) was observed.
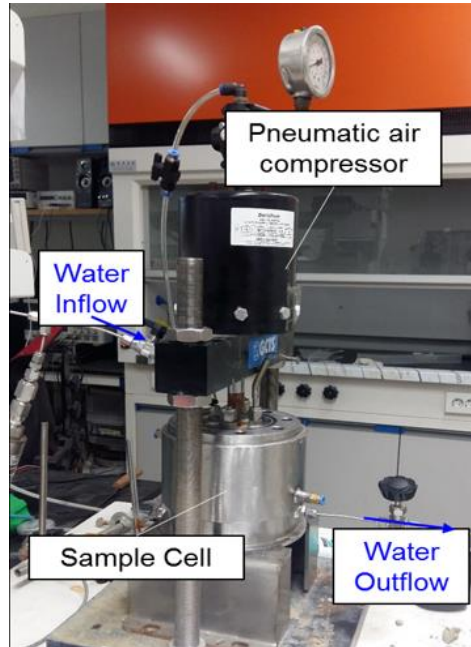
Fig. 2.3 Hydraulic conductivity experimental test setup

Soil consolidation / Elastic wave measurements

Soil consolidation tests were performed according the ASTM D 2435 testing method [77]. Additionally, p-wave and s-wave sensors were attached to the top and bottom locations of the consolidation mold for elastic wave measurements. The one dimensional loading was performed at 50 kPa, 100 kPa, 200 kPa, and 400 kPa increments. The loadings were performed until no further consolidation was observed. After each step of consolidation was finished the elastic wave measurements were performed. The experimental setup is shown in *Fig. 2.4*.
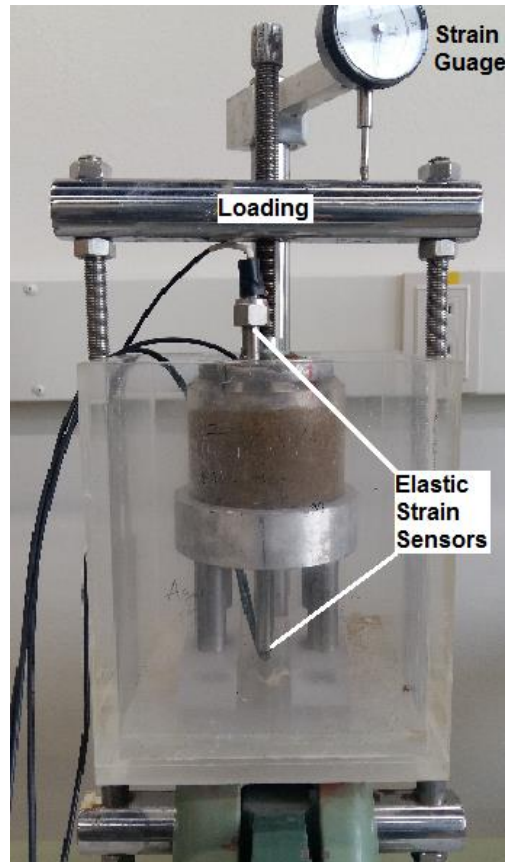
Fig. 2.4 Consolidation / Elastic wave measurement test setup

<u>*SEM (Scanning Electron Microscope)*</u>

SEM images were taken to observe the micro-scale direct interactions between soil particles and gellan gum biopolymers. 1 % gellan gum-treated sand samples were considered by collecting 0.5 cm^3 (*i.e.*, width 10 mm × length 10 mm × height 5 mm) bulk cubic samples from dried gellan gum-soil mixtures. The samples were situated on an SEM mount (diameter 25 mm) using carbon conductive tabs (Pelco Tabs^{TM}). Carbon paint (DAG-T-502) was applied to both the undisturbed and the disturbed sample edges and bottoms to provide sufficient grounding. Specimens were coated for 20 seconds using an Osmium plasma coater (OPC-60A) with osmium tetroxide (OsO$_4$) as the source of osmium. An extreme high-resolution scanning electron microscope (FEI Magellan 400L XHR) was used to observe the surface of the gellan gum-sand samples.

Chapter 3. Strengthening Effects of Gellan Treated Soils

3.1 Unconfined Uniaxial Compression Results

For the unconfined uniaxial compression tests and direct shear tests the specimens were mixed with differing sand to clay ratios of 10:0, 5:5, 8:2, and 0:10 ratios respectively. The gellan concentrations were set at 0%, 0.5%, 1.0%, 2.0%, and 5.0% to the weight of the sand or clay content.

Strengthening effects of gellan on uniaxial compression

In *Fig. 3.1* the effects of gellan concentrations on uniaxial compressive strength for pure sands can be observed. As can be seen, the overall strength of the samples tend to increase with an increase in gellan concentration. However, the increase in strength is not linear and shows a tendency to level off at gellan concentrations above 2.0%. This shows that there is an optimal strengthening efficiency of gellan gum and that the continual addition of gellan gum biopolymers will not have the desired strengthening effects. From *Fig. 3.1* it can be approximated that the optimal point of gellan concentration will be somewhere between 3.0 to 4.0 percent.
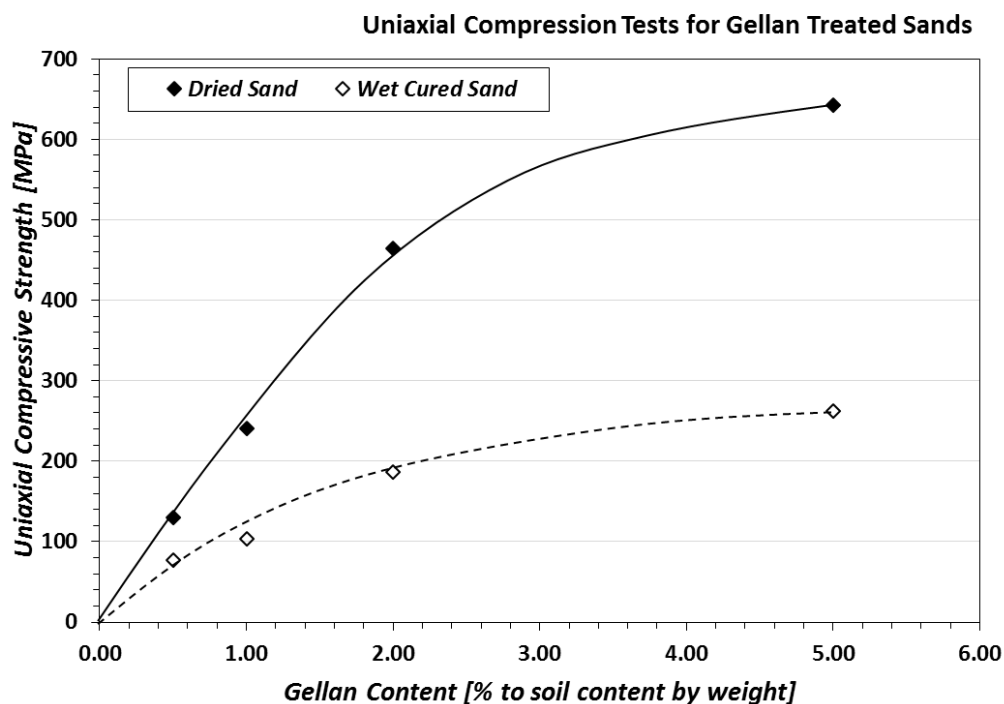
Fig. 3.1 Strengthening efficiencies of gellan gum biopolymer on Jumunjin sand

Additionally, it was observed that the dry specimens had a much larger overall strength than that of the wet specimens. This is most likely due to the densification and increase in stiffness of the gellan gels within the pores of the treated sand. In comparison with pure sand samples, the specimens with clay content showed a high correlation between the strength of the specimens to the content of clay particles (*Fig. 3.2*).
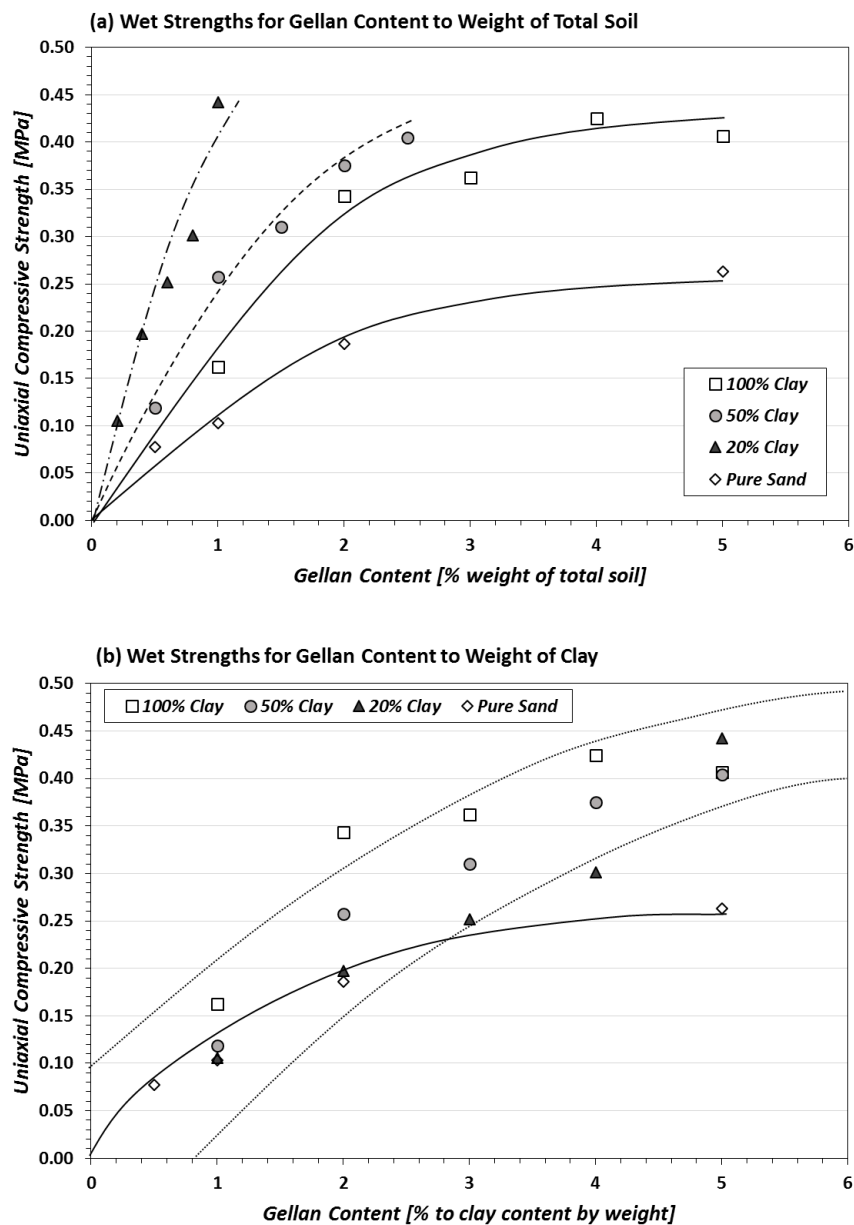
Fig. 3.2 Unconfined uniaxial compressive strengths of gellan treated soils with (a) gellan content compared to the weight of the total soil and (b) gellan content compared to the weight of only the clay content

As shown in *Fig. 3.2a*, the specimens with lower clay content (i.e. sand to clay ratio of 8:2) seem to have a much higher strengthening efficiency with only 1.0% gellan achieving similar wet strengths as 5.0% gellan for pure clay soils. However, when the specimens were plotted with gellan gum concentrations to the clay content not the total soil (i.e. 1.0% gellan for soils with sand to clay ratios of 8:2 will have the same gellan to clay ratio as 5% pure clay samples) in *Fig. 3.2b*, it was seen that all the soil types had very similar strengths with the general strengthening trends falling within a certain boundary. This showed that when in the presence of clayey soils, the strengthening efficiencies of gellan treated soils is highly dependent on the gellan to clay ratios not the gellan to total soil ratios. This effect is most likely due to the electrical charges present in clayey soils. This effect was also observed in the SEM images taken (*Fig. 3.3*).
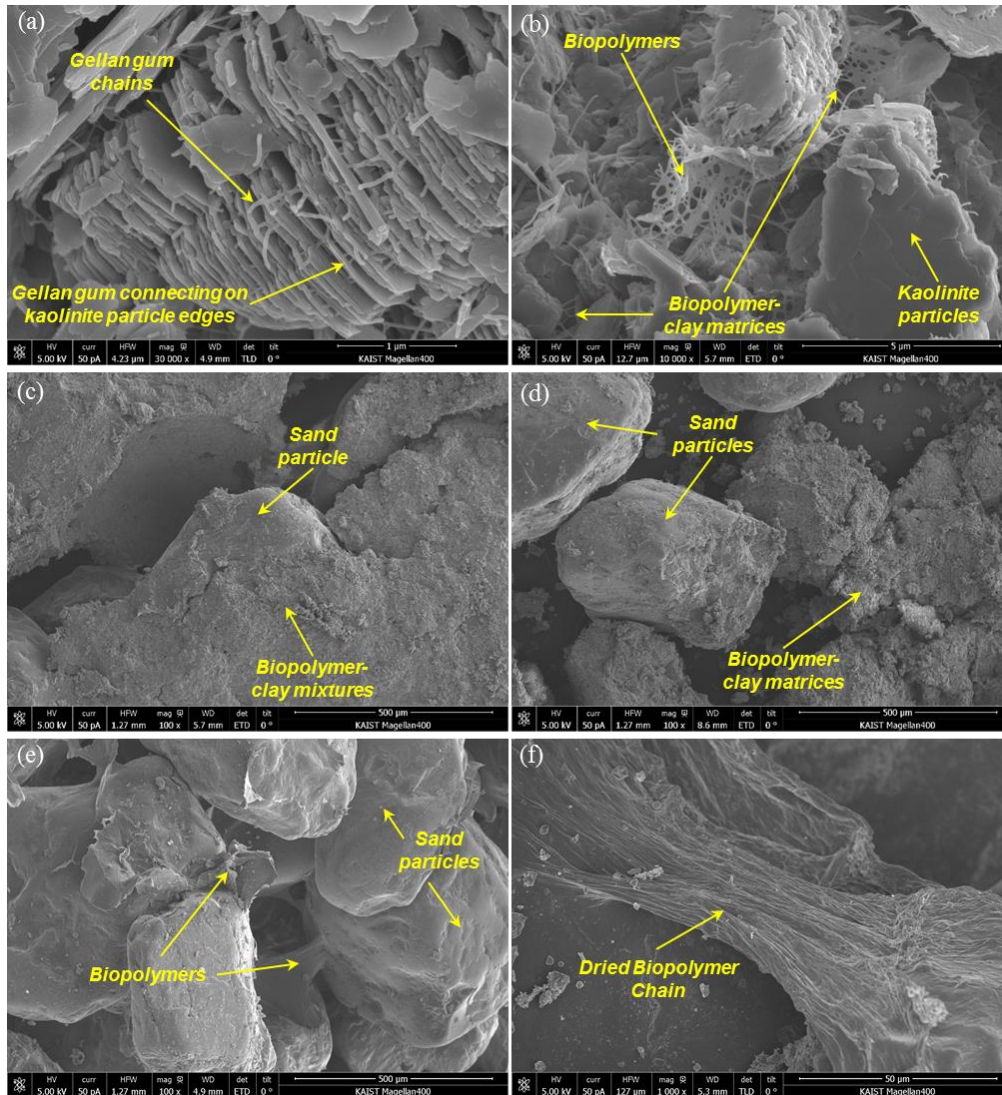
Fig. 3.3 SEM images of gellan treated soils (a & b) pure clay gellan mixtures, (b & c) gellan treated sand/clay mixtures, and (e & f) pure san gellan mixtures

From *Fig. 3.3e&f* we can see that when mixed with pure sand gellan acts as a coating agent encasing the gellan particles and providing additional connections and stronger interparticle interactions. These gellan biopolymer particles interact with each other more than they do with the sand particles forming biopolymer chains between the particles. However, when mixed with clay, unlike the pure sand mixtures, the gellan particles show a higher interaction with the clay particles than they do with other gellan particles (*Fig.3.3a&b*). Therefore, when gellan gum biopolymers are mixed with soils with clay particles *Fig. 3.3c&d* the gellan particles interact directly with the clayey soils aggregating the clay-gellan mixtures around the coarser sand particles achieving and overall binding effect without directing interacting or bonding with the sand particles.

The overall strengthening efficiencies of gellan treated soils have shown an extremely high correlation to the gellan-clay ratios, however, unlike pure sand soils where the strengthening effects level off after around 3.0 - 4.0% (*Fig. 3.1*), concentrations of gellan gum to clay above 4.0% shows a detrimental effect. This reduction in strength can be easily observed in the dry samples shown in *Fig. 3.4*.
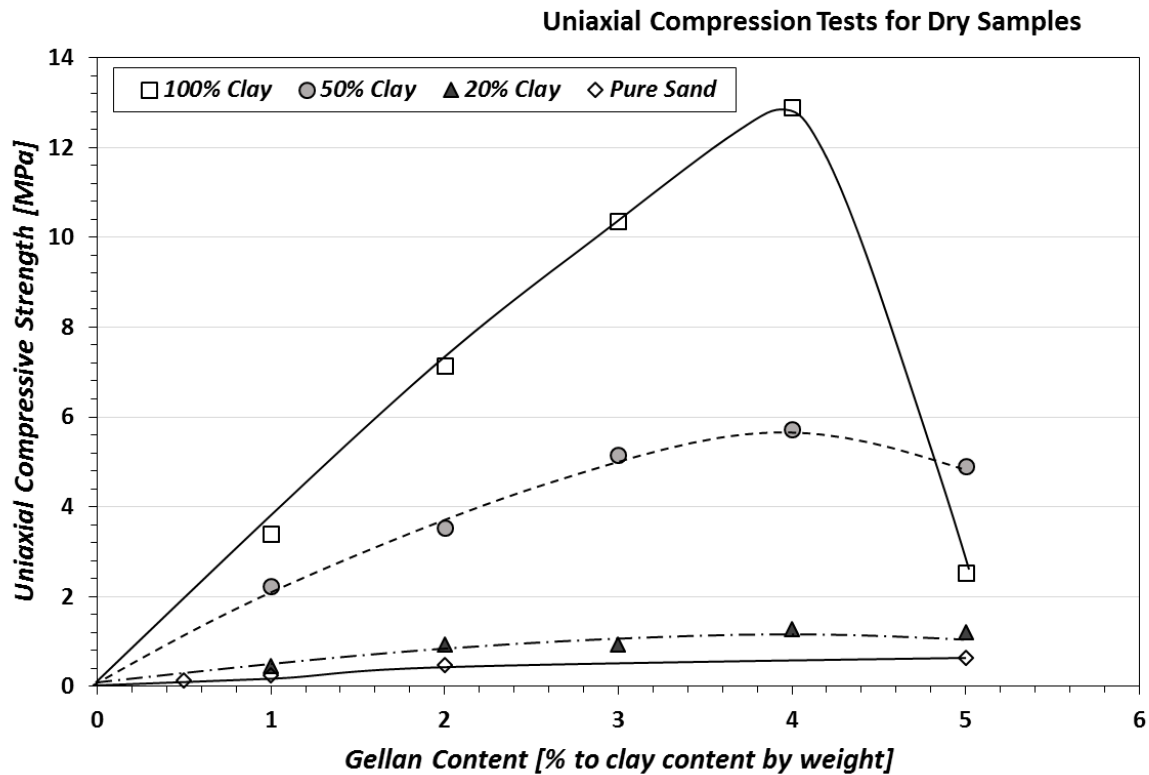

Fig. 3.4 Dry unconfined uniaxial compressive strengths of gellan gum treated sand-clay soils

This reduction in strength between the 4.0 to 5.0% gellan to clay content is most likely the result of several factors. First off, at 5.0% gellan to clay ratios the overall workability is greatly reduced by the viscosity of the mixture. With such a high viscosity the probability of air voids or the existence of weak planes is greatly enhanced. Additionally, due to the charge interactions of gellan and clay particles, rough estimates and calculations on the charge density and available ionic interactions of kaolinite show that around 4.0% gellan to kaolinite ratios may contain the maximum allowable ionic interactions of kaolinite clays. *Table 3.1* shows the approximations and variables used in this calculation.

