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Evaluation of Hydrogel–stabilized Expansive Soils in Mississippi for Sustainable Maritime Infrastructure Design

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1. Project Description

The development of transportation infrastructures, such as roads, motorways, and railway lines, requires earthworks, mainly for the construction of the subgrades and base. When the infrastructures were constructed on the top of problem soil, such as cohesionless soil and expansive soil, it may cause some damages or unsafe uncertainty for the infrastructures. Expansive soils can induce damage to structures built on them because those expansive soils can cause volumetric changes with moisture content change. Expansive soils are also defined as shrink-swell or swelling soils because of their unique properties and different clays have different susceptibility to swelling (Petry and Little, 2002). The major reason that happened in those expansive soils is the high montmorillonite content. Such soils expand when they are wetted and shrink when dried. This movement exerts pressure to crack sidewalks, basement floors, slabs, driveways, pipelines, and foundations (Wilson et al. 2000, Nalbantoğlu, 2004, Mokhtari and Dehghani, 2012). The damages due to expansive soils are sometimes minor maintenance, but often they are much worse, causing major structural distress. The estimated damage to buildings, roads, and other structures built on expansive soils, for example, exceeds 15 billion dollars in the US annually (Al-Rawas and Goosen, 2006).

According to the report of Expansive Soil in Mississippi in 1993, over 18% of the soil resource area in Mississippi is expansive clayey soil. The expansive soil is widely distributed in Mississippi, creates severe economic damage, and poses a continued threat to multimodal and maritime transportation infrastructure. Lee (2012) investigated the Yazoo clay, one type of most common expansive clay in Mississippi, in central Mississippi counties. From this study, the metropolitan Jackson area is directly located on top of the Yazoo clay as shown in Fig. 1. Any overlying non-clay deposits (alluvium, loess, etc.) are generally not thick enough to prevent moisture and water intrusion into the Yazoo clay, and these moisture changes result in expansive, swelling, shrinkage, and otherwise destructive behavior so detrimental to the roads, foundations, and related infrastructure in the central Mississippi region (Lee, 2012).

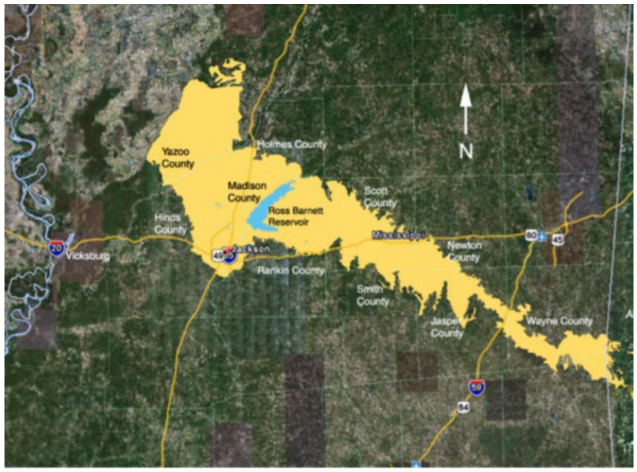

Fig. 1 The distribution of Yazoo clay in central Mississippi (Lee, 2012).

The damage of transportation structures due to the expansive soils in Mississippi includes (but is not limited to) the bumpy road surface so-called “roller coaster highway” in some sections of I-20, slope instabilities in cut sections, and retaining wall instabilities due to the swelling pressure. The problems related to the expansive soils are identified but not easily solved by traditional geotechnical engineering. Treatment of expansive soils needs substantial research and careful engineering. Mississippi DOT listed the expansive soil study as one of the top priorities of their research needs. Many transportation projects in central Mississippi have to deal with the treatment of Yazoo clay, which always includes lime treatment of the top subgrade soil (Al-Mukhtar et al. 2010).

Chemical stabilization of soil is an effective and popular technique that can improve the workability and shear strength of the soil. Chemical additives, such as cement, lime, gypsum, slag, alum and fly ash, have been used to improve the compressibility and strength characteristics of soil and numerous studies have been conducted on the mechanical properties of treated soil with traditional admixtures (Petry and Little, 2002, Seco et al. 2011, Ta'negonbadi and Noorzad, 2017). However, the use of these chemical stabilizers may cause negative effects on the surrounding environment, e.g. limits the growth of plants and altering groundwater quality. In addition, these traditional stabilizers could cause a more brittle behavior of the soil and this may affect the safety of geotechnical projects. Miller and Azad (2000) applied cement kiln dust as a soil stabilizer and found the treated soil exhibit brittle behavior during the unconfined compression test. Fatahi and Khabbaz (2012) indicated that cement-treated kaolinite had a significant improvement in mechanical properties, but it also changed to a more ductile material. Nontraditional stabilizers like salts, acids, lignosulfonates, and polymers have also gained much attention for civil engineering applications. Tingle and Santori (2003) reported a successful application of lignosulfonate and synthetic polymers for improving the mechanical properties of both fat clay and lean soils. Mirzababaei et al. (2017) investigated the effect of two polymers including 3 to 10% poly (methyl methacrylate) and 1 to 3% poly (vinyl acetate), respectively on the free swell potential of 3 different fat clay soils. They found that the addition of polymers can significantly improve the reduction in free swell potential and the formation of aggregated clay-granular matrices.

This project used hydrogel as a polymeric binder for stabilizing expansive clay. Hydrogel, a class of three-dimensional (3D) networks formed through the cross-linking of hydrophilic polymer chains embedded in a water-rich environment, possess broadly tunable physical and chemical properties (Seliktar, 2012, Zhang and Khademhosseini, 2017). Hydrogel is abundant in plant and animal tissue, with examples ranging from xylems and phloem to muscles and cartilages (Zhao

2014). Due to their unique integration of solid and liquid properties, the hydrogel is widely explored in diverse applications such as drug delivery, biomedicine, soft electronics, sensors, tissue engineering, and coating for medical devices (Gong et al. 2003, Langer and Tirrell 2004, Zhang and Khademhosseini, 2017). Multiple cross-linking often involving physical entanglement and chemical bonding of two types of polymer chains, have been combined to achieve hydrogel with superior toughness (Zhang and Khademhosseini, 2017). Gong et al. (2003) reported a strong hydrogel developed by inducing a double-network structure method. The double-network structure with PAMPA and PAAM hydrogel can sustain compression stress of 17.2 MPa and recover immediately after unloading. Sun et al. (2012) proposed a synthetic hydrogel by mixing Ca-alginate and polyacrylamide to achieve highly tough and stretchable properties. This alginate-polyacrylamide hybrid gel can be stretched to exceed 20 times its original length without rupture.

The superior toughness and mechanical strength of hydrogel bring much attention to improving the toughness and dynamic loading resistance in soil stabilization. To comprehensively evaluate the potential impact on improving the toughness and swelling behavior of expansive soil, knowledge, and scientific experiments on inducing hydrogel into the expansive soil are essential.

The objective of this project is to develop an alternative approach for stabilizing the expansive soil through hydrogel treatment. The expansive soil causes a variety of maritime transportation infrastructure problems, such as cracks, damage of pipelines, and the differential settlement of the foundation. In Mississippi, Yahoo clay, one type of expansive soil, causes significant concern during maritime design and maintenance. To address the need of MarTREC for sustainable and resilient transportation infrastructure preservation and building upon its experience and expertise in the area, this project studied the feasibility of using innovative hydrogel treatment as alternative expansive soil stabilization. Hydrogel is a network of polymer chains that are hydrophilic, which has physical entanglement and chemical bonding to integrate solid and liquid properties. Meanwhile, the superior toughness and mechanical strength of hydrogel can provide additional bonding force between soil particles and may reduce the swelling behavior of expansive soil. The hydrogel treatment may provide great and previously unexplored opportunities as cost-effective and sustainable preserving alternative approach for expansive soil stabilization in maritime infrastructure.

2. Materials and Methods

2.1 Clay

The clay soil used in this project was Yazoo clay, one type of most common expansive clay in Mississippi, at central Mississippi counties. In order to get more uniform clay soil samples, cracked Yazoo clay, which could go through the No. 10 (2 mm) sieve was selected. The sieve and hydrometer analysis were done to analyze the soil particle distribution of selected soil. The soil particle distribution curve is shown in Fig. 2. The liquid and plastic limit tests of Yazoo clay were also done in this project. Plastic limit = 21%, liquid limit = 62%, plasticity index = liquid limit – plastic limit = 41%.

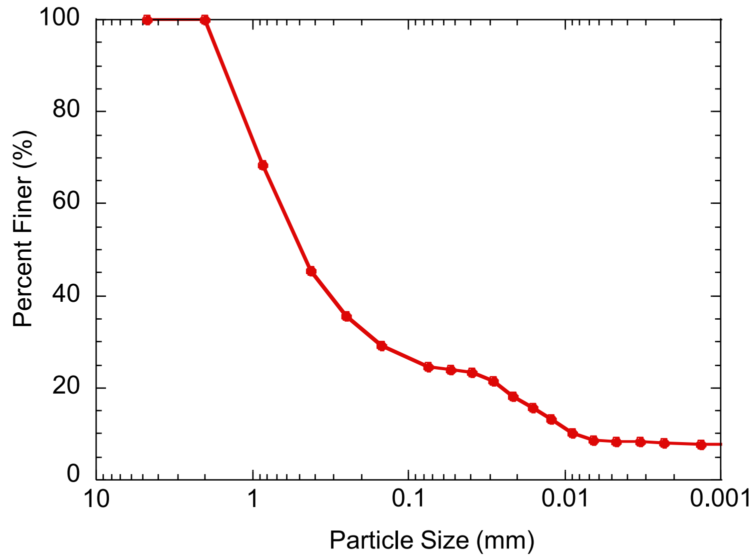

Fig. 2 Particle distribution curve of selected Yazoo clay soil.

2.2 Sand

Mississippi local sand was used in this project. It was classified as a poorly graded sand (SP) according to the Unified Soil Classification System (USCS). The sieve analysis method was used to determine the sand particle size distributions according to ASTM C136. The standard U.S. sieve was used in this study. The sand particle distribution curve was shown in Fig. 3. The coefficient of uniformity (C_u) and gradation (C_c) are 2.05 and 1.21, respectively. The specific gravity (G_s) is 2.65.

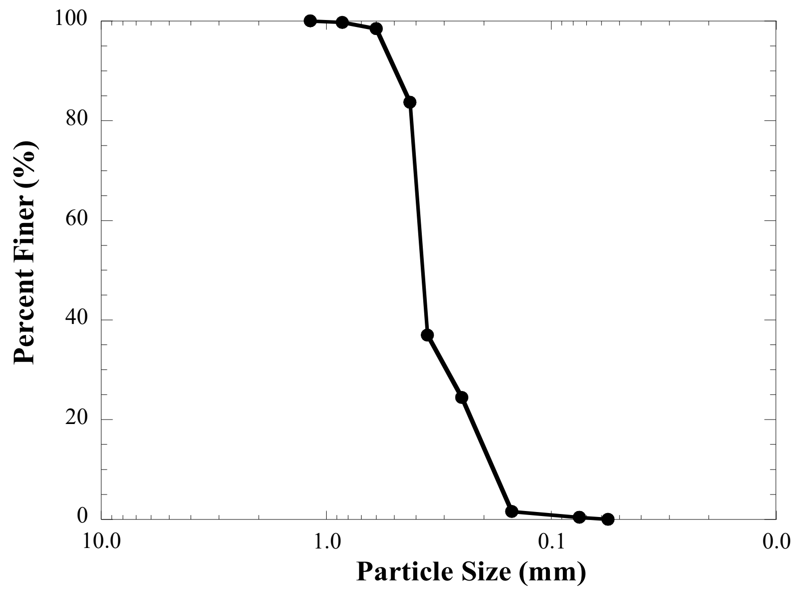

Fig. 3 Particle distribution curve of Mississippi local sand.

2.3 Ca-alginate hydrogel

The Ca-alginate hydrogel was prepared from sodium alginate solution that mixed the solution with $CaCl_2$ agents (K.Y. Lee, D.J. Mooney, 2012). The sodium alginate was delivered as powder and the gel solution was created when the powders were mixed with water. The sodium alginate powder used in this study was supplied by ACRON (CAS No. 9005-38-3). The sodium alginate solutions were prepared in DI water at room temperature. Four different sodium alginate contents (0.1%, 0.2%, 0.3% and 0.4% by weight of dry sand) were used for this project.

2.4 Hydrogel-impregnated clay sample preparation

Sodium alginate solution (~20 mL) was mixed with sand (100 g) to a workable status at room temperature as shown in Fig. 2 (a). The mixture was compacted in a mini compaction mold with a diameter of 33.0 mm (1.3 in.) and a height of 71.1 mm (2.8 in.) (Fig. 2 (b)). After compaction, the sample was extruded out and merged into a 0.5 M $CaCl_2$ solution as shown in Fig. 2 (c). The $CaCl_2$

solution was used as ionic crosslinking agent with sodium alginate to form the Ca-alginate hydrogel. The formatted Ca-alginate hydrogel can cement the sand particles together and improve the mechanical performance of the sand. Different reaction times (1, 3, 5, 7, 14, 28 days) in the CaCl2 solution were investigated to explore the optimum performance of hydrogel-impregnated sand. All testing samples were prepared in triplicate. Four different curing conditions were selected to investigate the effect of curing temperature on the properties of hydrogel-impregnated sand. After removing the samples from the reaction tank, the hydrogel-impregnated sand was either (1) air-dried at room temperature (25 °C) for 28 days, (2) oven-dried in 50 °C for 24 h, (3) oven-dried in 80 °C for 24 h, or (4) oven-dried in 100 °C for 24 h.

The clay samples were prepared using the material described above, with the proportions of 20 ml of sodium alginate ($C_6H_9NaO_7$) solution �$^{WW_{HH}}$�$_{WW_{s}}$ � mixed with a mix of 100g dry soil and 1.1g calcium chloride ($CaCl_2$) in a workable status at room temperature. The mixture was compacted in a cylindrical mold with 38 mm (1.5 in.) diameter by 76 mm (3 in.) height, in 4 layers compacted with five compaction stokes each layer, the samples were crimped and smoothed with a spatula. The molds were varnished with petroleum jelly as a release lubricant before using. The sample were left in the mold for the first 24 hours and air dried for 7 days after taken out from molds.