Table 3.1. Calculations for the maximum possible ionic interactions possible for kaolinite clays and the total amount of gellan gum particles required to fill this number.

Kaolinite		Gellan gum		
Charge Density =	8.3E-19 m^2/ion	Molar Mass ≈		1,000 g/mol
Specific Surface =	20 m^2/g	# of gellan particles to equivalent ionic charge ≈		1:1
Therefore possible # of ions in 100g of Kaolinite ≈	**2.40E+21 ions**	# of gellan gum "ions" ≈	4.00%	2.41E+21 ≈ **2.40E+21**
			5.00%	3.01E+21 **> 2.40E+21**

The calculations shown in *Table 3.1* imply that any additional addition of gellan gum into kaolinite past 4.0% will not aid in the increase in strength, but it may instead result in the reduction of compressive strength (*Fig. 3.4*) due to the ionic interference caused by the excess gellan gum biopolymers. This data also implies that with different clays with different charge densities the maximum concentration of gellan gum may be altered. *Fig.3.5* shows a schematic model of the possible biopolymer interference that may result in the reduction in strength with a surplus of biopolymers.
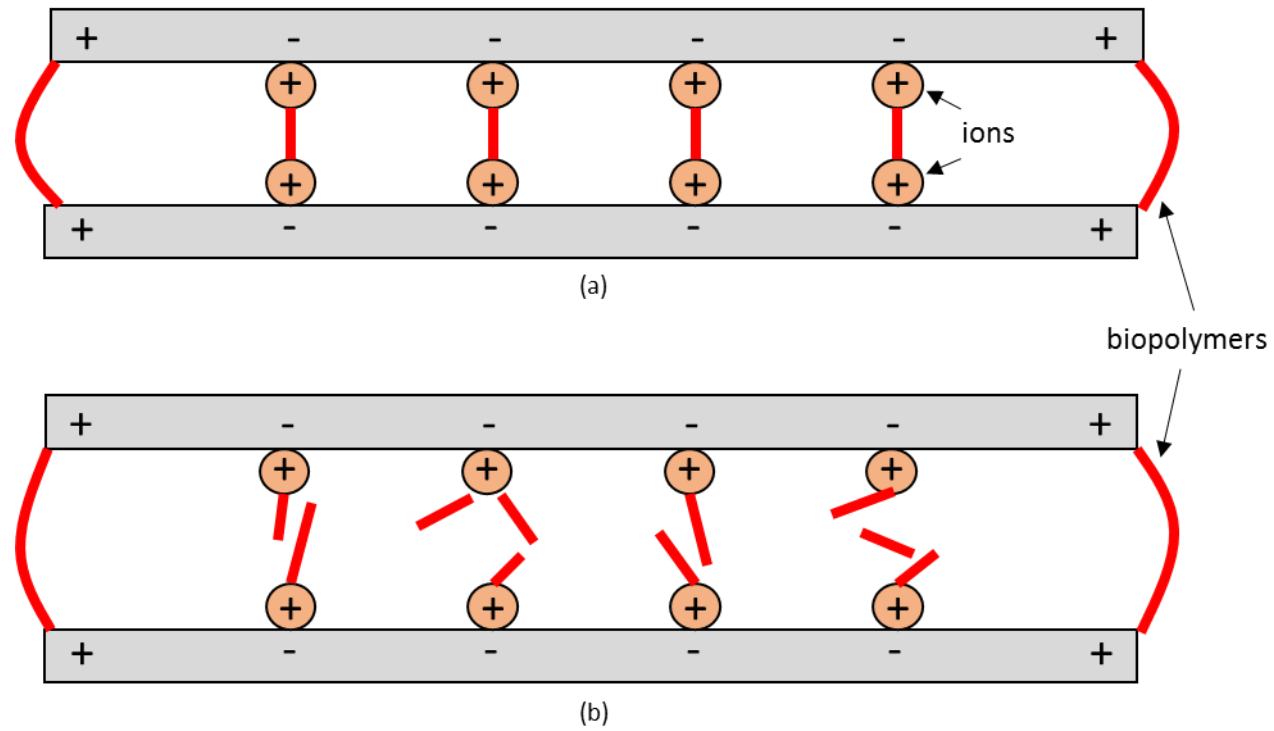
Fig.3.5 Schematic model for possible interference reaction for a surplus of electrical charge interactions

(a) 4.0% gellan to clay concentration (b) 5.0% gellan to clay concentration
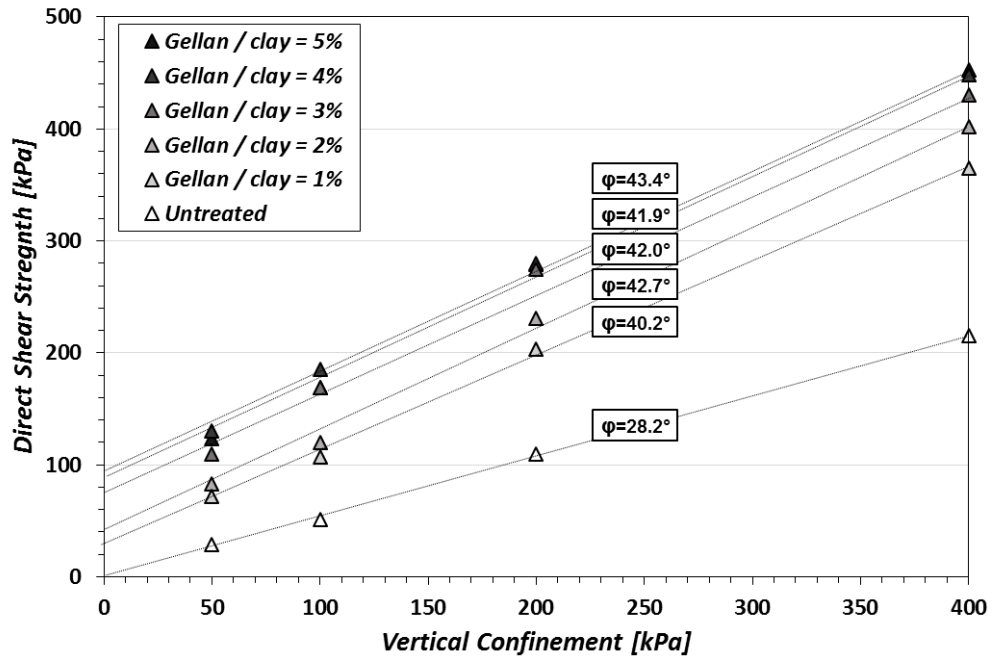
3.2 Direct Shear Results

Direct Shear Results

The direct shear results can be seen in *Fig. 3.6*. The friction angle (ϕ) of pure sand does not show a noticeable variation with the presence of gellan gum hydrogels (water content (W/C) = 30%) inside inter-granular pores, regardless of the gellan hydrogel concentration, while the inter-particle cohesion (c) increases substantially with an increase of gellan concentration (*Fig. 3.6a*). The friction angle of untreated soils decreases with decreasing sand to clay ratios (i.e., ϕ = 29.3° for pure sand → ϕ = 18.7° for pure clay), while the soils with clay show a remarkable increase of friction angle with an increases in gellan concentration as seen in *Fig. 3.6b, c, and d*. The maximum increment is found at sand to clay ratios of 8:1 (*Fig. 3.6b*). This indicates that the friction angle of the gellan gum treated soils is mainly governed by the interactions of the gellan gum – clay particles rather than gellan to total soil ratios. Meanwhile, the cohesion of gellan gum-treated soils increases consistently with increasing gellan concentrations for both gellan to clay and gellan to total soil ratios, revealing the important role of the gellan gum gel (i.e. gellan gum to water) concentration on cohesion enhancement, regardless of the soil type.

(a) Pure Sand Direct Shear
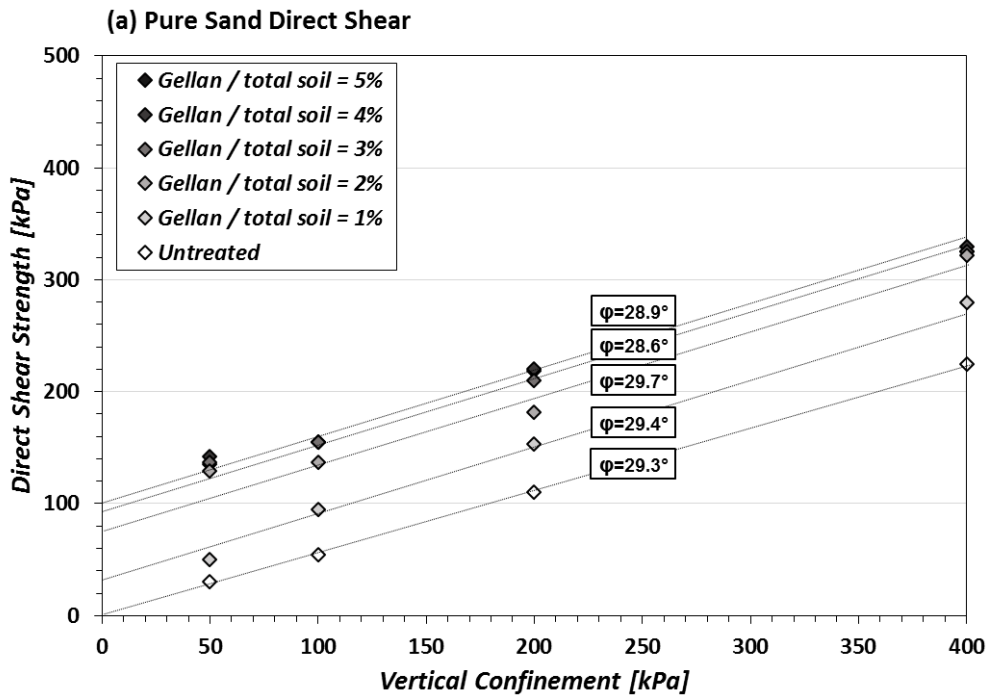
(b) 20% Clay Direct Shear

(c) 50% Clay Direct Shear
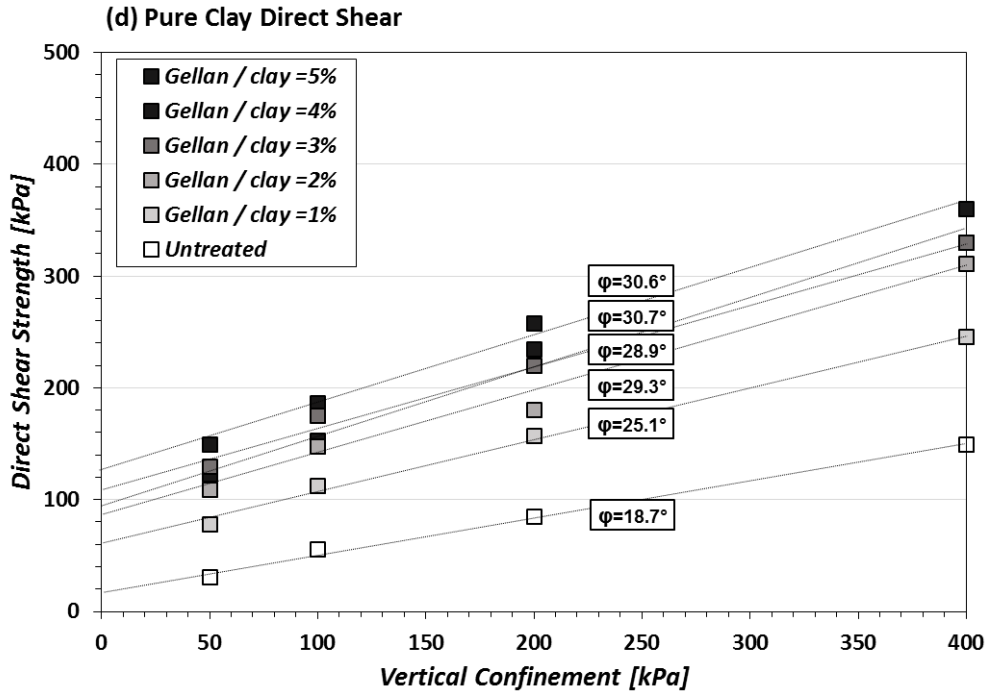
(d) Pure Clay Direct Shear
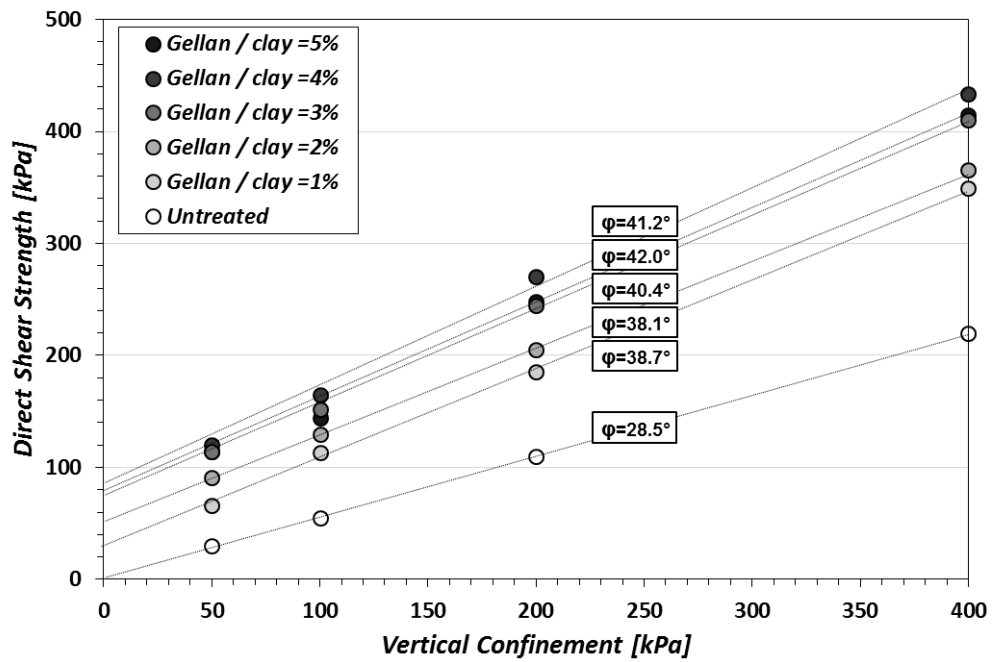
Fig. 3.6 Direct Shear results for gellan gum-treated soils on the $\sigma - \tau_f$ plane

Increases in cohesion and friction angle with gellan treatment

With regards to the increasing trends of cohesion and friction angle of the soil when compared to the gellan content of the total weight (*Fig. 3.7*), a general increase in both cohesion for all soil types are observed while increases in friction angle are only present in soils with clayey soils. Overall, the increase in cohesion seems to follow a general trend converging at higher gellan concentrations. The increase in cohesion is attributed to the increase in the interparticle connections which is present in all soil types. The friction angle however does not increase for all soil types. The pure sand is the only soil type that did not exhibit any increases in friction angle with an increase in gellan concentrations. Instead the pure sand soils exhibited nearly no changes in the friction angle with changes in the gellan concentrations. On the other hand all of the soils containing clayey soils had a dramatic increase in friction angle with a small addition of gellan gum biopolymers and subsequent increase in friction angle with higher concentrations of gellan. Additionally, the soils containing sand particles had a higher untreated friction angle due to the presence of granular soils (i.e. sand) while the pure clay had an extremely low untreated friction angle due to the nature of clay soils. The increase in friction angle

with increases in gellan concentrations with the presence of clay particles is due to the high electrical interactions between the gellan gum biopolymers and clay particles. These interactions allow for the coagulation of clay particles into a larger whole acting like a larger granular soil particle allowing for an increase in friction angle.

(a) Cohesion
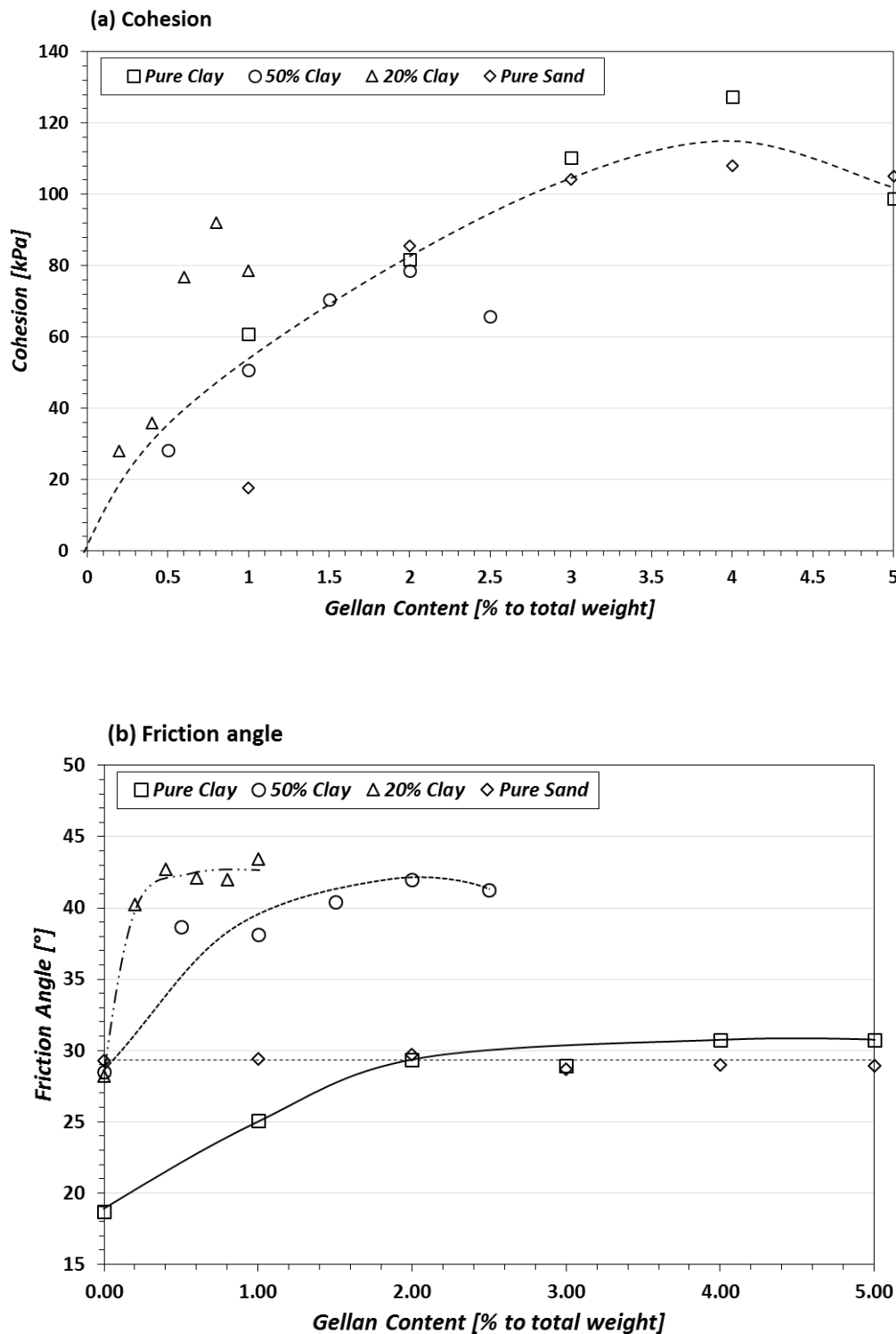
(b) Friction angle

Fig. 3.7 (a) Cohesion and (b) Friction angle of gellan gum treated soils with changes in gellan concentrations

When the cohesion and friction angle of the clayey soils were plotted against the gellan content to the clay weight (*Fig. 3.8*), several other points were observed. Firstly, the cohesion of the clayey samples (*Fig. 3.8a*) seemed to show a similar trend to that of the uniaxial compressive strengths in that after 4.0% gellan to clay content the strength diminishes.

(a) Cohesion
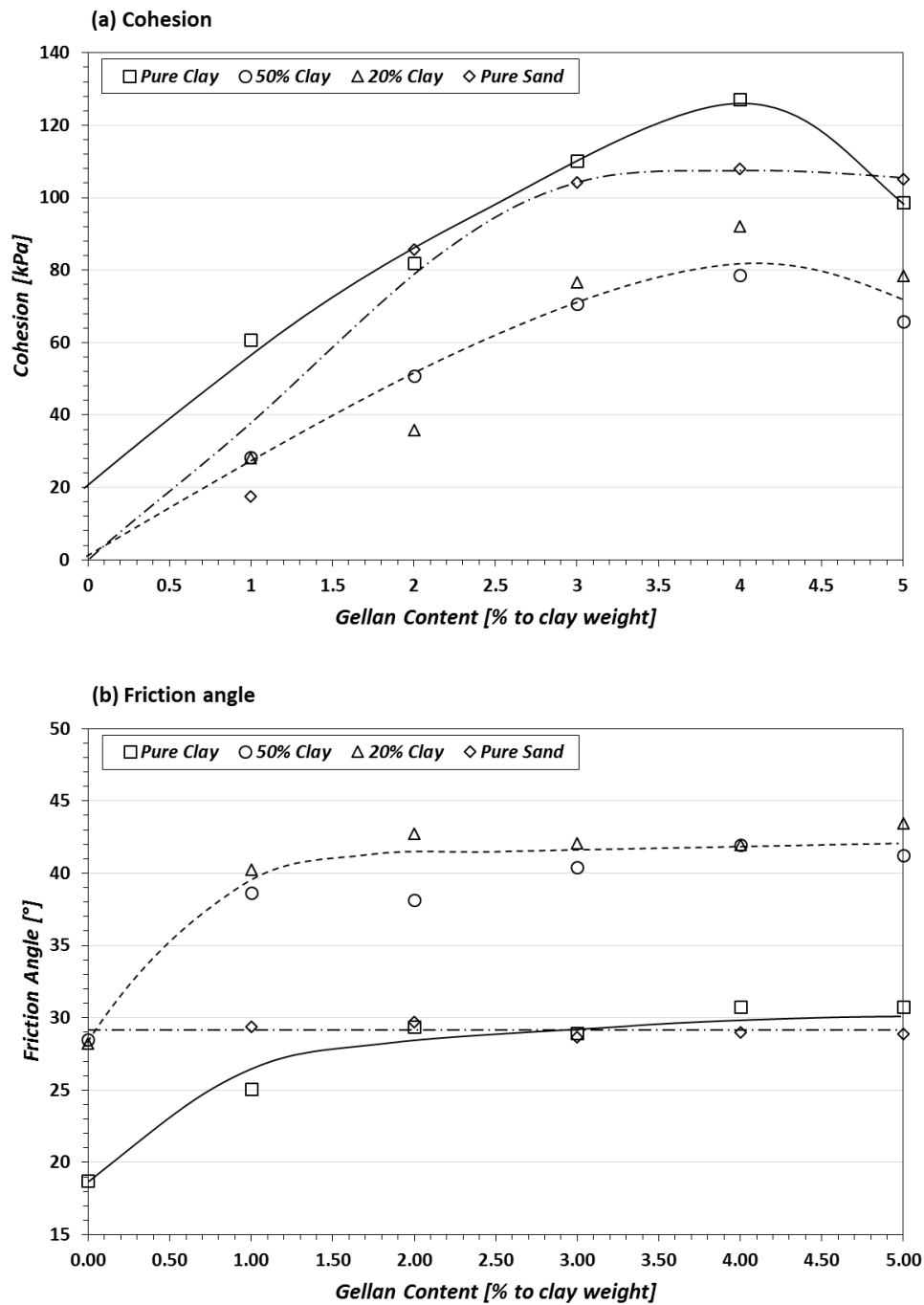
(b) Friction angle

Fig. 3.8 (a) Cohesion and (b) Friction angle plotted against gellan to clay ratios

The friction angle on the other hand (*Fig. 3.8b*), has a dramatic increase with the initial addition of gellan gum at 1.0% to clay ratio, and a gradual increase with an increase in gellan content.

The increase in the friction angle of the clayey soils is attributed to the increase in dilation of the soil. The soil dilations are shown in *Fig. 3.9*. As shown the large amounts of gellan treatment induce larger dilations. These dilations are caused by the aggregation of the clay particles giving it a frictional resistance that is shown in the direct shear results.
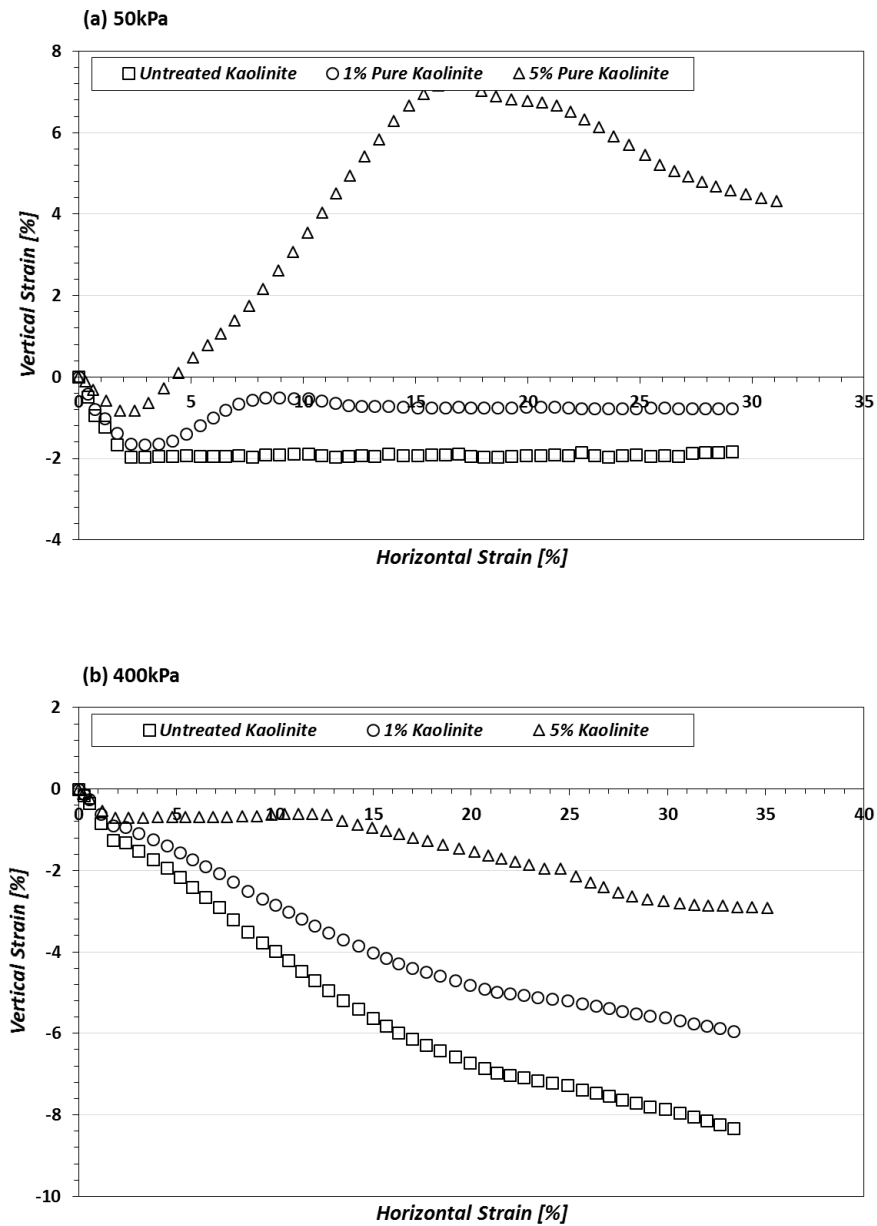

Fig. 3.9 Dilation effects of gellan treatment on kaolinite at (a) 50 kPa and (b) 400 kPa
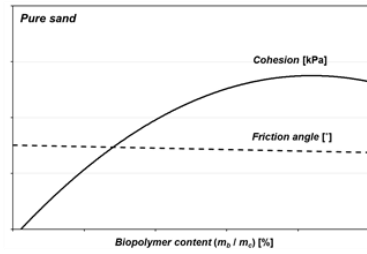
3.3 Analysis and Discussion

From the results of the unconfined uniaxial compressive tests and direct shear tests, it was found that the higher concentrations of gellan gum biopolymer did in-fact increase the overall strength. However, it was also found that the strengthening parameters of the soil was highly dependent on the clay content of the soil, or more specifically the biopolymer to clay content. An increase in strength was seen with a biopolymer to clay ratio of up to 4.0%, but further increases in biopolymer to clay ratios showed a detrimental effect to the overall strength of the soils. The reasons for this behavior has been assumed to be related to the charge density of the clay, but no conclusive evidence has been seen for this hypothesis.

The direct shear results showed us that the addition of gellan gum biopolymers into the soil increased the cohesive properties of all types of soils. While for clay soils, the presence of gellan gum showed dramatic increases in the friction angle, most likely due to the coagulation of the clay particles. These effects are demonstrated in *Fig. 3.9*. As shown in *Fig. 3.9a*, the gellan gum biopolymers only encompass the sand particles without directly bonding with the surface. The biopolymers fill the pore spaces increasing the interparticle connections and stiffness which increase the cohesion of the sand particles. The clay particles on the other hand was shown to be capable of directly interacting with the biopolymers (*Fig.3.3a&b*). Therefore when the clay particles interact with the biopolymers a structure similar to that of *Fig. 3.9c* will take hold. Due to the higher interactions between the clay particles and the gellan biopolymers, when gellan gum is mixed into the sand-clay soil mixtures, the gellan gum biopolymers only interact with the clay particles to form a rigid mortar like binder that encompasses the sand particles (*Fig. 3.9b*). This rigid structure when sheared will form larger structures that induce an increase in friction angle as shown in *Fig. 3.9b*. Therefore in the presence of clay particles, the strengthening agent should not be considered to be solely the gellan gum biopolymer, but the gellan-clay mixtures within the soil. Overall, the presence of gellan gum biopolymers seem to induce clay like properties to sand particles by providing cohesive strengths and sand like properties to clay particles by increasing the friction angle of the soil. The key findings for the strengthening effects of gellan gum on sand and clay soils is summarized in *Table. 3.2*.

Table 3.2. Summary of the Key Findings for the strengthening efficiencies of gellan treated soils.

	Key Findings
Uniaxial Compressive Tests	• Increase in strength with an increase in gellan concentration • Strengthening efficiencies are highly dependent on the biopolymer to clay content • Direct electrical interactions between clay particles and biopolymers were observed • Biopolymers envelope sand particles but does not have direct interactions with sand • Increase in interparticle connections improve compressive strengths • Decrease in strength was observed after 4.0% gellan to clay ratios
Direct Shear Tests	• Increase in cohesion with an increase in biopolymer content • No major change in friction angle for pure sand soils • Dramatic increase in friction angle with the introduction of gellan into clayey soils • Subsequent increases in friction angle with increases in gellan concentration for clayey soils • Decrease in cohesion was observed after 4.0% gellan to clay ratios
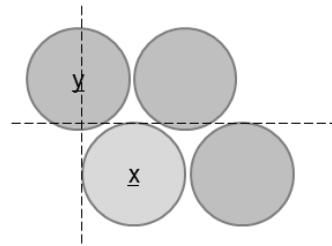
Constant ϕ and c variation   Untreated sand at rest   Gellan gum-treated sand   Gellan gum-treated sand at shear
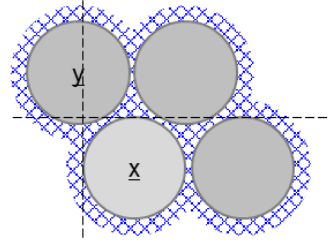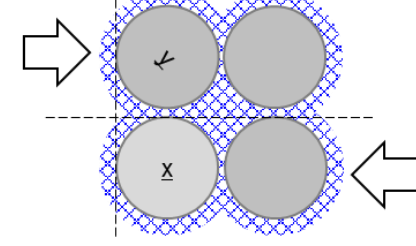
(a) Pure sand
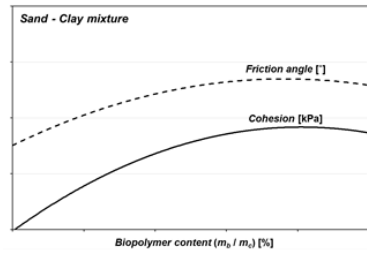
Both ϕ and c increase   Untreated soil at rest   Gellan gum-treated soil   Gellan gum treated soil at shear

(b) Sand – clay mixture

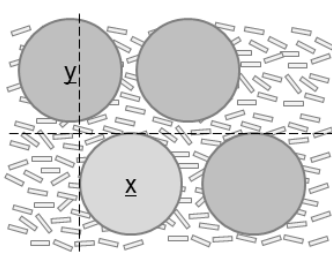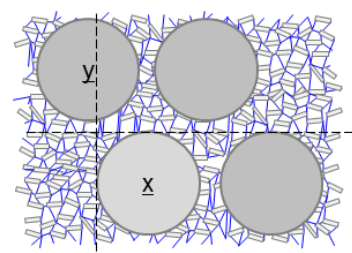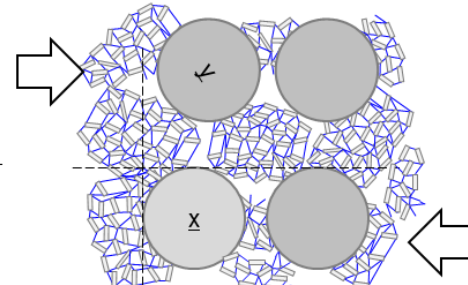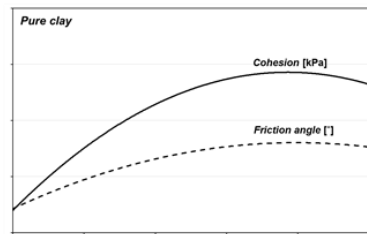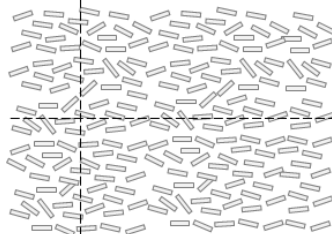Both ϕ and c increase   Untreated clay at rest   Gellan gum-treated clay   Gellan gum treated clay at shear
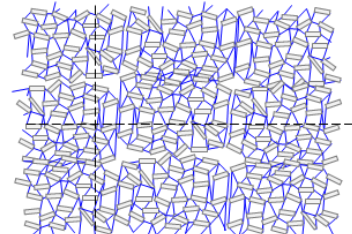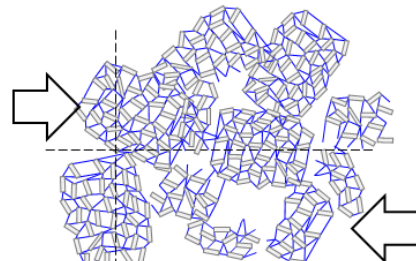
(c) Pure clay

Fig. 3.10 Schematic model of the microstructure of gellan gum treated soils

Chapter 4. Hydraulic Effects of Gellan Treated Soils

4.1 Hydraulic Conductivity

For the hydraulic conductivity tests, for the ease of measurements, two types of soil were used. The first is the previously used jumunjin standard sand of S. Korea, and the second is Saemangeum site soil (size distribution curve shown in *Fig. 4.1*). The Saemangeum site soil was used due to the difficulties in measuring the permeability of pure clays and to represent real site conditions for construction. The Saemangeum soil had approximately 20% of fines which were found to be mostly clay in nature, and this soil was chosen to represent the soils containing fine clays in this portion of the study.