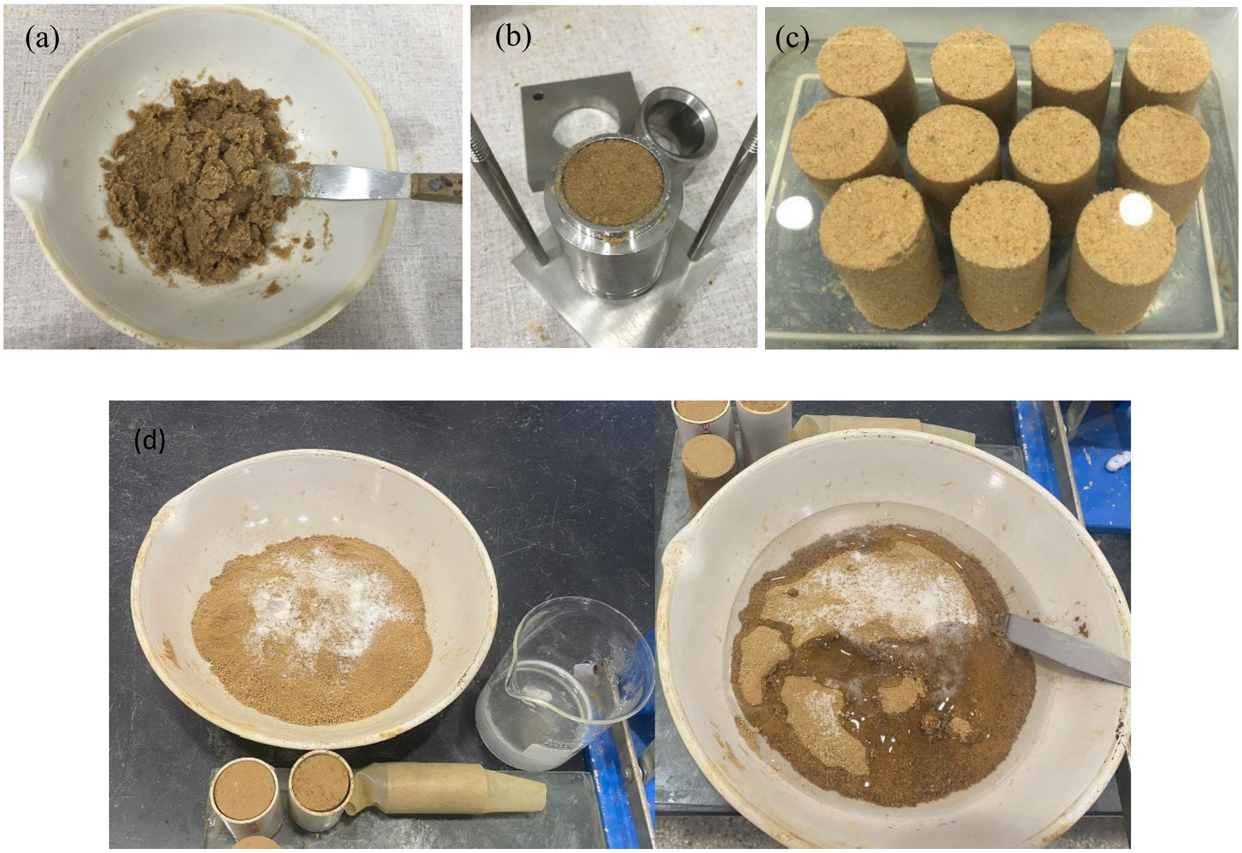

Fig. 4 Images of sample preparation (a,b,c) sand samples; (d) clay samples.

2.5 Unconfined compression test

The hydrogel-impregnated samples for the unconfined compression test were cylinder-shaped with a 2H:1D ratio (diameter of 33.0 mm and height of 71.1 mm). The unconfined compression test was conducted under strain-controlled conditions at a uniform loading rate of 1.5%/min following ASTM D2166.

2.6 Swelling Measurements

The swelling potential tests according to ASTM specification were carried out on hydrogel-impregnated clay samples. The 0.5 M Ca dry $CaCl_2$ powder was added in 150 g clay soil and mixed well with 35 mL sodium alginate solution, then the hydrogel-impregnated clayey soil was compacted in the mold as shown in Fig. 5. The distilled water is applied to the specimen until saturation. An electronic vernier caliper is used to measure the height of the specimen. The increasing reading of the vernier caliper is recorded each day. After three days the reading began to be constant, which means that the soil reached the maximum swelling potential. The swelling of the clay soil sample without any addition, after 3 days was 0.85 mm.

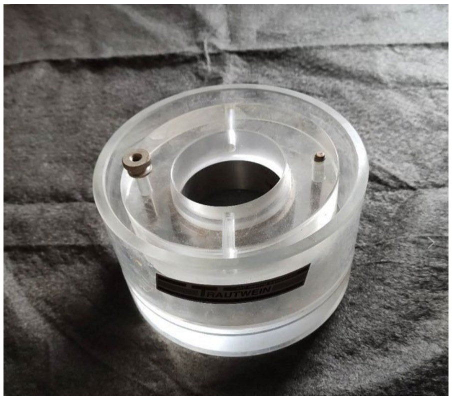

Fig. 5 Images of mold for the swelling test.

2.7 Permeability Test

The falling head permeability testing method is used to test the hydraulic conductivity of the hydrogel-impregnated sand following ASTM D5084-16a. For untreated sand, the constant head permeability testing method is used to conduct permeability tests following ASTM D2434-68.

2.8 Consolidated and Undrained Triaxial Test

Consolidation undrained triaxial compression test is conducted under 50, 100, and 200 kPa cell pressure at a constant axial strain rate of 1.0% stain/min. The tests terminated after the stain reached 15%.

2.9 Durability tests

Durability tests of hydrogel-impregnated soil samples are carried out according to standards ASTM D 560 for freeze-thaw cycles and ASTM D 559 for wet-dry cycles. The UCS tests are conducted on these samples every 3 cycles.

2.9.1 Freeze-thaw

Every freeze-thaw cycle began by introducing specimens in a freezing cabinet with constant temperature of -23 °C for 24 h. Next, the samples were placed in the moist room at temperature of 25 °C and relative humidity of 100% for 24 h. The number of freeze-thaw cycles was up to 12 times in this study. The mass loss after each freeze-thaw cycle was measured. After each freeze-thaw cycle, the hydrogel-impregnated samples were thawed at 50 °C for 24 h before testing.

2.9.2 Wet-dry

Every wet-dry cycle began with oven drying for 24 h at 50 °C. Then, specimens were immersed underwater for 24 h at 25 °C. The number of wet-dry cycles was up to 12 times in this study. The mass loss after each wet-dry cycle was measured.

2.10 Scanning Electron Microscopy (SEM) Analysis

SEM images are taken to observe the micro-scale connections between hydrogel and sand particles. The selected samples including untreated sand and hydrogel-impregnated sand under wet and dry conditions were mounted on the stubs with adhesive carbon conductive tabs. The prepared samples were observed by secondary electron detection.

3. Results/ Findings

3.1 Hydrogel-impregnated Sand

3.1.1 Effect of reaction time on strength improvement of hydrogel-impregnated sand

The UCS of hydrogel-impregnated sand with 0.4% sodium alginate content at different reaction time in the $CaCl_2$ solution was shown in Fig. 6. The reinforced sandy soil commonly exhibited a brittle behavior (Bu et al. 2018, Zhao et al. 2014). In contrast, the failure strain of hydrogel-impregnated sand could reach up to 6%, indicating a good ductility behavior. Meanwhile, all samples existed residual strength after the peak strength, which demonstrated a good elastic behavior. The UCS of hydrogel-impregnated sand increased with reaction time up to 3 days, and then the UCS started to reduce. This could be due to the degradation or decrosslinking of the hydrogel. Shoichet et al. (1996) found that increased exposure of calcium-crosslinked alginate to sodium citrate can result in decreased gel strength because sodium citrate chelates calcium, thereby decrosslinking calcium alginate. Rowley et al. (1999) also indicated that the ionically crosslinked alginates lost their mechanical properties over time due to an outward flux of crosslinking ions into the surrounding medium. The exchange between divalent crosslinking ions (e.g., Ca^{2+}) with monovalent ions from the surrounding environment causes alginate hydrogels to degrade (Breger et al. 2015). In this study, the sodium ions in the solution may degrade the Ca-alginate with time. Therefore, the optimum reaction time for Ca-alginate is 3 days.