Fig. 4.1 Particle size distribution of Saemangeum soil

Bio-clogging effects

Results of the changes in the hydraulic conductivity with an increase in gellan content is shown in *Fig. 4.2*. As seen the hydraulic conductivity of the soil drops down to a final permeability of approximately 1×10^{-8} cm/s with an increase in gellan regardless of the soil type used. Although the final hydraulic conductivity is the same for both the jumunjin sand and saemangeum soil, due to the fine soils in the saemangeum soil, the hydraulic conductivity of gellan treated saemangeum soil drops down faster and reaches 1×10^{-8} cm/s slightly quicker than gellan treated jumunjin sand. The saeman-

geum soil reaches the final permeability mark around 1.0% gellan concentrations, but jumunjin sand reaches this mark at approximately 1.5% gellan concentrations. This indicates that although the soil type may affect the hydraulic conductivity before the 1.5% gellan content mark, after this the type of soil becomes negligible due the hydraulic conductivity being almost completely dependent on the bio-clogging effects of gellan gum. The point at which the permeability levels off to this finial permeability mark is the point at which the pore spaces in the soil are fully filled with the gellan biopolymer creating a full bio-clogging effect. At the lower concentrations (i.e. before the final permeability mark (0.5% gellan)), the pore spaces are not fully occupied by the gellan biopolymers and as such have a higher permeability.
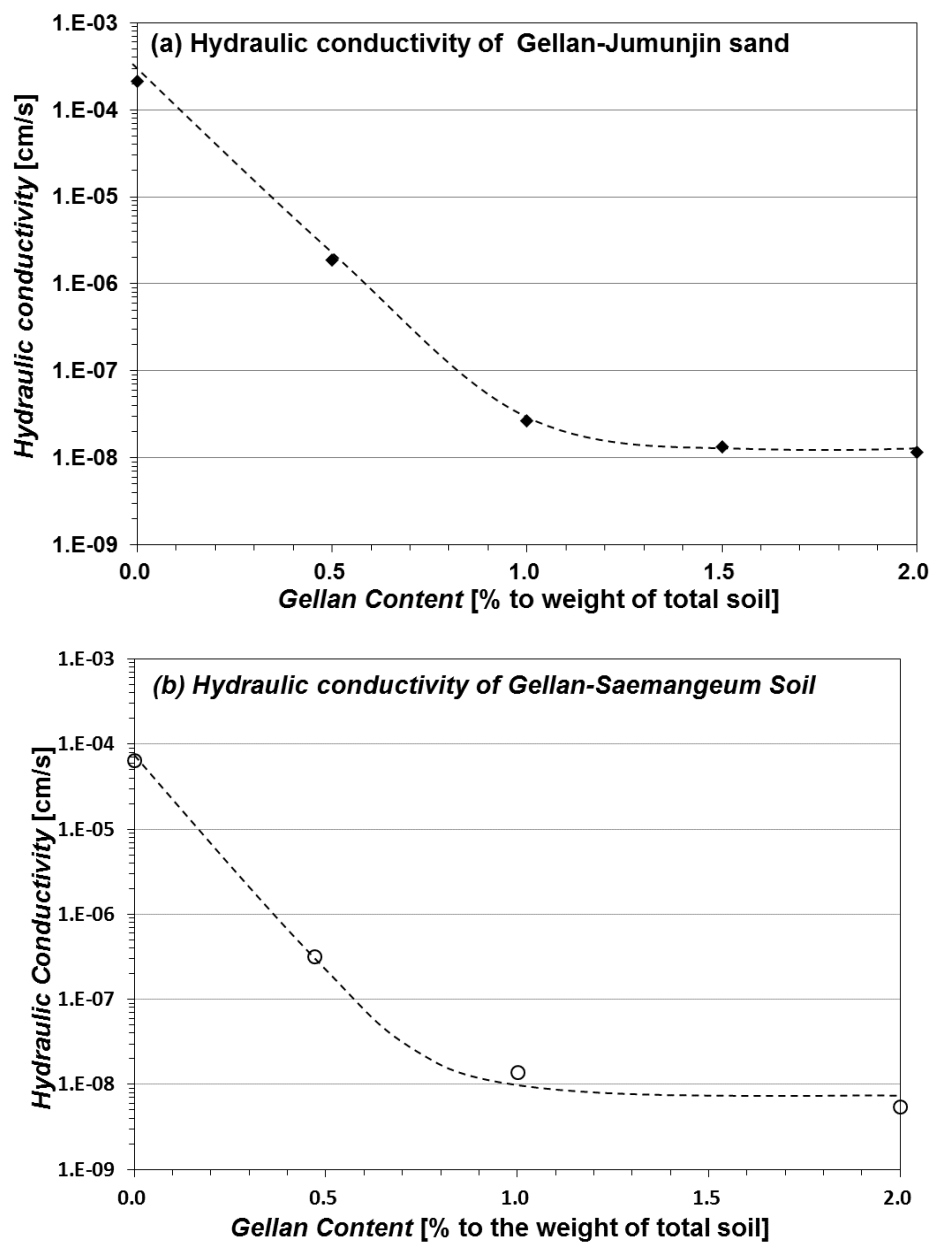
Fig. 4.2 Changes to the hydraulic conductivity with an increase in gellan content for

(a) Jumunjin sand (b) Saemangeum soil

When we observe the changes in the hydraulic conductivity due to an increase in the effective stress (*Fig. 4.3*) it can be seen that there is not significant change. However, although the change in permeability is small it was seen that the gellan treated jumunjin sands had a larger decrease in permeability than the gellan treated saemangeum soils. This difference is a result of the difference in the internal structure of the gellan within the voids of the soils. For gellan treated jumunjin sand, the internal structure is similar to *Fig. 3.9a* while the internal structure of gellan treated saemangeum soil is similar to that of *Fig. 3.9b*. As mentioned in chapter 3, with the presence of clay particles the gellan clay mixtures form a more rigid structure, and with a higher stiffness the effects of confinement on the permeability will be reduced as shown in *Fig. 4.3b*.
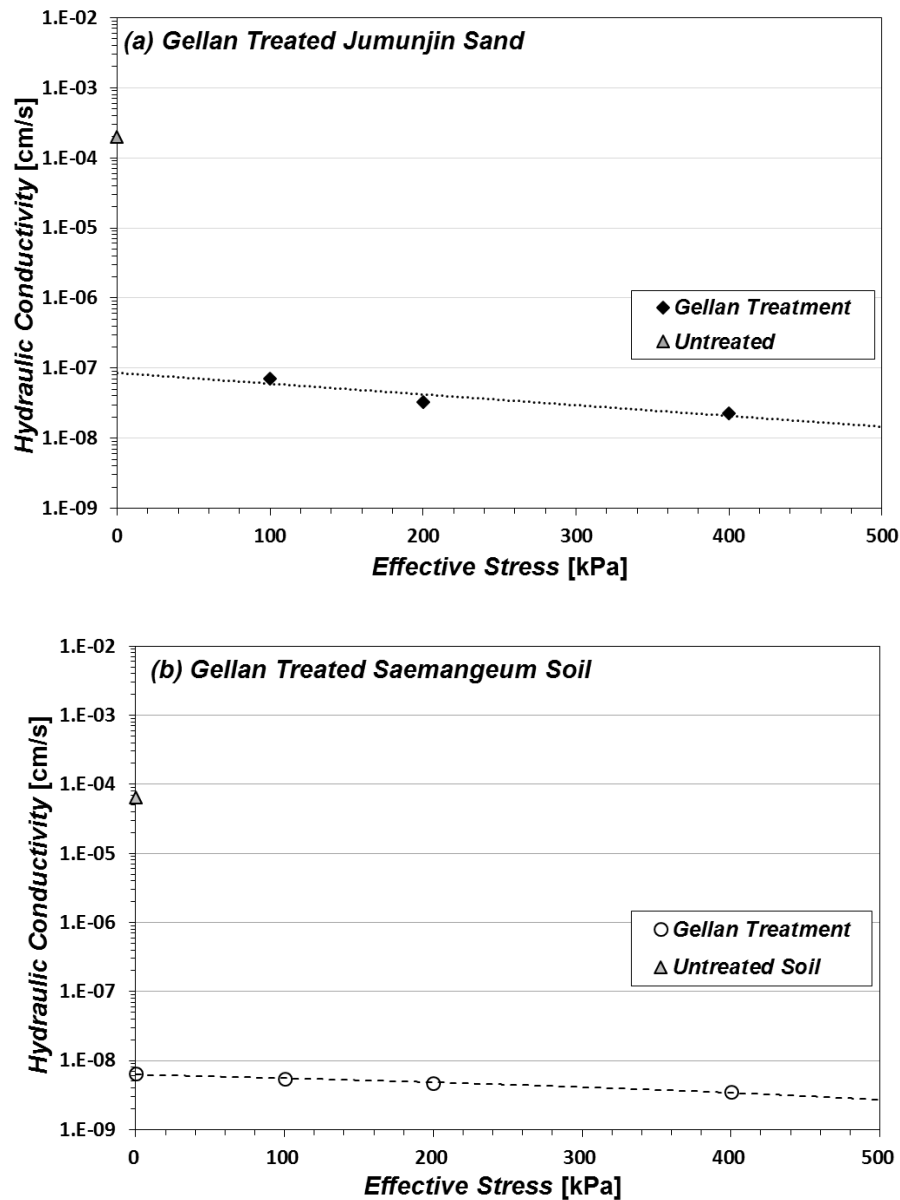
Fig. 4.3 Changes in the hydraulic conductivity with an increase in effective stress for

(a) Jumunjin sand (b) Saemangeum soil

Changes in the hydraulic conductivity with an increase in the pore pressures are shown in *Fig. 4.4*. As can be seen, the behaviors of gellan treated soils greatly differed with an increase in the pore pressure. This is once again the result of the structural differences between gellan treated sand and gellan treated soils with clay particles shown in *Fig. 3.9*.
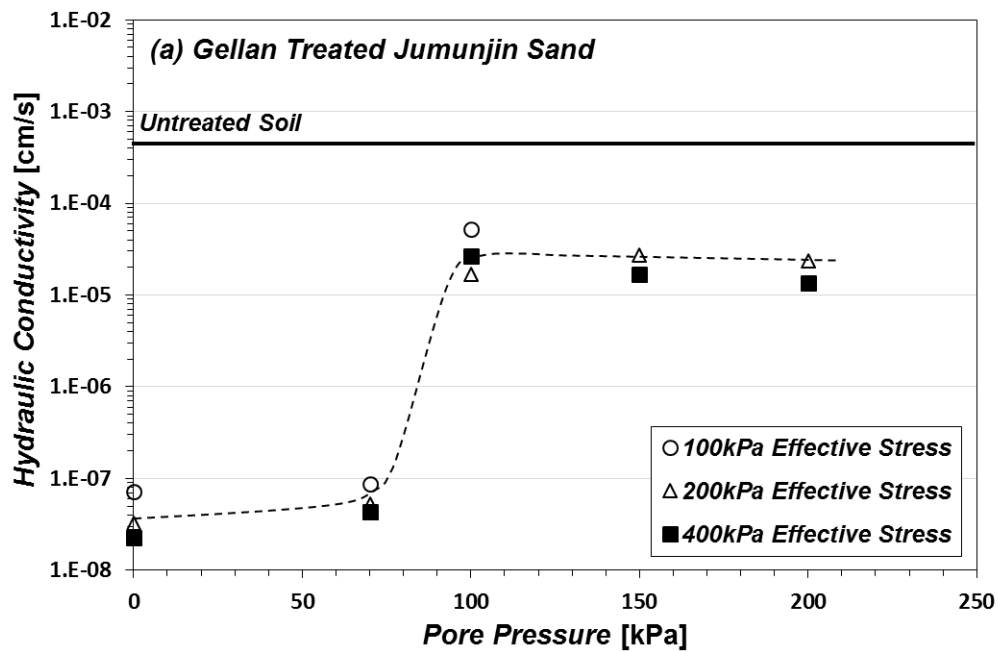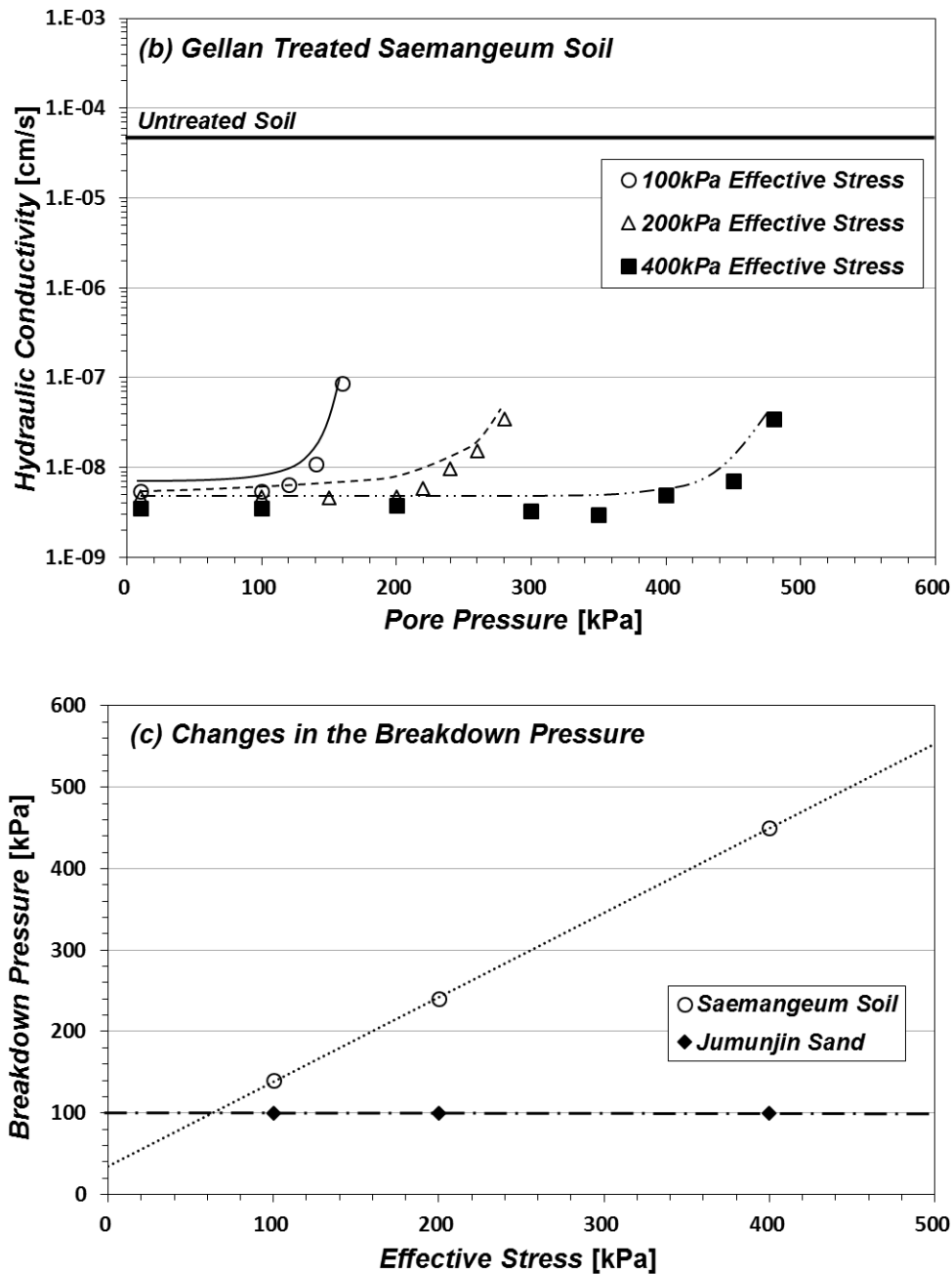
Fig. 4.4 Changes in the hydraulic conductivity with changes in the pore pressure of (a) Jumunjin sand
(b) Saemangeum soil and (c) Breakdown pressure of the soils

For the gellan treated jumunjin sands (*Fig. 4.4a*), the hydraulic conductivity of the soil remained constant until when pore pressure of 100 kPa was applied onto the soil, at which point the hydraulic conductivity was greatly increased. This increase in the hydraulic conductivity is due to the breakdown pressures of the soil. However, since the path of water flows through the void spaces in the soil structure and the voids in the pure sand samples are filled with a pure gellan gel structure, the strength of this breakdown pressure has a very close correlation with the strength of the gel itself. This can be observed when comparing the breakdown pressure to the strength of the pure gel shown in *Fig. 4.5*.
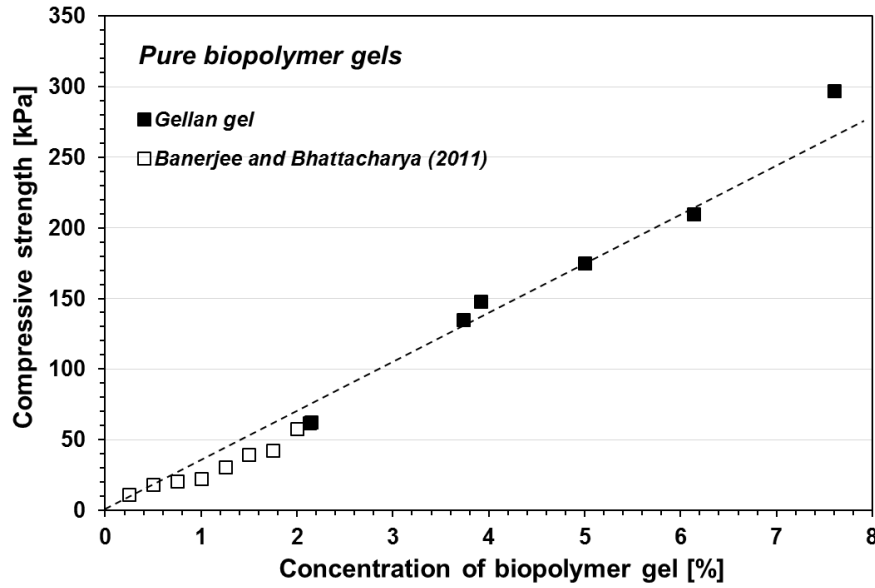
Fig. 4.5 Strength of pure gellan gels (data used from Banerjee and Bhattacharya 2011) [78]

The gellan-jumunjin mixture was composed of 1.0% gellan to jumunjin weight and 30% water content. Therefore, the gellan concentration in the gel will have been 3.33% to the weight of the water. When we take the compressive strength obtained in *Fig. 4.5* at 3.33% the compressive strength comes out to be approximately 120 kPa. Since the compressive strength of polymer based materials is around 20% higher than the tensile strength [79], the tensile strength of gellan gum biopolymer at 3.33% can be approximated to 100 kPa. Since the breakdown pressure will be the result of tensile failure, it can be seen that the breakdown pressure for gellan sands is mostly dependent on the tensile strength of the gellan gels. Additionally, the breakdown pressure was the same for all effective stresses (*Fig. 4.4c*). Assuming that the settlement observed when an effective stress was applied on the gellan sand mixture was a result of the expulsion of water from the gellan gels, the increase in gellan concentration in the gellan gel was negligible. As such, there would be no changes in the tensile strength of the gellan gels resulting in not changes in the breakdown pressures of gellan treated pure sands at different effective stresses.

For the saemangeum soils the breakdown pressure was seen to increase almost linearly with an increase in the effective stress (*Fig. 4.4b&c*). Unlike the pure sands, the void spaces are not only filled with gellan gels for the saemangeum soils. Due to the high interactions between the clay particles and the gellan gum biopolymers, the voids are filled with a rigid gellan-clay structure, and as shown in *Fig. 3.9*, both the cohesion and friction angle of gellan clays mixtures increase with an increase in confinement. Therefore, it can be said that an increase in effective stress has an increase in the strength of the gellan-clay mixtures within the voids of the coarse grained soils, which is observed in *Fig. 4.4c*.

From the results, it was seen that the saemangeum soil was capable of withstanding pressures around 40 kPa higher than the effective stress on the soil.

4.2 Cyclic Wetting / Drying Behavior

For the cyclic wetting and drying behavior, the unconfined uniaxial compressive strengths of gellan treated sands were observed. The samples were prepared at gellan concentrations to the weight of the soil at 0.5, 1.0, and 2.0%. Due to only using pure sand for this portion of the study all gellan concentrations discussed will be the gellan concentration to the weight of sand. The samples were observed at two different moisture conditions: fully saturated and air dried. Immediately after mixing, once the samples were cooled down to room temperature the first test was performed. This condition immediately after mixing was called the initial condition. After the samples were made they were left to air dry at 24°C until fully dried to represent the dried conditions. Once dried the samples were once again submerged in water to achieve full saturation in 24 hrs (wet condition). Ten of such drying and wetting cycles were performed, and the compressive strengths along with the changes in density and volume were observed at each step.

Changes in the compressive strength and stiffness with cyclic wetting and drying

The unconfined compressive strength and stiffness variations of gellan gum-treated sands at each cycle (*Fig. 4.6*) show that the maximum unconfined compressive strength and stiffness (E_{50}) of the dried samples deteriorated nearly linearly (*Figs. 4.6a&b*), while the wet samples show a relatively large reduction compared to the strength of the initial condition (i.e., wet mixtures before primary drying) and leveled off after a certain number of cycles (*Fig. 4.6c*).

With the wet strength, the .5% gellan treated sands reached the residual strength of 14 kPa after the 1st drying and wetting cycle, while 1% and 2% sands reached this residual strength at approximately the 5th and 10th cycle, respectively. The E_{50} of the wet samples (*Fig. 4.6d*) showed relatively constant values for 0.5 and 1% sands, while 2% samples converged with the other two gellan concentrations at around the 8th to 10th cycle.

(a) Dry gellan gum-sand mixtures

(b) Dry gellan gum-sand mixtures
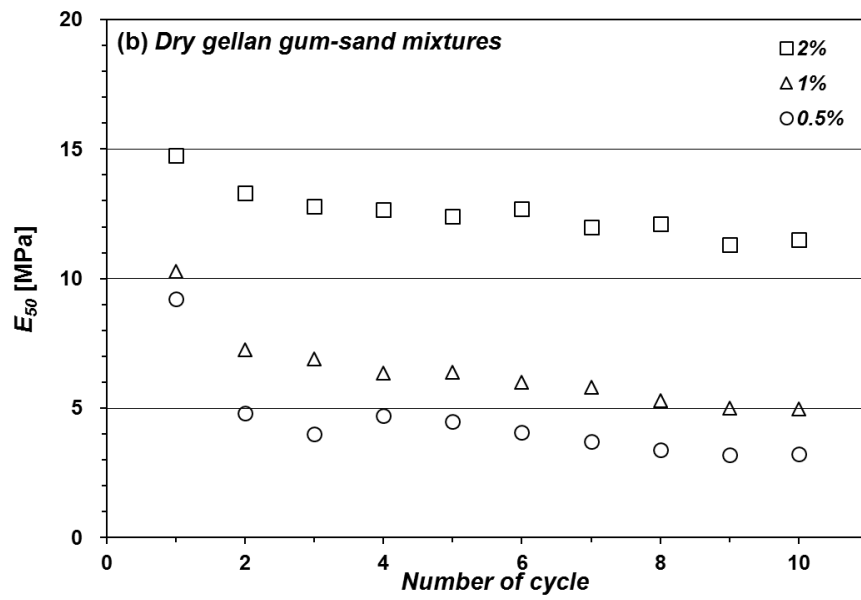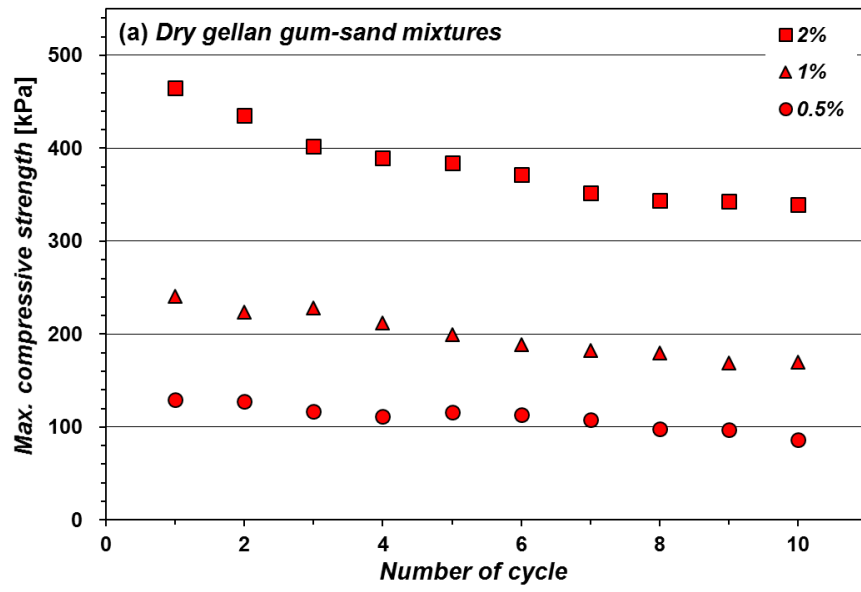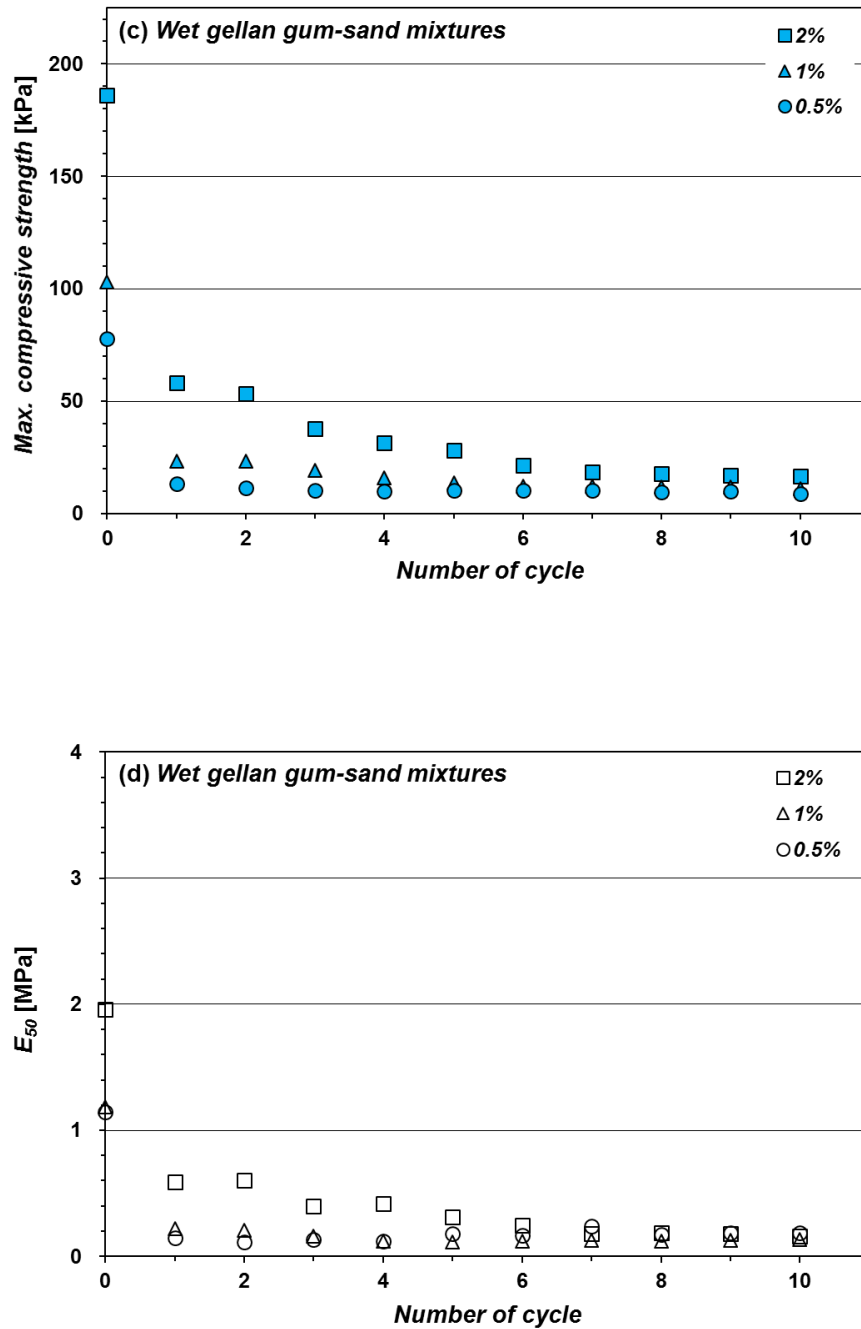
Fig. 4.6 Compressive strength and stiffness of gellan treated sands with an
increase in wetting and drying cycles

Overall, higher gellan gum concentrations provide larger wet strength resistance against strength deterioration. Meanwhile, even though dry samples show similar linear reductions, higher gellan concentrations induce a larger amount of strength deterioration. Further linear extrapolations of the strength deterioration of dried gellan gum-treated sands (*Fig. 4.6a*) converge to a single point approximately at the 35th cycle where the compressive strength becomes zero, regardless of the gellan concentration to the mass of the soil, which implies the artificial cohesion provided by gellan gum bi-

opolymers to cohesionless sands remains effective up to 35th cycle of wetting and drying regardless of biopolymer to soil concentrations.

Changes in the volume and dry density with cyclic wetting and drying

Series of volumetric strain and accompanying dry density variations of gellan gum-treated sands under wetting and drying cycles are summarized in *Fig. 4.7*. Instant volumetric strain (i.e., volume difference between subsequent wetting and drying cycles) variations (*Fig. 4.7a*) generally show volumetric shrinkage along drying, while volumetric expansion occurs with wetting due to the water adsorption characteristic of the gellan gum biopolymer. Higher biopolymer concentrations render larger variations in volumetric strain, where 0.5% gellan sands showed the lowest volume deviation (i.e., less than 5%) between adjacent wetting and drying cycles.
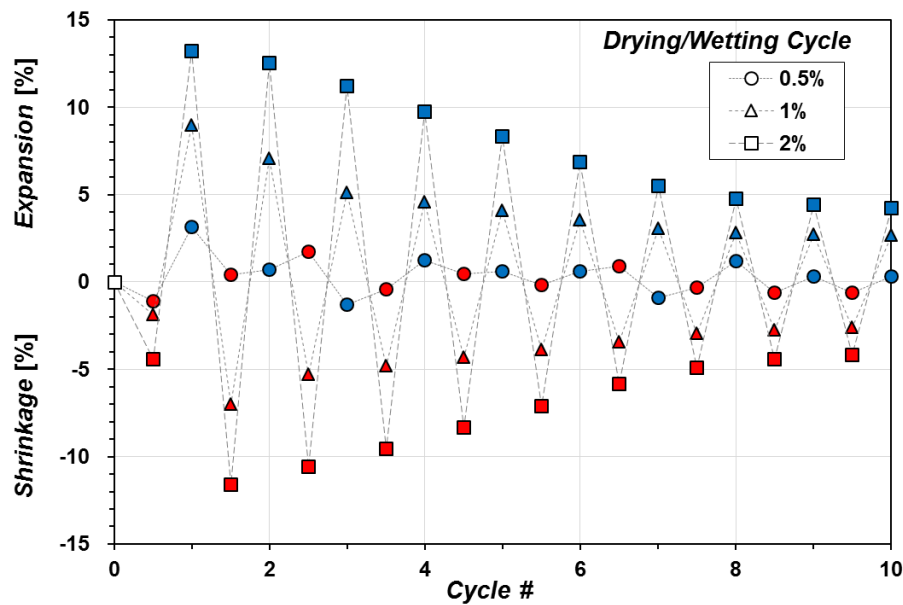
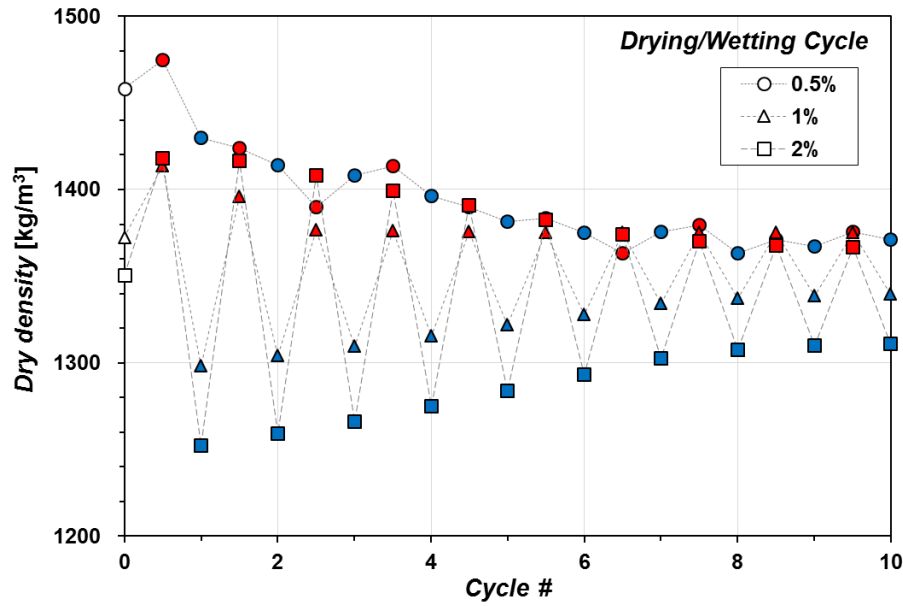*Fig. 4.7 Volumetric and dry density of gellan treated sands with*
an increase in wetting and drying cycles

The permeability results show that approximately 1 - 1.5% is the optimal condition for gel-type biopolymers to fully fill the pore spaces of sand with their hydrogels, while at lower concentrations such as 0.5% pores are not fully filled, even when fully saturated in water, due to the shortage of water adsorption matter (i.e., gellan gum). The dry density variation of gellan gum-treated sands (*Fig. 4.7b*) shows that higher gellan gum concentrations render lower initial dry density due to the incompressible gellan gum hydrogels that fill pore spaces between sand particles. However, the overall dry density (median point between wet and dried points for the same cycle number) of gellan gum-treated sands diminishes with wetting and drying cycles, while it tends to converge to a certain value after the 6th cycle, like the compressive strength of re-wetted samples. Meanwhile, deviations between dried and wet conditions decrease with higher cycles, indicating a reduction of the hydro-sensitivity (e.g., structural disturbance) of gellan gum gels due to repeated swelling and dehydration.

Once initially mixed gellan gum-sand mixtures are subjected to drying, the dry densities of gellan gum-treated sand increase with decreased moisture content, regardless of gellan concentration due to the significant volumetric shrinkage of the gellan gels filling pore spaces between sand particles. Dry shrinkage of gellan gum hydrogels exerts tensile force on the sand particles thereby reducing the overall specimen volume, while increasing both dry density and unconfined compressive strength of gellan gum-treated sands on the contrary. The reduction of the dry densities of the dried specimens with an increase in cycle number indicates that the tensile force provided by gellan gum hydrogels reduces with further wetting and drying cycles. This weakening of dried gellan gels is a result of the reduction in gellan gum monomer interactions caused by the interference of water molecules.

On the other hand, the dry densities of wet specimens increase with cyclic wetting and drying. For the primary drying, gellan gum monomers accumulate around sand particles, especially near the inter-particle contact points between the sand particles due to matric suction. However, when dried gellan gum gels are exposed to water again, hydrophilic swelling of the gellan gum gels repels sand particles, which induces overall volumetric expansion (i.e., dry density decrease) of gellan gum-treated sand. Meanwhile, with further wetting and drying cycles, more gellan gum monomers disassociate from the main structure, which reduces the total amount of swelling for wet samples. As a result, the overall dry density of saturated gellan gum-treated sands could increase with a higher number of cycles, as shown in *Fig. 4.7b*. Moreover, the similar dry density value of dried samples at the final (10th) cycle regardless of gellan concentration implies a minor effect of gellan gum gels on the soil structure due to the structural disturbance and weakening of gellan gum gels. This point will be the equilibrium point at which the gellan monomers concentrate around the sand particles and particle contact points are similar throughout the various gellan gum concentration cases, with the remaining gellan monomers having been disassociated from the main structure into the pore spaces.

4.3 Analysis and Discussion

Hydraulic conductivity results showed that the effects of bio-clogging in the soil is capable of reducing the hydraulic conductivity to around 1×10^{-8} cm/s when the gellan to soil concentrations are above 1.0%. The effects of bio-clogging cuts off the flow paths within the soil voids by filling it with the biopolymer mixtures. However, after reaching a permeability of 1×10^{-8} cm/s the hydraulic conductivity does not reduce further. This implies that when the permeability reaches 1×10^{-8} cm/s, found to be around 1.0% gellan concentrations, the voids in the soil are fully occupied by the gellan biopolymer mixtures, thereby an additional increase in gellan concentration does not increase the volume occupied by the gellan mixtures but instead the density of the gellan gels within the soil.

In addition, it was observed that when clay particles are present in the soil, the breakdown pressures increase linearly with the effective stress increase (*Fig. 4.4*) exhibiting soil like characteristics, but in the absence of clays the breakdown pressures are solely dependent on the gellan gel properties within the soil. These results shows that the gellan gum biopolymers have entirely different structures within the soil when clay particles are present in the soil. The pure sands (i.e. without clays) behavior is highly dependent on the gellan gel properties showing that the structure within the sands is simply the gellan gels filling up the pores within the sand matrix, whereas the soils with clay particles showed behaviors in breakdown pressures closer to soils than pure gels indicating that the gellan structures within such soils interact directly with the clay particles forming a rigid clay-gellan structure. These results are highly in line with the schematic model shown in *Fig. 3.9*.
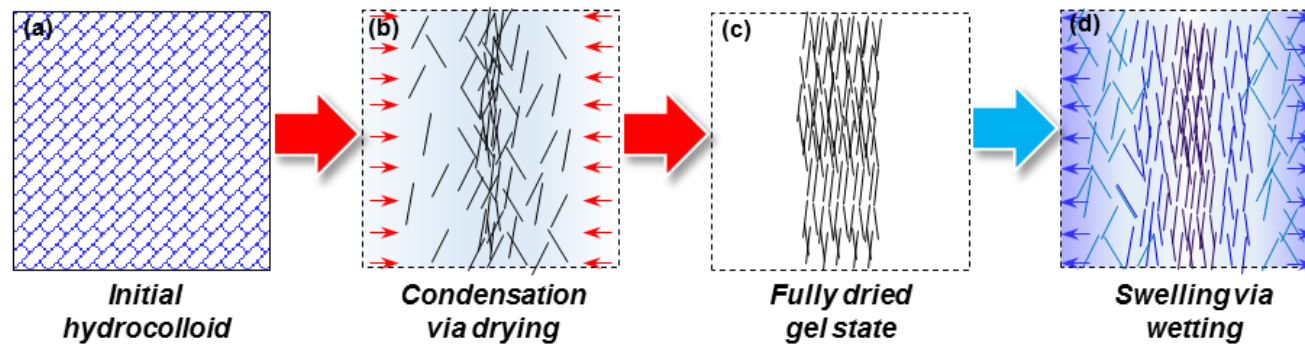
With the wetting / drying cyclic behaviors, it was observed that the gellan biopolymers had large water absorbance capabilities when observing the shrinkage and expansion from the drying and wet-

ting processes. However, with an increase in wetting and drying cycles the overall changes in the volume were diminished showing that a permanent disturbance in the gellan structure was occurring. A schematic model for the drying and wetting processes of the gellan gels is shown in *Fig. 4.8*. As shown, when the gellan gels are first made and mixed with the soil (i.e. the initial condition) the gels form a very structured hydrocolloid state (*Fig. 4.8a*), but due to water making up 97% of this gel structure, as the gellan gels dehydrate (*Fig. 4.8b&c*) a large change in the volume results in the formation of dense and thin films of biopolymers (also observed in the SEM images shown in *Fig.3.3e&f*). Due to this compaction of the gellan particles with dehydration, when the biopolymer films are rehydrated (*Fig. 4.8d*), the biopolymer absorb the water around in due to the highly hydrophilic nature of gellan gum, but it is unable to revert back to the initial structure shown in *Fig.4.8a*. Therefore, after the initial drying process the wet strengths shown in *Fig.4.6* have a large strength reduction between the initial conditions and the 1st wet conditions.