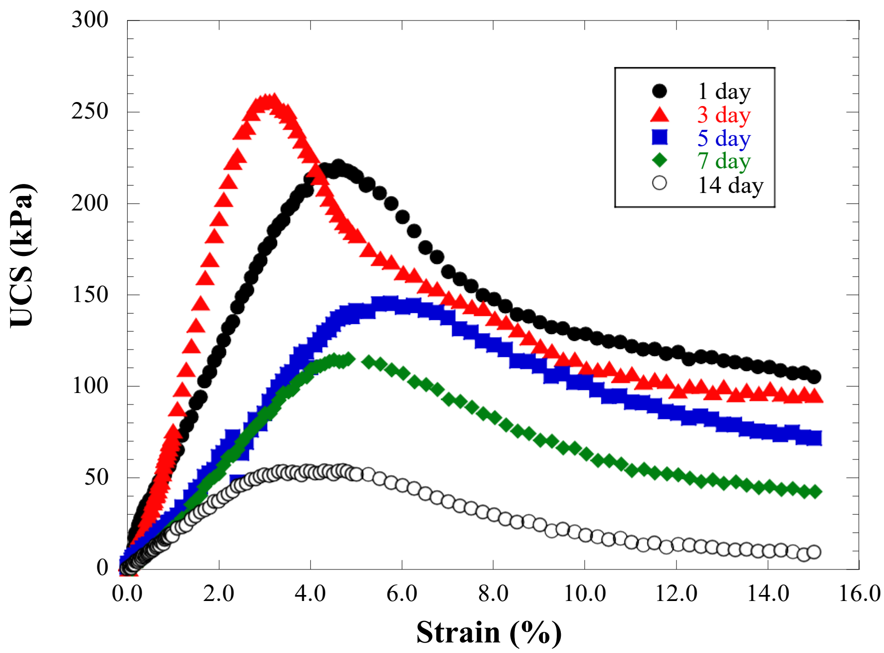

Fig. 6 The UCS of hydrogel-impregnated sand with 0.4% sodium alginate content at different reaction times.

3.1.2 Effect of sodium alginate content on strength improvement of hydrogel-impregnated sand

The UCS of hydrogel-impregnated sand at different sodium alginate contents after 3 days' reaction time was shown in Fig. 7 (a). It can be seen that the UCS of hydrogel-impregnated sand increased with the increase of sodium alginate content. The strength of hydrogel-impregnated sand at 0.4% sodium alginate content (260 kPa) was around two times higher than that at 0.1% sodium alginate content (140 kPa). Bu et al. (2018) found that the UCS of the optimum lime-treated sand (15% by weight of dry sand) was 140 kPa which is similar to hydrogel-impregnated sand with 0.1% sodium alginate. The UCS of hydrogel-impregnated sand was lower than that of cement-treated sand, but it is still comparable in such a lower percentage additive (0.4%). Consoli et al. (2009) reported that the UCS of 2.0% cement-treated sand was around 250 kPa which was similar to that of hydrogel-impregnated sand with 0.4% sodium alginate. Chang et al. (2015) mixed different contents of gellant gum with sand to improve the strength behavior of sand, and the results indicated that the UCS increased with gellant gum content. The UCS of 2% gellan gum-treated sand is around 180 kPa. Meanwhile, the residual strength of hydrogel-impregnated sand increased with the increase of sodium alginate content, and hydrogel-impregnated sand with 0.4% sodium alginate content had a residual strength of 100 kPa. This agrees with what Chang et al. (2015) reported that the gellan gum contents had a positive effect on residual strength of gellan gum treated sand.

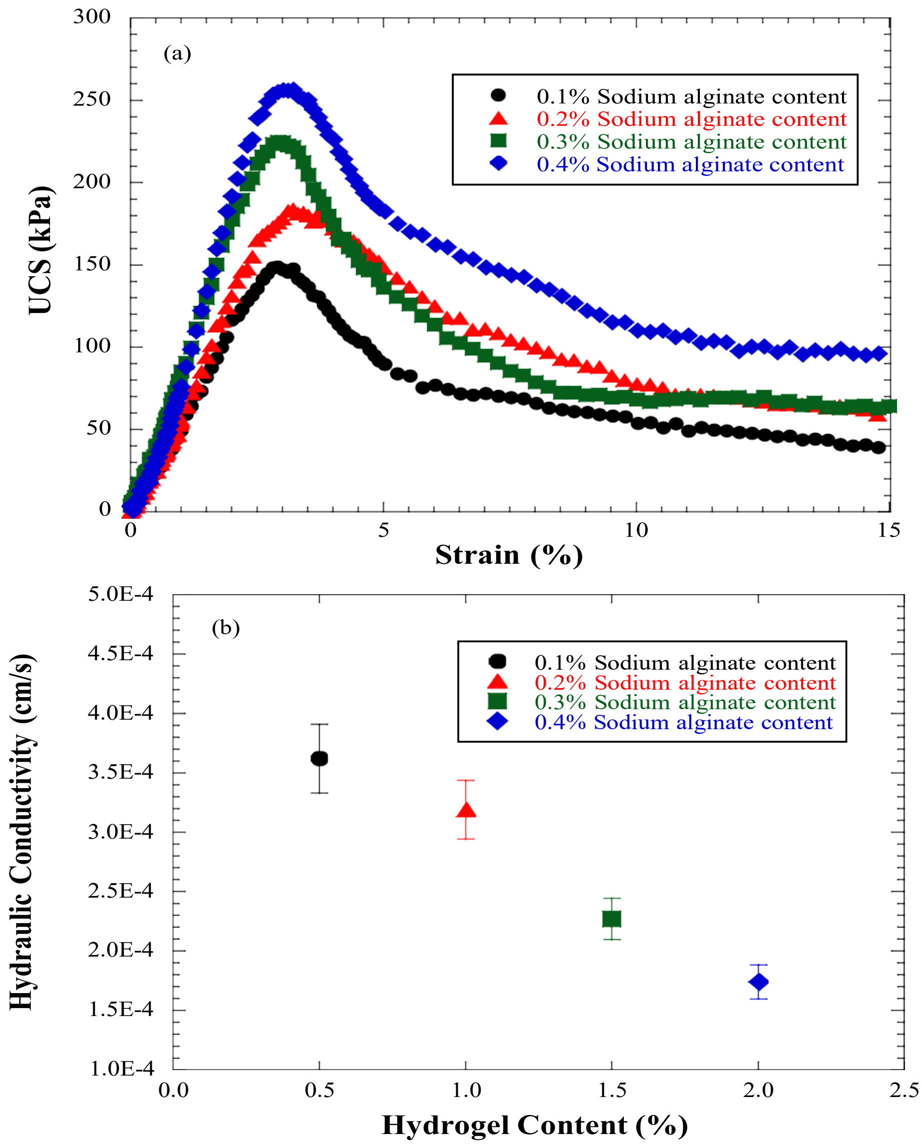

Fig. 7 The effect of sodium alginate content on (a) stress-strain curve; (b) hydraulic conductivity of hydrogel-impregnated sand.