The overall schematic model of the sand biopolymer interactions through the wetting and drying cycles in shown in *Fig.4.9*. As shown, the initial state starts with a very structured gel filling up the pore spaces within the sands, and as the gels dehydrate the structure densifies due to the formation of very firm and strong biopolymer films that exert a tensile force on the sand particles inducing a large volumetric shrinkage and increase in dry density (*Fig.4.7*). However with consecutive wetting and drying processes, the outer layers of the biopolymer films display larger disturbances by dissociating the biopolymers from the main biopolymer structures (*Fig.4.8d*). Through such disturbances, the gradual loss of biopolymer connections result in the reduction in both strength and stiffness for the gellan treated sands (*Fig.4.6*). When the biopolymers are dehydrated after such disturbances, the gellan biopolymer films will experience a reduction in density and intermolecular interactions greatly reducing the swelling and shrinkage potential of the sand-gellan structures (seen in *Fig. 4.7*). The sands with higher gellan concentrations will only have larger disturbances due to the higher concentration of the gellan biopolymers filling the voids. As such, larger volumetric changes and reduction in strength and stiffness will occur (seen in *Figs.4.6&4.7*). The key findings for this chapter have been summarized in *Table4.1*.

Table 4.1. Summary of the Key Findings for the hydraulic effects of gellan treated soils.

	Key Findings
Hydraulic Conductivity Tests	• There is a decrease in permeability with gellan treatment due to bio-clogging • At approximately 1.0% gellan content the permeability levels off to 1×10^{-8} cm/s. • Permeability of 1×10^{-8} cm/s is the point at which the pore spaces are fully occupied with gellan biopolymers. • No large changes in the permeability with an increase in effective stress • The breakdown pressure of soils with no fines is completely controlled by the gellan gel properties • The breakdown pressure of soils with fines increases linearly with the effective stress
Cyclic Wetting and Drying Tests	• Nearly linear decrease in dry strength and stiffness is observed with increasing cycle • Wet strengths and stiffness show a convergence in strength to around 14 kPa and 0.14 MPa respectively regardless of gellan concentration • Higher gellan concentrations have faster strength deterioration in the dry state, but slower strength deterioration in the wet state • Higher gellan concentrations induces larger volume shrinkage / expansion with drying / wetting • Increase in drying / wetting cycles reduce the overall changes in volume and dry density

Fig. 4.8 Illustration of the phase transform of gellan gum with drying and wetting. (a) Initial hydrocolloid state. (b) Gel condensation via dehydration. (c) Fully dried gels. (d) Swelling via re-hydration.
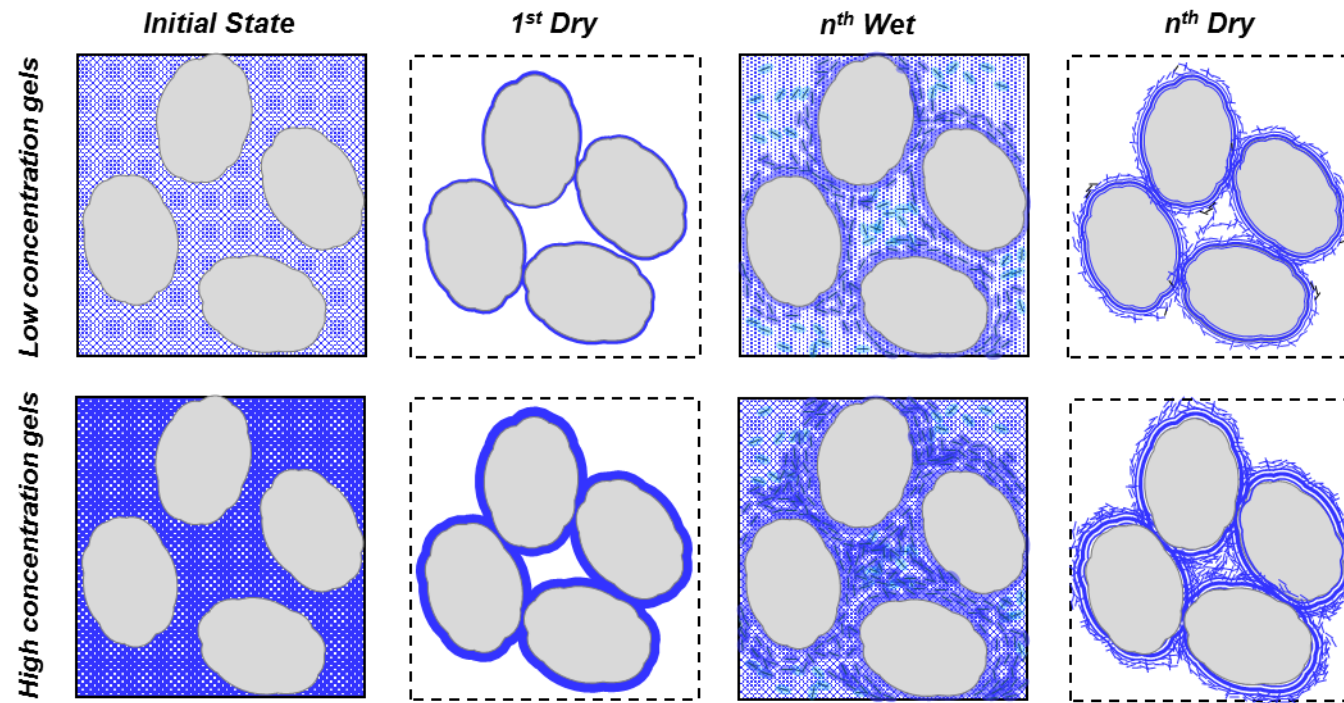
Fig. 4.9 Schematic diagram of cyclic drying and re-wetting mechanism of gellan gum-treated sands.

Chapter 5. Effects of Gellan treatment on Consolidation / Stiffness

5.1 Consolidation Behavior

For the consolidation and stiffness behaviors, an oedometer test was performed with p / s wave sensors attached to the top and bottom caps of the cell. This test was performed to observe the effects that gellan gum treatment on soil has on the consolidation and stiffness of the treated soils.

Pure sand and kaolinite soils were used in the untreated and 1.0% gellan treated states, and a step confinement of 50, 100, 200, and 400 kPa was applied over a period of time. At the end of each loading the p and s waves were measured to approximate the stiffness of the soils. Additionally, a test on the pure gellan gel (with a gellan to water concentration of 3.33%) was also conducted to understand the behavior of gellan gels in the soil. All tests were performed under the drained and submerged conditions.

The consolidation test for the pure gellan gel condition is shown in *Fig.5.1*. As shown, the consolidation of the pure gellan gel never leveled off and continually increased at a given rate regardless of the loading. This continuous straight loading path shows that the pure gellan gel sample was expelling water at a constant given rate.
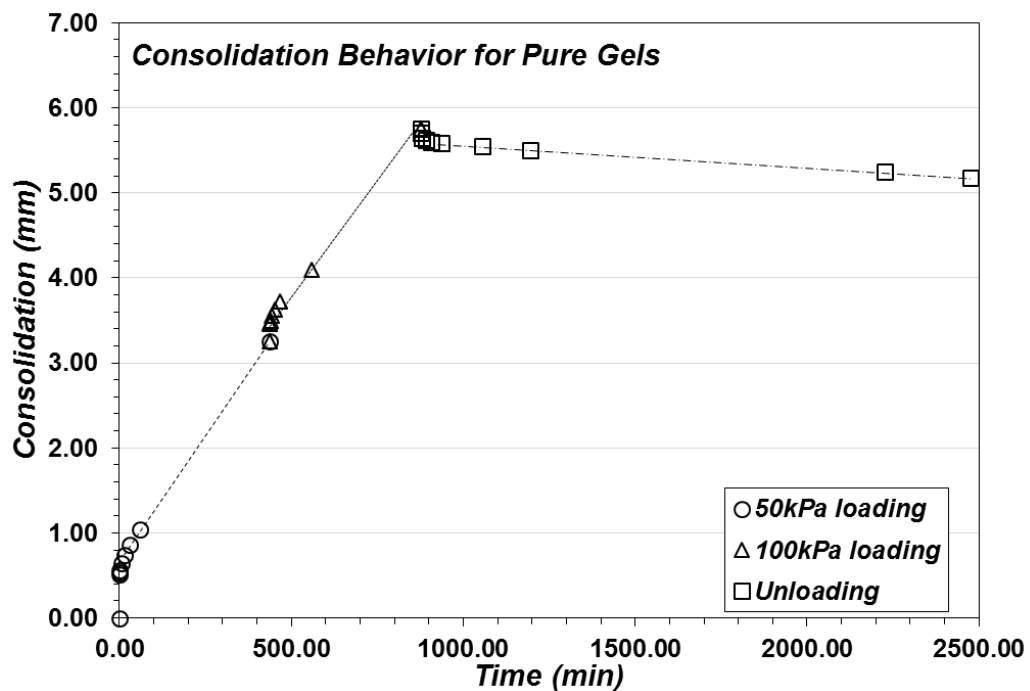

Fig.5.1 Consolidation of pure gellan gel over time

The unloading path of the pure gellan gels shows similar behaviors as the loading paths. A linear expansion of the gel was observed with a given time. This shows that due to the hydrophilic nature of the gellan gum biopolymers, the absorption capabilities of the gel allow for volume expansion with the absorbance of water.

When this gellan gum is mixed with sand and clay the consolidation behaviors show very different properties (*Fig.5.2*). For all loading conditions the gellan treated kaolinite samples displayed a larger consolidation than the untreated kaolinite samples. This increase in consolidation is most likely due to the reduction in the adsorbed double layer of the clay specimens when electrically interacting with the gellan gum biopolymers. With the ionic characteristics of the gellan biopolymers, when interacting with the kaolinite clay particles, the water molecules are not held as strongly by the clay particles. Therefore, with a weakened interaction between the clay and water molecules, a given load will produce much higher consolidation effects with an easier drainage of water molecules from the soil layer.
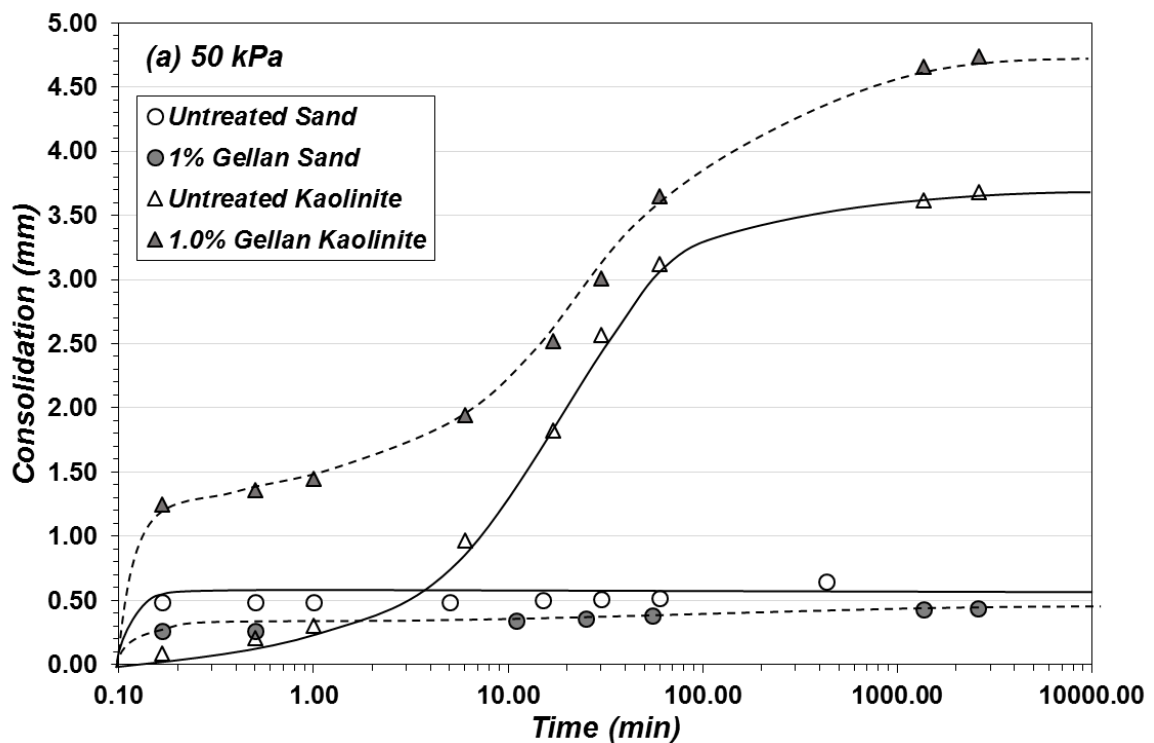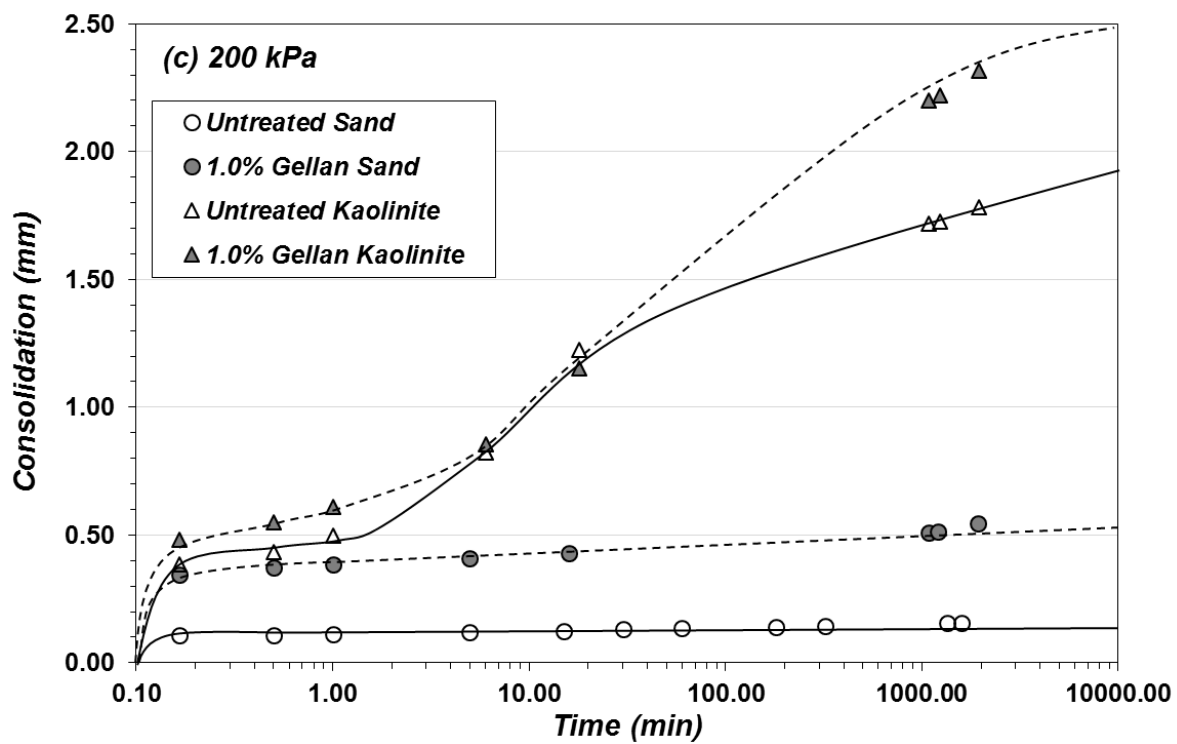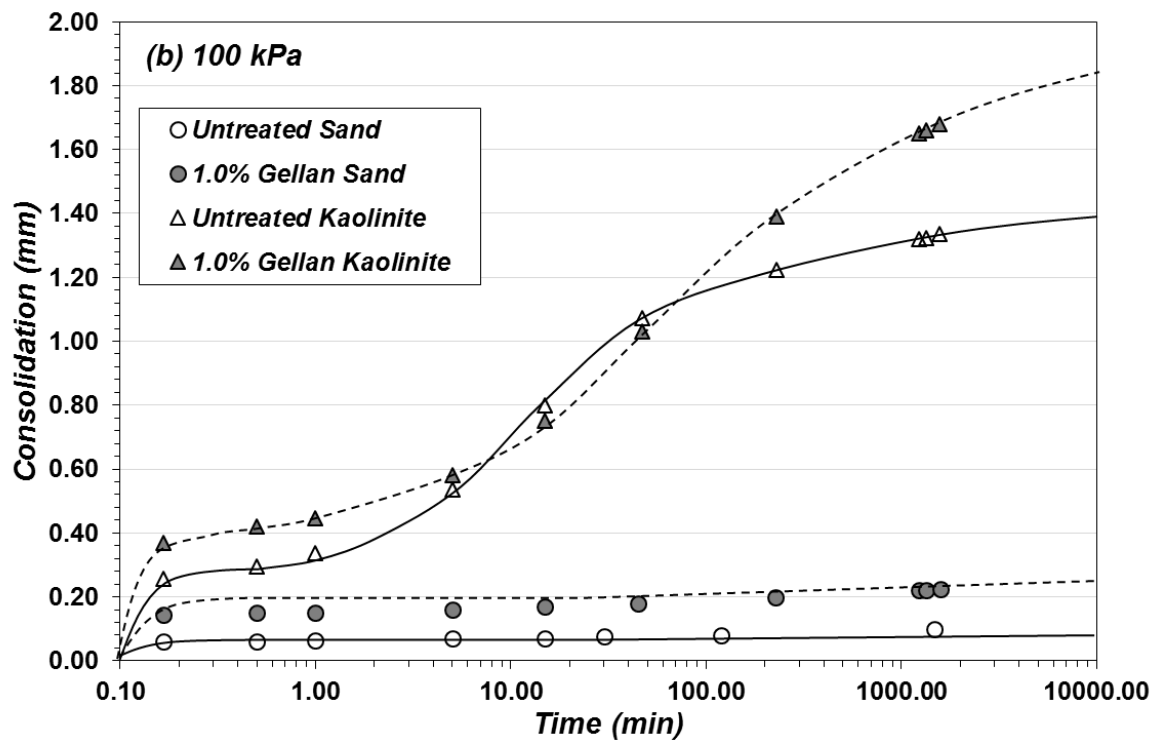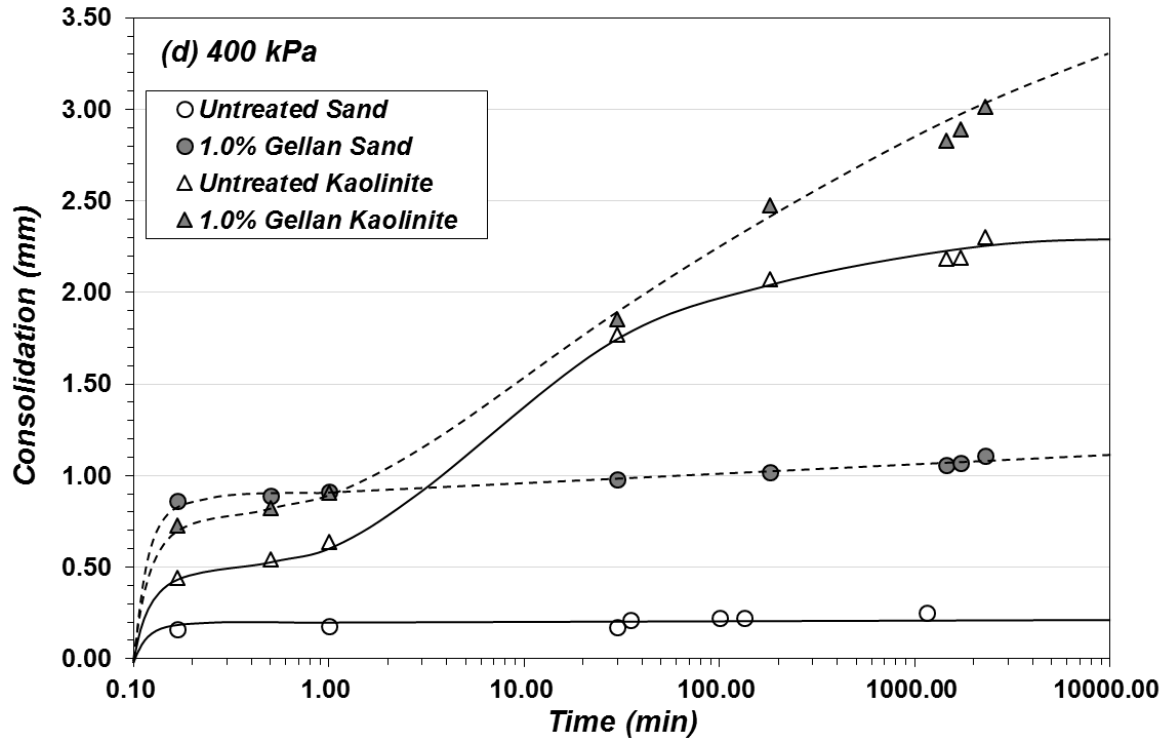
Fig.5.2 Consolidation behaviors of untreated and 1.0% gellan treated sands and kaolinite for