The hydraulic conductivity of hydrogel-impregnated sand at different sodium alginate contents was investigated in this study as shown in Fig. 7 (b). In general, the higher was sodium alginate content, the lower hydraulic conductivity of hydrogel-impregnated sand would be. The hydraulic conductivity decreased from an untreated condition (~10^{-2} cm/s) to hydrogel-impregnated sand with 0.4% sodium alginate content (~1.8×10^{-4} cm/s), indicating that the void spaces between sand particles were filled and cemented by hydrogel.

3.1.3 Effect of curing temperature on strength improvement of hydrogel-impregnated sand

Four different curing conditions were selected to investigate the effect of curing temperature on the UCS of hydrogel-impregnated sand. After removing from the reaction tank, the hydrogel-impregnated sand is either (1) air-dried at room temperature (25^0C) for 28 days, or (2) oven-dried in 50^0C for 24 h, or (3) oven-dried in 80^0C for 24 h, or (4) oven-dried in 100^0C for 24 h. Fig. 8 showed the stress-strain curve of hydrogel-impregnated sand with 0.4% sodium alginate content at different curing temperatures. The wet condition means that the samples are tested without curing. It can be seen that the performance of stress-strain for hydrogel-impregnated sand was significantly affected by the curing temperature. The highest UCS is around 430 kPa under 50^0C oven-dried condition, and the lowest one is 160 kPa under 100^0C oven-dried condition. Chang et al. (2015) studied the strength behaviors of gellan gum-treated sand under different curing conditions. They reported that the UCS of the air-dried sample was higher than that of the wet sample, which is opposite to the results in this study. This could be due to that during the air-dry process (28 days), the remaining sodium ions in the wet sample may degrade/decrosslinking the Ca-alginate over time.

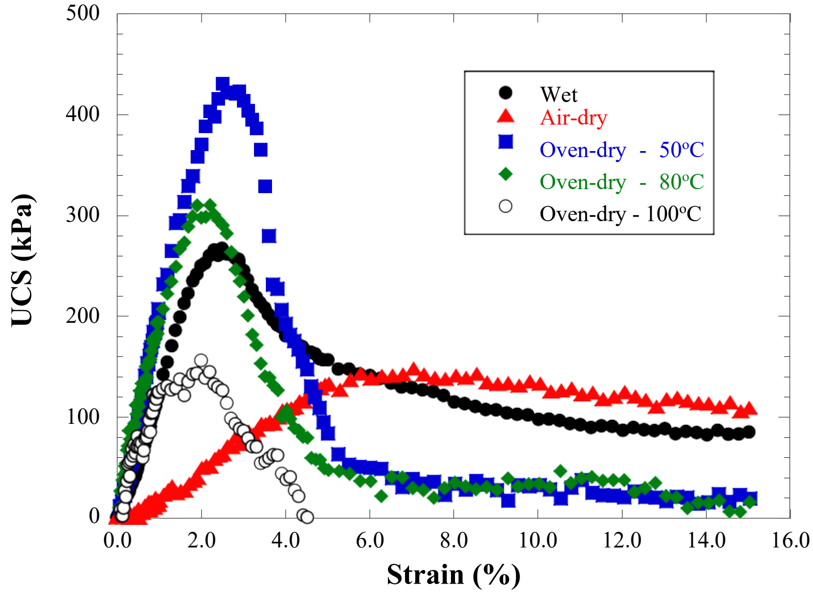

Fig. 8 The stress-strain curve of hydrogel-impregnated sand under different curing conditions.

The failure modes of hydrogel-impregnated sand at different curing temperatures were shown in Fig. 9. In the case of the wet condition, the sample does not completely break after peak strength and is still cemented by hydrogel, achieving a residual strength of 90 kPa at 15% strain. The failure sample exhibited a shear zone failure mode as shown in Fig. 9 (a), an X-sharp shear band, and several small cracks appeared in the failure sample. Asghari et al. (2003) found a similar failure mode for lime-cemented sand. Fig. 9 (b) showed the failure sample under 28 days air-dried condition. The sample failed with a barreling or drum shape and no crack was identified, indicating a uniform status of the sample. This is consistent with the result from the stress-strain curve in Fig. 8, the air-dried sample presented a superior ductility, and the failure strain was around 7% and had a 100 kPa residual strength at 15% strain. Plé and Lê (2012) also reported that the fiber-reinforced silty clay soil presented a drum shape failure mode, which indicated that the strain localization is prevented by the presence of the fibers. When the hydrogel-impregnated sample was cured at a higher temperature, the ductility and strength significantly changed. Fig. 9 (c) showed the failure sample at 50°C curing temperature, and the sample exhibited a shear failure mode. Meanwhile, the peak strength reached around 430 kPa but the stress reduced dramatically after peak stress. The residual strength left only around 20 kPa at 15% failure strain. When the curing temperature increased to 100°C, the failure strain reduced to around 2.0%, and the peak stress reduced to 160 kPa. The sample became brittle and weak with no residual stress. The top of the sample was totally broken and the failed part became loosely sand as shown in Fig. 9 (d).

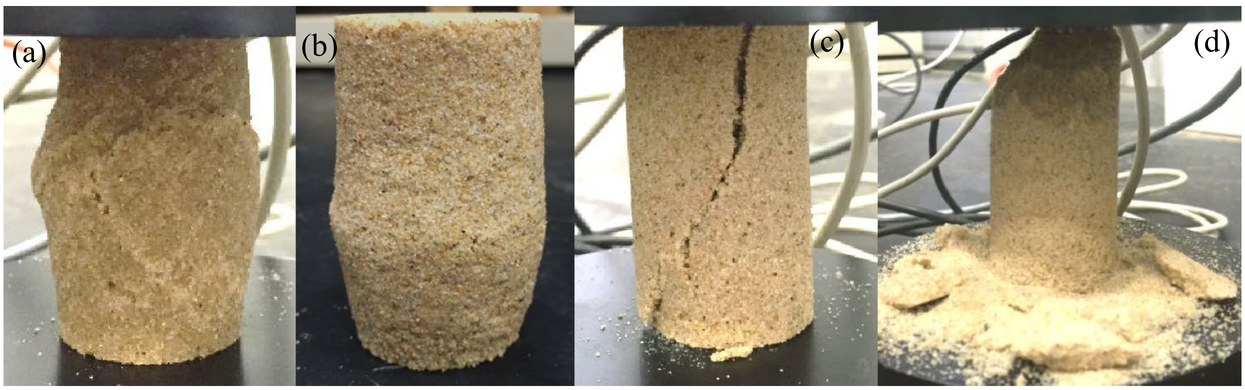

Fig. 9 The failure mode of hydrogel-impregnated sand under (a) wet condition; (b) air-dry condition; (c) 50^{0}C oven-dried condition; (d) 100^{0}C oven-dried condition.

The SEM images of untreated sand and hydrogel-impregnated sand were shown in Fig. 10. The untreated sand does not have cohesion, and the shape of untreated sand was irregular as shown in Fig. 10 (a). The image of hydrogel impregnated sand under wet conditions was shown in Fig. 10 (b). The hydrogel uniformly warped the sand particles and cemented them together, resulting in the reduction of void space. This is consistent with the results of hydraulic conductivity in Fig. 7 (b). The hydrogel connection shrank in size after the hydrogel-impregnated sample was cured at 50°C as shown in Fig. 10 (c). However, the strength of 50 °C dried sample increased which may cause by the fact that the hydrogel becomes a dried solid material during the drying process.