(a) 50 kPa, (b) 100 kPa, (c) 200 kPa, and (d) 400 kPa

However, the behavior of the untreated and 1.0% gellan treated sands differ from the behavior of the kaolinite specimens. At lower confinements of 50 kPa (*Fig.5.2a*) the consolidation amount of the gellan treated specimens are slightly lower than the untreated samples. This can be contributed to the increased stiffness that resists the consolidation due to the gellan treatment. However, as the confinement increases the gellan treated sands display larger and larger consolidation effects with larger confinements (*Fig.5.2b,c,d*). This increase in the consolidation with an increase in the loading is largely due to the progressive failure of the gellan gels within the pores of the sand specimens and the lubrication effects that these gellan gels can have on the sand particles. When compared with the breakdown pressure results in chapter 4 (*Fig.4.4a*) it was seen that at confining loadings of 100 kPa the gellan gel structure within the sand particles experienced breakages that resulted in the increase in hydraulic conductivity. Similarly after 100 kPa loadings the oedometer results showed an increase in consolidation most likely due to the same structural changes experienced in the hydraulic conductivity tests. With progressive loadings further changes to the gellan gel structure coupled with the lubrication effects that the gels would have on the sand particles induced greater consolidations than the untreated samples. This increase in consolidation can also be observed in the dry density changes with progressive loadings seen in *Fig. 5.3*.
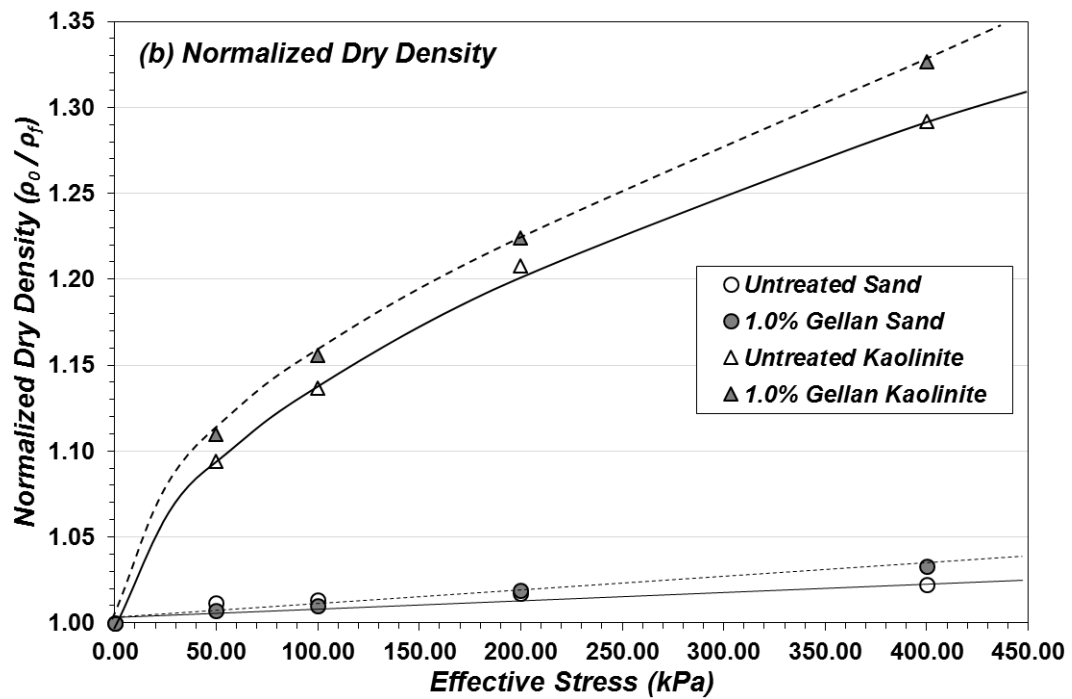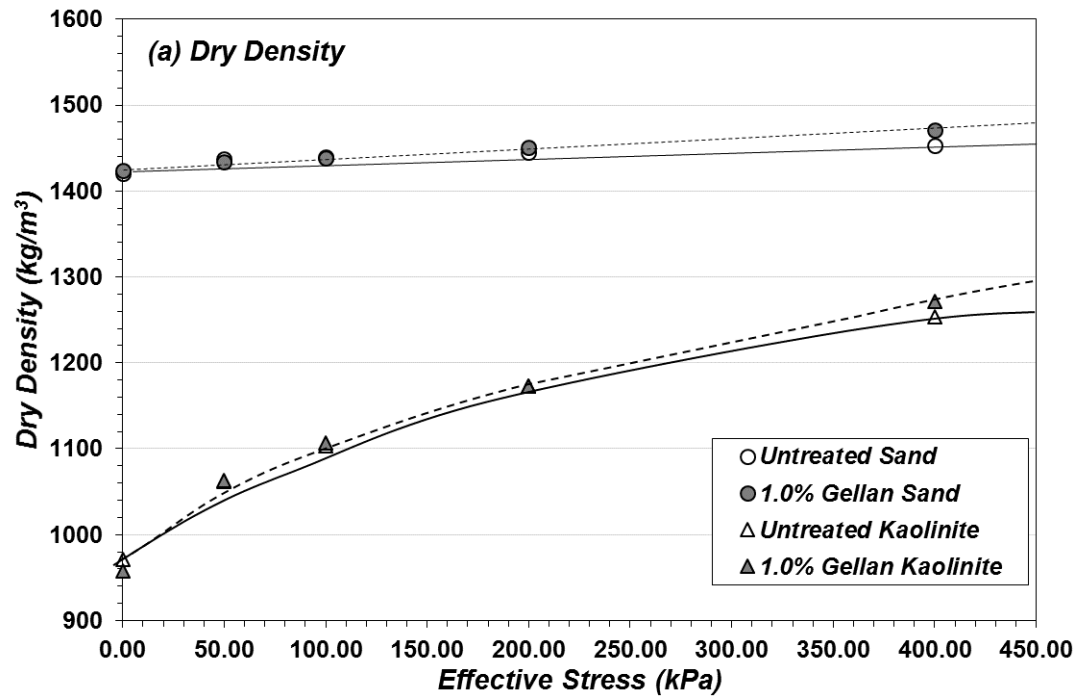
Fig.5.3 Changes in the dry density for untreated and 1.0% gellan treated soils for

(a) the dry density and (b) the normalized dry density

As seen in *Fig.5.3a* the kaolinite samples experience larger changes in the dry density with larger consolidation effects. The dry densities of the sand specimens do not experience a large variation with an increase in the effective stress, however, a linear increase is observed with an increase in the effective stress. It can also be seen that the 1.0% gellan treated soils have a larger increase in the dry density. This difference can be easier seen in when the dry densities are normalized to their initial mixing dry densities *Fig.5.3b*. Both the gellan treated sand and kaolinites specimens show a larger increase in the dry density than its untreated counterparts. Additionally, the difference in dry density seems to get progressively larger at higher effective stresses.

The unloading curves can be seen in *Fig.5.4*. The untreated sands reached the maximum expansion fairly quickly while remaining relatively constant afterwards. However, the gellan treated sands displayed an initial expansion larger than that of the untreated sands, and afterwards the gellan treated sands did not reach an equilibrium state and continually expanded much like the pure gel sample. This shows that the gellan gum biopolymer are extremely hydrophilic and induce swelling by absorbing water into the soil gellan mixture.
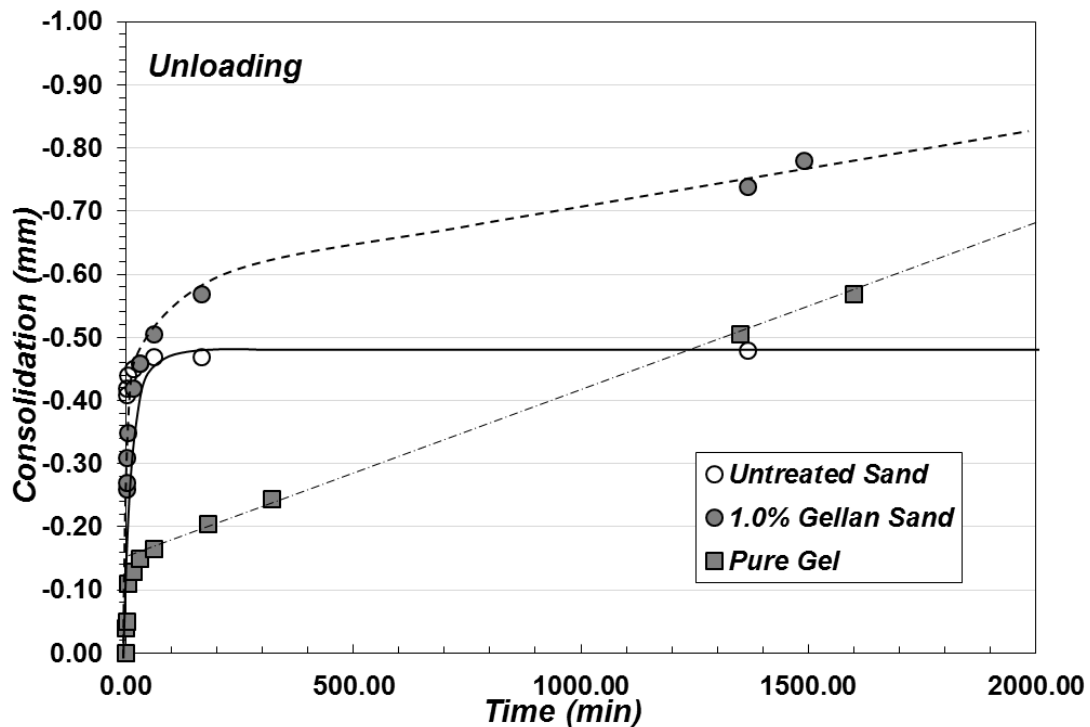
Fig.5.4 Unloading curves of untreated and gellan treated sands and pure gellan gels

5.2 Stiffness Behavior

The p and s wave arrive times were measured with each step loading discussed in the previous section. The p and s wave velocities were then found and are shown in *Fig.5.5*.
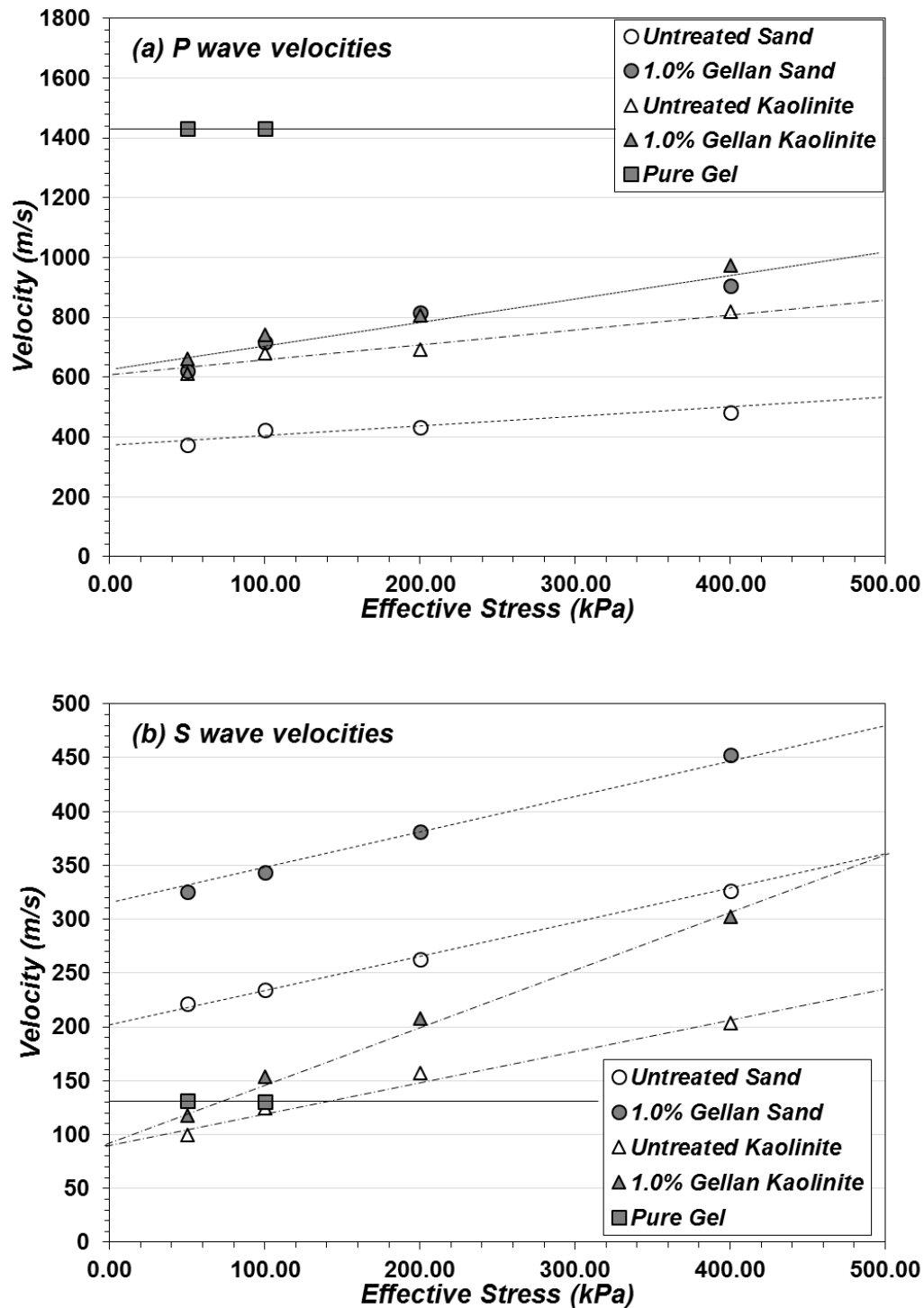

Fig.5.5 (a) P and (b) S wave arrive times for untreated and gellan treated sands, kaolinite, and pure gels at various loading conditions

As expected the wave velocities for both the p and s waves increase with an increase in confinement. Of the p wave velocities, the untreated sands showed the lowest p wave velocities at around 400-500 m/s, while the untreated kaolinite had velocities of 600-800 m/s. Above the untreated kaolinite specimens, the p wave velocities of the gellan treated soils came out to be similar regardless of the soil type. Additionally, the p wave velocities of the gellan treated soils had a higher rate of increase with each step loading than the untreated soils. The pure gel p wave velocities came out to be approximately 1430 m/s, which is the p wave velocity of water. From this we can see that the p wave characteristics of the pure gellan gel is controlled by the properties of water, however, when this gel is mixed into soils it has the properties of increasing the p wave velocities of soils.

The s wave characteristics (*Fig. 5.5b*) of the gellan treated soils showed a very high correlation with the shear properties of the gellan treated soils discussed in chapter 3. Gellan treatment increased the overall s wave velocities of sands without increasing rate of increase with effective stress. Much like the cohesive and frictional properties from the direct shear results, the s wave velocity of gellan treated sands were increased by approximately 120 m/s for all effective stress conditions with no noticeable increase in the rate of increase (friction angle). For the gellan treated kaolinite specimens, the wave velocities at the lower effective stresses were fairly similar, however with an increase in the effective stress the differences in the s wave velocities gradually increased with the gellan treated samples exhibiting larger velocities than the untreated conditions. Similarly to the direct shear results the pure sand samples only exhibited a vertical shift in the velocity with gellan treatment (i.e. increase in cohesion but not friction angle), while the pure kaolinite samples exhibited an larger s wave velocity increases with higher effective stresses (i.e. increases in the friction angle). As such these results showed a large correlation with the results shown from the direct shear tests.