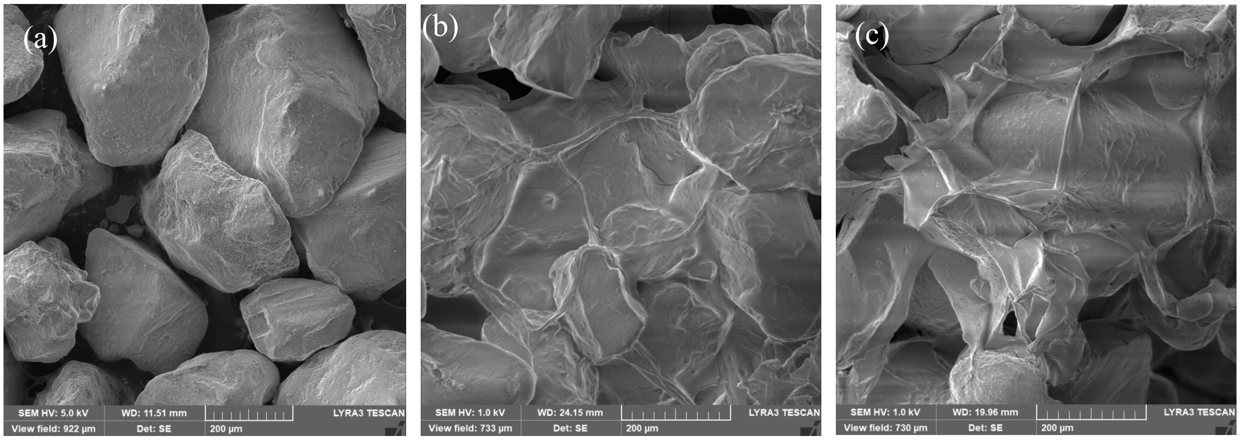

Fig. 10 SEM images of a) Untreated Mississippi sand; b) hydrogel-impregnated sand under wet condition; c) hydrogel-impregnated sand under dry condition (50^0C oven-dried).

3.1.4 Shear strength of hydrogel-impregnated sand

The natural repose angle of Mississippi sand was shown in Fig. 11 (a) which was around 32°. The consolidated and undrained triaxial tests were conducted on hydrogel-impregnated sand with 0.4% sodium alginate, and three different confining pressures (100 kPa, 200 kPa, and 400 kPa) were selected. Fig. 11 (b) showed the Mohr circle curves and failure envelop obtained from triaxial compression strength tests on hydrogel-impregnated samples. The test results showed that the cohesion and friction angle of hydrogel-impregnated sand is 150 kPa and 16° respectively. Sandy soil is well-known as cohesionless soil. The gelation connection provided by hydrogel enhanced the connection between sand particles and improved the cohesion of sandy soil. Li et al. (2015) investigated the shear strength of MICP-treated sand (0.18 M Ca) and found that the cohesion of MICP-treated sand increased to 20 kPa which was much lower than that of hydrogel-impregnated sand, and the friction angle of MICP-treated sand was similar to that of hydrogel-impregnated sand.

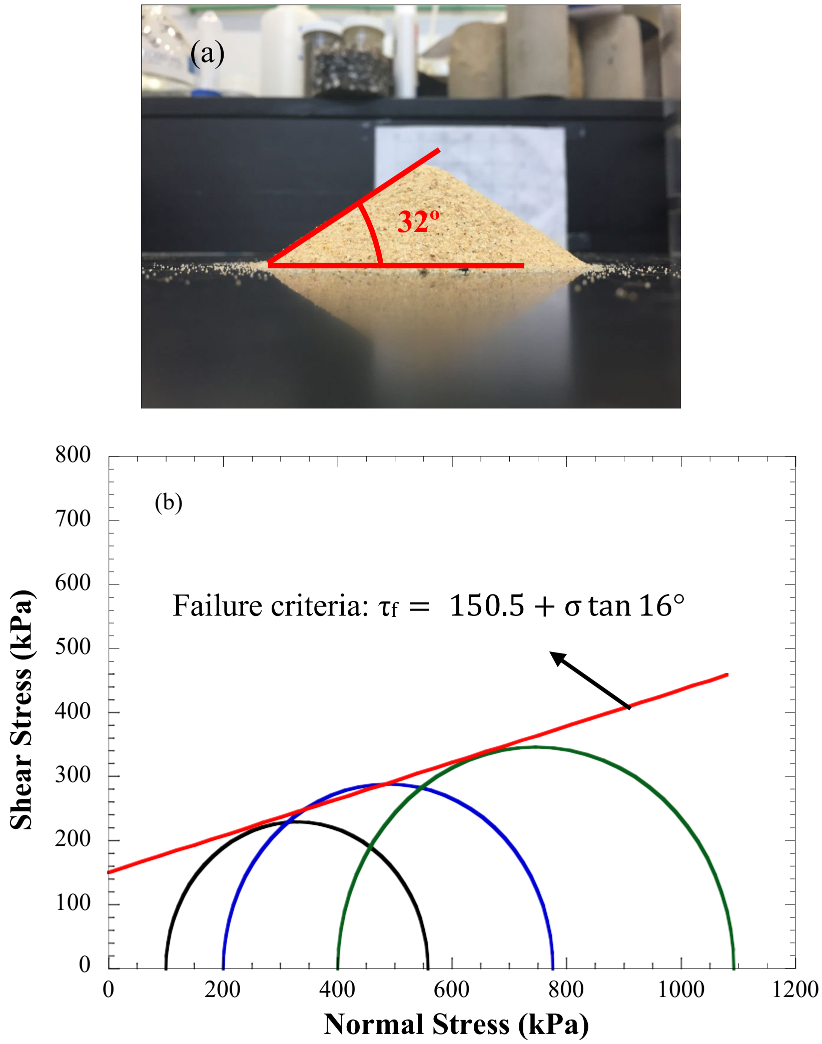

Fig. 11 (a) The nature repose angle of Mississippi sand; (b) Mohr circle and failure envelop of hydrogel-impregnated sand with 0.4% sodium alginate.

3.1.5 Durability test on hydrogel-impregnated sand

The durability of hydrogel-impregnated sand was tested through wet-dry and freeze-thaw cycles. The effect of wet-dry and freeze-thaw cycles on the UCS of hydrogel-impregnated sand was shown in Fig. 12. The samples used for durability test are hydrogel-impregnated samples with 0.4% sodium alginate content at curing temperature of 50°C. It is found that no significant difference was noticed for the samples subjected to 3 wet-dry or freeze-thaw cycles. After 3 cycles, the UCS of hydrogel-impregnated sand started to decrease with the increase of wet-dry or freeze-thaw cycles. After 12 wet-dry or freeze-thaw cycles, 60% of the original UCS of hydrogel-impregnated sand remained. Kampala et al. (2013) used fly-ash to reinforce clay soil, and the UCS reduced over 50% after 6 wet-dry cycles. Chang et al. (2015) studied the strength behavior of 2% gellan gum-treated sand and found that the UCS dropped dramatically from 435 kPa (dry condition) to 45 kPa (re-submerged condition). This result indicated that the gellan gum-treated sand was not recoverable once the gellan gum gel is condensed through dehydration. Eskişar et al. (2015) found that the cement-treated clay reduced 50% strength after 5 freeze-thaw cycles. With these studies, it is indicated that the Ca-alginate hydrogel has a good durability performance.