Using the wave velocities, the Young's modulus, shear modulus, and poisson's ratio were approximated using the following equations:

$$V_P = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E}{\rho} \frac{1-\gamma}{(1+\gamma)(1-2\gamma)}}$$

(1)

$$V_S = \sqrt{\frac{G}{\rho}}$$

(2)

$$\gamma = \frac{0.5 \left(\frac{V_P}{V_S}\right)^2 - 1}{\left(\frac{V_P}{V_S}\right)^2 - 1}$$

(3)

Where V_P is the p wave velocity, V_S is the s wave velocity, γ is the poisson's ratio, ρ is the density of the soil, M is the bulk modulus, E is the Young's modulus, and G is the shear modulus. Using equation 3, the poission's ratios were obtained for each of the various conditions shown in *Fig.5.6*. The pure gel once again showed characteristics of water with a poission's ratio of 0.5. Gellan treatment on sands and clays displayed differing changes. The gellan treatment on sand increased the poission's ratio from 0.23 to 0.34, while the kaolinite samples actually had a decrease in the poission's ratio with gellan treatment from 0.48 to 0.47. The increase in poission's ratio for sand can be attributed to the presence of an infill material (i.e. gellan gels) within the pores of the sands. Due to the stiff nature of the gel and the water like properties of the gel, an increase in the poission's ratio was observed. However, with the kaolinite samples, the presence of the gellan gels reduced the adsorbed layer of the clay particles thereby moving away from the properties of water and closer to the structure of coarse soils. Therefore, a decrease in the poission's ratio with gellan treatment was observed with the kaolinite samples.
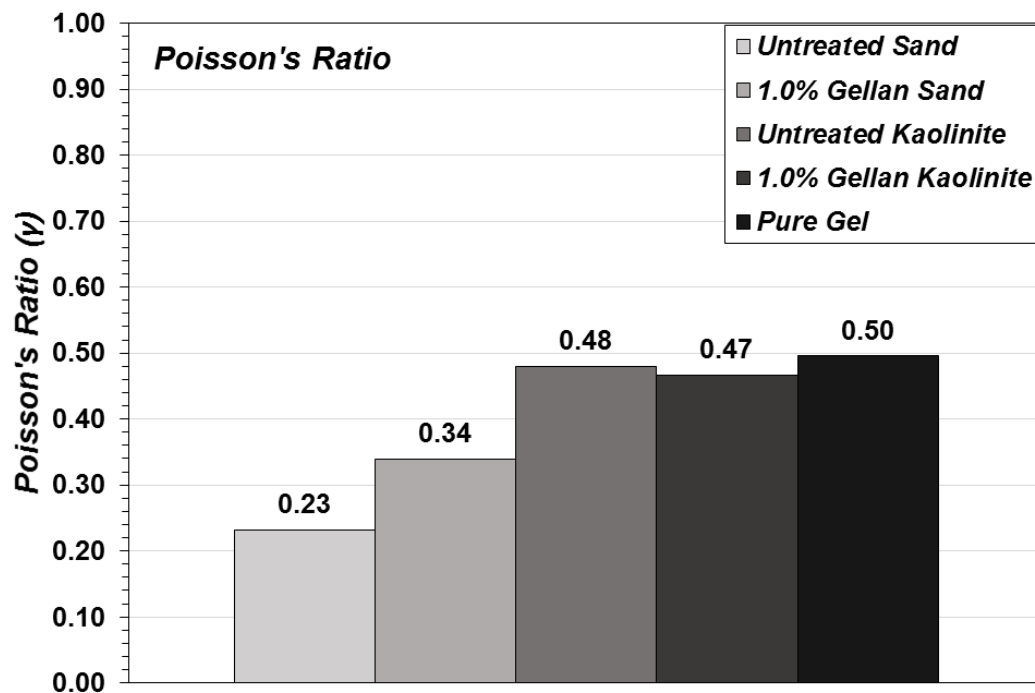

Fig.5.6 Poission's ratio of gellan treated and untreated soils

Using equations 1 and 2 alone with the poission's ratio and the wave velocities, the constrained modulus and the shear modulus of the soils were obtained (*Fig. 5.7*).
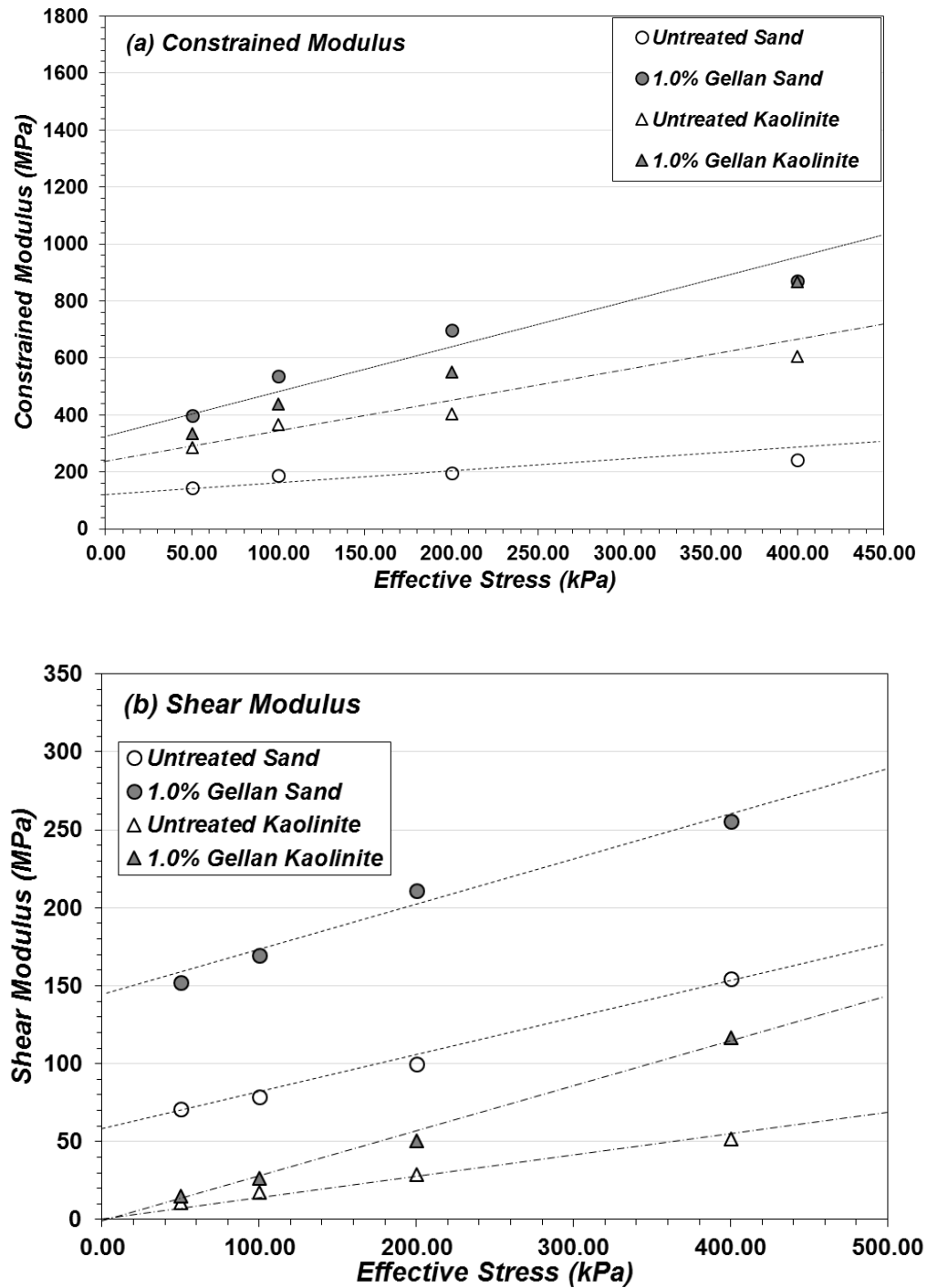

Fig.5.7 (a) Constrained modulus and (b) Shear modulus of untreated and gellan treated soil with an increase in effective stress

As observed the use of gellan gum biopolymer in the soil improve both the constrained and shear modulus. With the constrained modulus, the effects of gellan gum achieve similar results for both sand and kaolinite samples. The shear modulus on the other hand is once again closely in line with the direct shear results, with the sand shear modulus experiencing a vertical shift of around 100 MPa, and the kaolinite shear modulus experiencing a larger shear modulus increase with larger effective stresses.
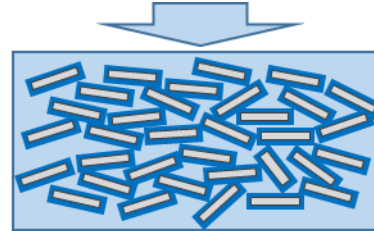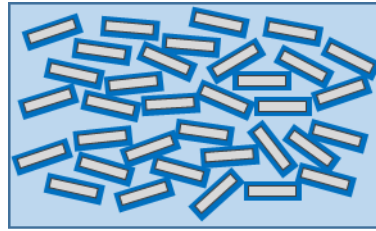
5.3 Analysis and Discussion

Several key factors were once again found in this test. It was found that although the use of gellan gum biopolymers in soils have been capable of increasing the stiffness of the soils, the consolidation of the soils was also observed to increase with gellan gum treatment. For sand soils this increase in consolidation happens after 100 kPa effective pressures are applied. For an understanding of this increase we can once again look towards the hydraulic permeability results explained in chapter 4. The results shows that the gellan gels within the sand started to breakdown at pore pressures of 100 kPa. Therefore, when an applied stress of above 100 kPa is applied onto the gellan sands, the pressures can result in the restructuring of the gellan gels within the pores of the sands which in turn would increase the consolidations around those areas.

With the gellan treated kaolinite, the consolidation was observed to be larger than the untreated kaolinite regardless of the confining pressures. The reason for this increase is attributed to the reduction of the adsorbed double layer of the clay particles with an introduction of gellan particles. A schematic model of this behavior can be seen in *Fig.5.8*. As shown due to the large adsorbed layer of the clay particles, the repulsion between the adjacent adsorbed layers will hinder the consolidation. However, with the presence of gellan particles, which act as ions, the surface charges interact with the biopolymer particles instead of the water molecules. Therefore, a reduction in the double layer thickness will result in the water molecules being held with less force and thereby increasing the consolidation capabilities of the soil while simultaneously improving the stiffness of the soils. The key findings have been summarized in *Table 5.1*.
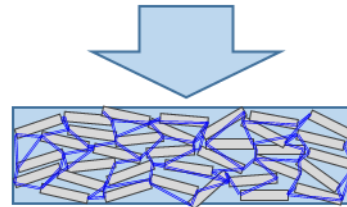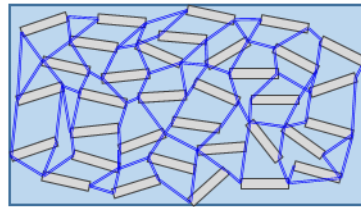
Table 5.1. Summary of the Key Findings for the consolidation and stiffness results.

	Key Findings
Consolidation Tests	• Pure gellan gels exhibit linear loading behaviors nearly indefinitely • Gellan treated sands show larger and larger consolidations at higher confining pressures • Gellan treated kaolinite show larger consolidations than the untreated kaolinites • Gellan treated soils have higher dry densities with consolidation • Unloading paths are linear for gellan treated soils due to water absorption
Wave Velocity Tests	• Pure gellan gels have p wave velocities equivalent to water and show a small s wave velocities • Gellan treatment increase both p and s wave velocities of soils • Gellan treatment s wave properties and shear modulus behaviors are highly in line with the direct shear results in chapter 3 • Gellan treatment increases the poission's ratio for sand but decrease the poission's ratio for clays

Fig.5.8 Schematic model of the compatibility of (a) untreated and (b) gellan treated clays

Chapter 6. Conclusion

This study investigated the structural and behavioral properties of gellan treated soils. Specifically with a focus on the presence of clay particles and water molecules. With the results and findings of each experimental test a detailed schematic model of the structure and behavior of the gellan treatment was provided. These investigation provided numerous insights into the properties of these gellan treated soils, and the importance of many factors, such as the gellan to clay ratios. A general overview of the various finding with each experimental test is provided in *Table 6.1* below.

The variations in the soil properties based on the presence or absence of clays is shown in *Fig. 6.1*. With pure sandy soils, the majority of the properties are based on the biopolymer gel itself, and the properties of the biopolymer gel. The cohesive strength, breakdown pressures, and the overall strengthening effects of gellan treated sands are highly dependent on the properties of the gellan gel itself.
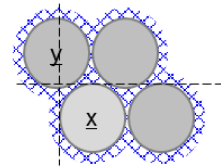
With clay soils however, due to the direct interactions of the gellan particles with the clay particles, a large dependency is placed on the gellan to clay content. Since the particles interact directly with the clay soils, the gellan clay mixtures does not simply enhance the soil with the gel properties (i.e. cohesive strength) but instead work together to form a interworking structural matrix that acts simultaneously with properties of a soil and a gel (i.e. increase cohesion and friction angle). However, with both cases of sands and clays, the use of gellan gum has shown to be capable of reducing the permeability of the soils, and it also provides high hydrophilic properties that may disrupt the structure of the biopolymers. Additionally, the use of gellan has been seen to provide clay like properties to sands (i.e. cohesion, secondary consolidation) and sand like properties to clays (i.e. increased friction angle, rigid structures).

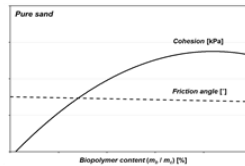*Table 6.1. Overall summary of the Key Findings in this study.*

	Key Findings
Uniaxial Compressive Tests	• Increase in strength with an increase in gellan concentration • Strengthening efficiencies are highly dependent on the biopolymer to clay content • Direct electrical interactions between clay particles and biopolymers were observed • Biopolymers envelope sand particles but does not have direct interactions with sand • Increase in interparticle connections improve compressive strengths • Decrease in strength was observed after 4.0% gellan to clay ratios
Direct Shear Tests	• Increase in cohesion with an increase in biopolymer content • No major change in friction angle for pure sand soils • Dramatic increase in friction angle with the introduction of gellan into clayey soils • Subsequent increases in friction angle with increases in gellan concentration for clayey soils • Decrease in cohesion was observed after 4.0% gellan to clay ratios
Hydraulic Conductivity Tests	• There is a decrease in permeability with gellan treatment due to bio-clogging • At approximately 1.0% gellan content the permeability levels off to 1×10^{-8} cm/s. • Permeability of 1×10^{-8} cm/s is the point at which the pore spaces are fully occupied with gellan biopolymers. • No large changes in the permeability with an increase in effective stress • The breakdown pressure of soils with no fines is completely controlled by the gellan gel properties • The breakdown pressure of soils with fines increases linearly with the effective stress
Cyclic Wetting and Drying Tests	• Nearly linear decrease in dry strength and stiffness is observed with increasing cycle • Wet strengths and stiffness show a convergence in strength to around 14 kPa and 0.14 MPa respectively regardless of gellan concentration • Higher gellan concentrations have faster strength deterioration in the dry state, but slower strength deterioration in the wet state • Higher gellan concentrations induces larger volume shrinkage / expansion with drying / wetting • Increase in drying / wetting cycles reduce the overall changes in volume and dry density
Consolidation Tests	• Pure gellan gels exhibit linear loading behaviors nearly indefinitely • Gellan treated sands show larger and larger consolidations at higher confining pressures • Gellan treated kaolinite show larger consolidations than the untreated kaolinites • Gellan treated soils have higher dry densities with consolidation • Unloading paths are linear for gellan treated soils due to water absorption

Wave Velocity Tests	• Pure gellan gels have p wave velocities equivalent to water and show a small s wave velocities • Gellan treatment increase both p and s wave velocities of soils • Gellan treatment s wave properties and shear modulus behaviors are highly in line with the direct shear results in chapter 3 • Gellan treatment increases the poission's ratio for sand but decrease the poission's ratio for clays

Fig.6.1 Variations in the gellan treated soil properties with the presence of clays

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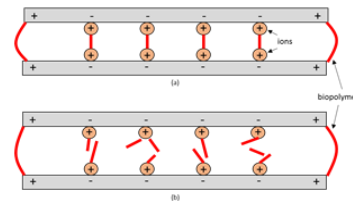
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Summary

Structural and Behavioral Analysis of Gellan Treated Soils

고대부터 현재에 이르기까지 토양의 처리 및 특성 개선은 주요한 건설 분야 중 하나이다. 역청 또는 찹쌀 모르타르를 사용하여 토양을 강화하던 고대 시절부터 문명의 발전과 함께 지반공학 분야에서의 내구성 및 건축 자재는 지속적인 발전을 보였다. 토양 처리의 주요 목적은 지반의 공학적인 특성을 향상시키는 것이다. 이러한 특성들은 흙의 강도, 투수 조절, 내구성 및 환경의 활성화를 위한 방법들이 포함되어있다. 토양 처리 방법 중 가장 많이 사용되고 있는 물질은 시멘트이다. 시멘트는 높은 강도, 내구성 및 양생기간 동안 탄산 칼슘을 형성하여 지속적으로 강도가 증진되는 등많은 장점을 갖고 있다. 그러나 시멘트의 사용은 많은 이산화탄소 발생 및 발열과 같은 다양한 환경적인 문제점들을 갖고 있다.

그에 따라 최근에는 시멘트를 대체할 수 있는 친환경적인 토양 바이더에 대한 연구와 개발이 진행 되고 있다. 그 중 생물학적인 물질을 사용하는 방법이 많은 관심을 받으며 많은 연구가 진행되고 있다.

바이오 폴리머는 생물학적 유기체에 의해 만들어진 유기 폴리머이다. 본 연구에서는 젤란 검 바이오 폴리머로 처리된 흙을 사용하여 겔형 폴리머의 구조 및 거동을 조사를 하였다.

일축 압축 강도, 직접 전단 시험, 투수 시험 및 압밀 시험 등의 각종 지

반공학 실내실험을 통해 젤란 검으로 처리된 흙의 다양한 구조 및 거동을 조사하였다. 특히 점토 입자 및 물 분자의 반응성에 대해 집중적으로 분석하였으며, 이를 통해 폴리머와 점토 비율의 중요성, 물의 상호 작용 모델을 포함한 다양한 토양의 특성을 도출하였다.

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List of Publications

Dissertation

1.   Jooyoung Im (2015), "Structural and Behavioral Analysis of Gellan Treated Soils", *M.Sc. Thesis*, Korea Advanced Institute of Science and Technology, Daejeon, South Korea

International Conference papers

1.   **Im J**., Chang I., Cho G. C. (2013), "Dynamic Properties of Biopolymer Treated Jumunjin Sand", *26th KKHTCNN Symposium on Civil Engineering, Singapore,* Nov. 18-20

2.   **Im J**., Chang I., Cho G. C. (2014), "Soil Strengthening Behavior of 1% Gellan Treated Jumunjin Sand", *27th KKHTCNN Symposium on Civil Engineering, Shanghai,* Nov. 10-12

3.   **Im J**., Chang I., Kwon Y. M., Cho G. C., Lee J. H. (2015), "Development of a Water Resistant Biopolymer Compound for Soil Strengthing", *28th KKHTCNN Symposium on Civil Engineering, Bangkok,* Nov. 16-18

International Journal papers

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2.   Chang I., Prasidhi A.K., **Im J.**, Cho G.C. (2015) "Soil strengthening using thermos-gelation biopolymers", *Construction and Building Materials*, published.

3.   Chang I., Prasidhi A.K., **Im J.**, Shin H.D, Cho G.C. (2015) "Soil treatment using microbial biopolymers for anit-desertification purposes", *Geoderma*, published.