Meanwhile, the natural environment contains many microorganisms that may also have an impact on the stability of Ca-alginate impregnated sand. Studies have concluded that the decreased mechanical strength of Ca-alginate was due to the entrapped growing microorganism (Dey et al. 2011, Eikmeier & Rehm, 1987). Therefore, the effects of microorganisms on the mechanical properties of hydrogel-impregnated samples need to be further studied.

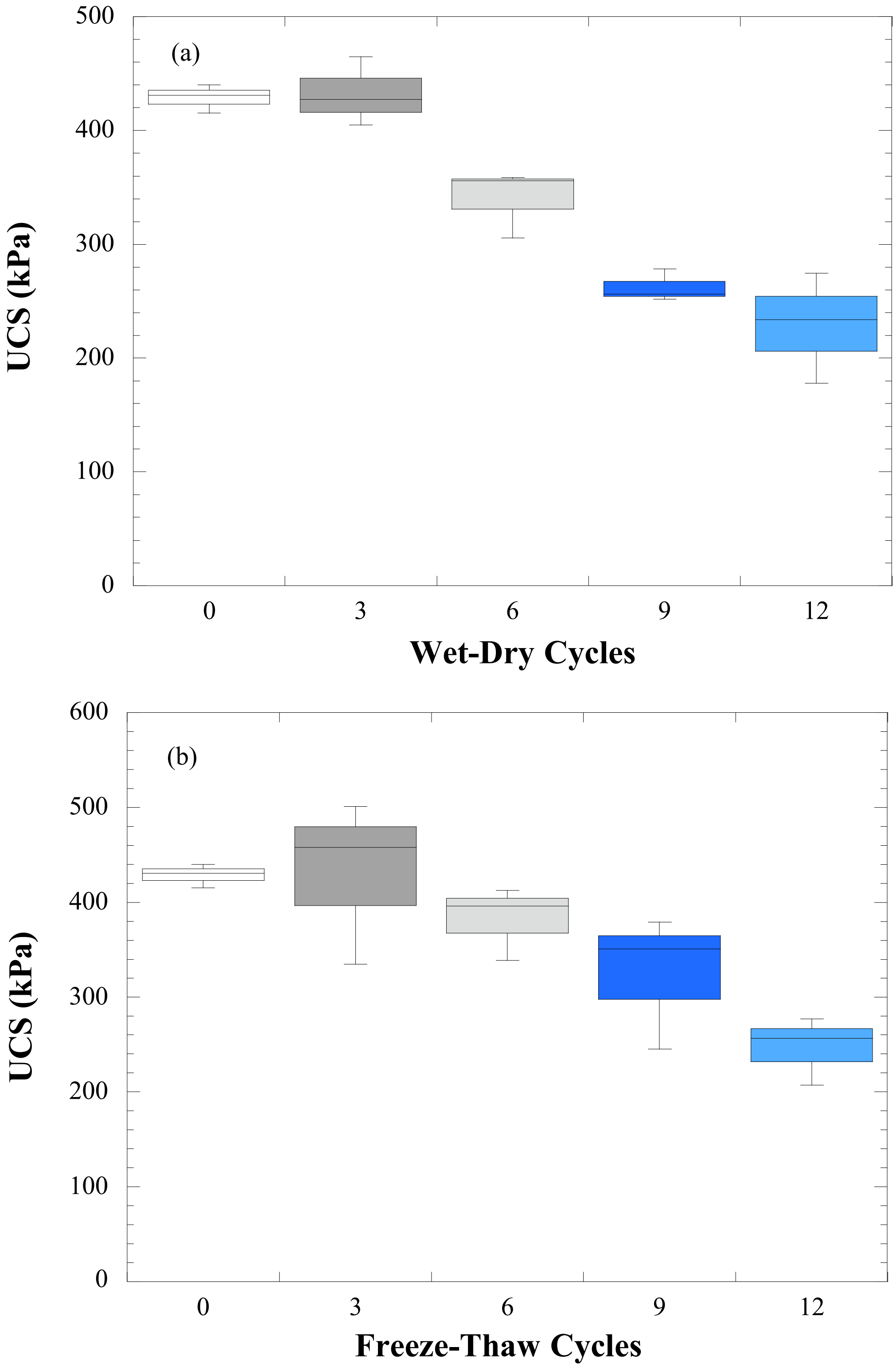

Fig. 12 The effect of wet-dry (a) and freeze-thaw (b) cycles on unconfined compressive strength of hydrogel-impregnated sand

3.2 Hydrogel-impregnated Clay

Depend on the previous study on hydrogel-impregnated sand, hydrogel-impregnated clay was investigated in this part.

3.2.1 Effect of sodium alginate content on strength improvement of hydrogel-impregnated clay

The hydrogel-impregnated clay UCS samples were cured for 3 days' reaction time without and with 0.1%, 0.2%, 0.3%, and 0.4% sodium alginate content in 0.5 M $CaCl_2$ solution. The clay samples were air-dried for 28 days before UCS testing. The UCS results of hydrogel-impregnated clay at different sodium alginate contents were shown in Fig. 13. The UCS of hydrogel-impregnated clay decreased with the increase of sodium alginate content. The strength of clay samples without sodium alginate (3200 kPa) was the highest, which was about 4.3 times of clay samples with 0.4% sodium alginate content (750 kPa). But the strain of hydrogel-impregnated clay samples increased along with higher sodium alginate content and the hydrogel-impregnated clay with 0.4% sodium alginate content had a residual strength of 750 kPa. The addition of sodium alginate had a positive effect on the residual strength of hydrogel-impregnated clay. The produced Ca-alginate hydrogel improved the ductility of hydrogel-impregnated clay samples significantly.

The failure modes of hydrogel-impregnated clay with different sodium alginate content (0.1%, 0.2%, 0.3%, 0.4%) were shown in Fig. 14. The sample with 0.1% sodium alginate content broke completely. The sample with 0.2% sodium alginate content broke slightly with very small compression. While the sample with 0.3% sodium alginate content broke completely with larger compression. But the sample with 0.4% sodium alginate content filed with a shear zone failure mode and largest compression. The sample failed with a barreling or drum shape.

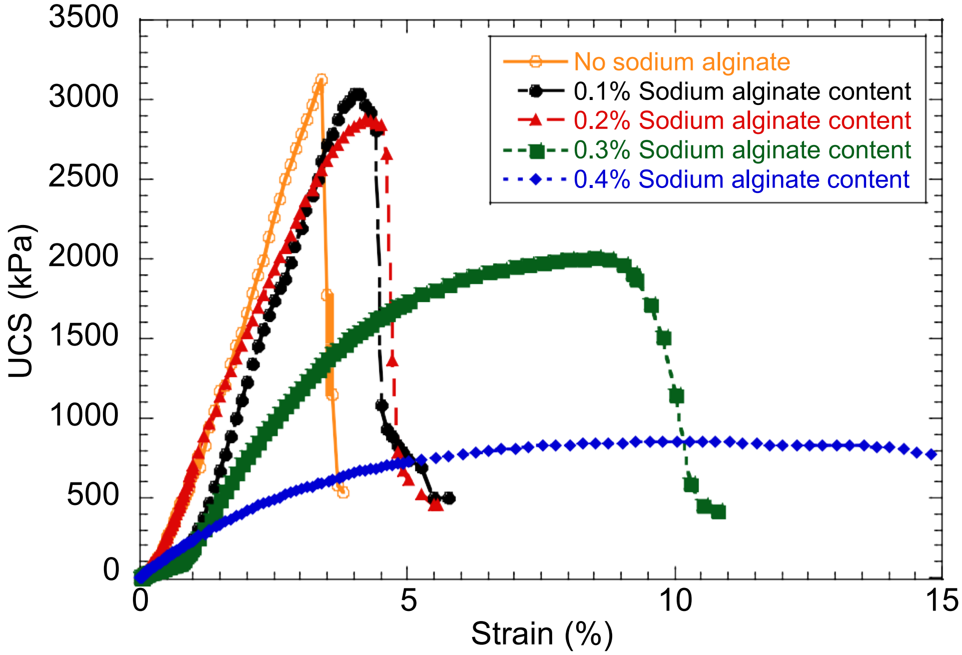

Fig. 13 The stress-strain curve of hydrogel-impregnated clay under different sodium alginate content.

Fig. 14 The stress-strain curve of hydrogel-impregnated clay under different sodium alginate content.

3.2.2 Swelling test on hydrogel-impregnated clay

The swelling potential test was conducted on hydrogel-impregnated clay soil. The test was carried out as mentioned before. Figs. 15 and 16 show the maximum swelling deformation for each mixture. From these figures, one can conclude that the addition of sodium alginate decreases the swelling deformation. And higher sodium alginate content gave more help to reduce the swelling deformation of clay soil. The addition of 0.4% sodium alginate decreased the swelling deformation from 0.8 to 0.5, giving a reduction of the swelling deformation of 38.7%.

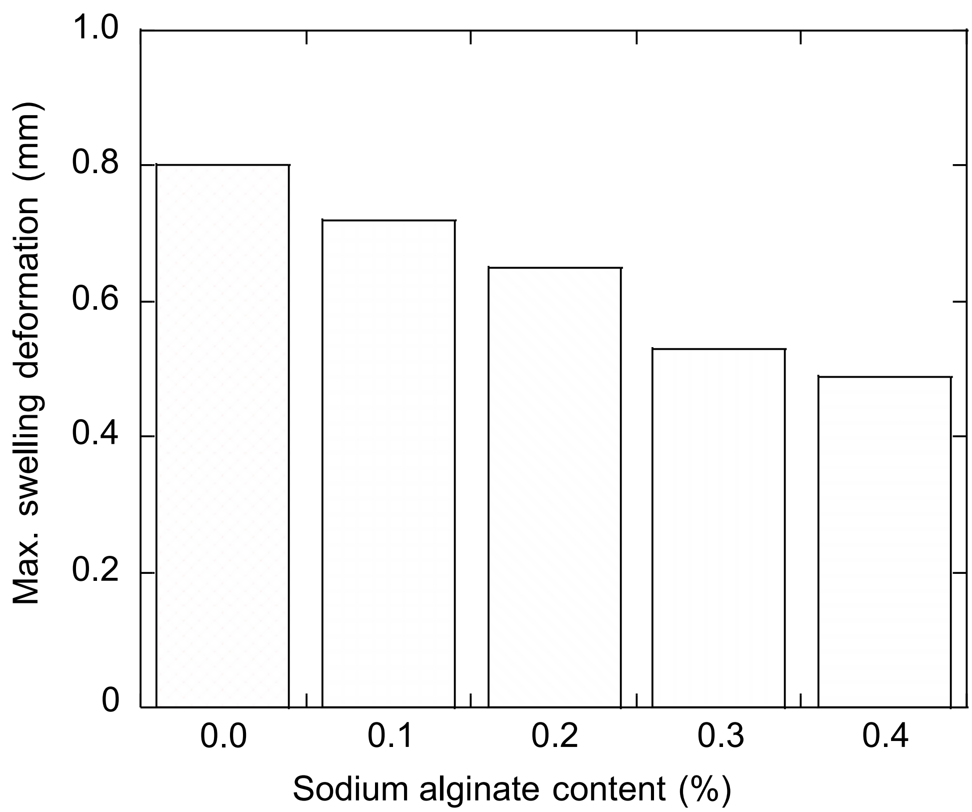

Fig. 15 Maximum swelling deformation with and without sodium alginate addition.

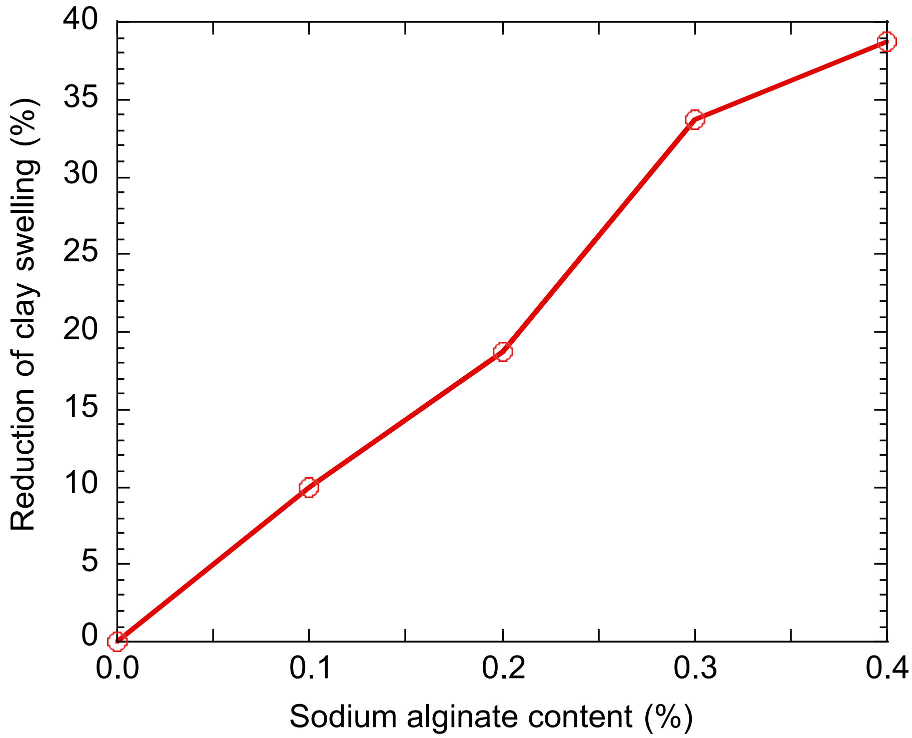

Fig. 16 Reduction of swelling deformation with different sodium alginate content.

3.2.3 Durability test on hydrogel-impregnated clay

The durability of hydrogel-impregnated clay was tested through wet-dry and freeze-thaw cycles. The effect of wet-dry and freeze-thaw cycles on the UCS of hydrogel-impregnated clay was shown in Fig. 17. The samples used for the durability test are hydrogel-impregnated clay samples with 0.4% sodium alginate content at a curing temperature of 50°C.

Similar to hydrogel-impregnated sand, there was no significant decrease happened for clay samples subjected to 3 wet-dry or freeze-thaw cycles. After 3 cycles, the UCS of hydrogel-impregnated clay began to decrease along with the increase of wet-dry or freeze-thaw cycles. After 12 wet-dry and freeze-thaw cycles, 60% and 80% of the original UCS of hydrogel-impregnated clay remained. The results indicated that the Ca-alginate hydrogel has a good durability performance against wet-dry and freeze-thaw cycles.

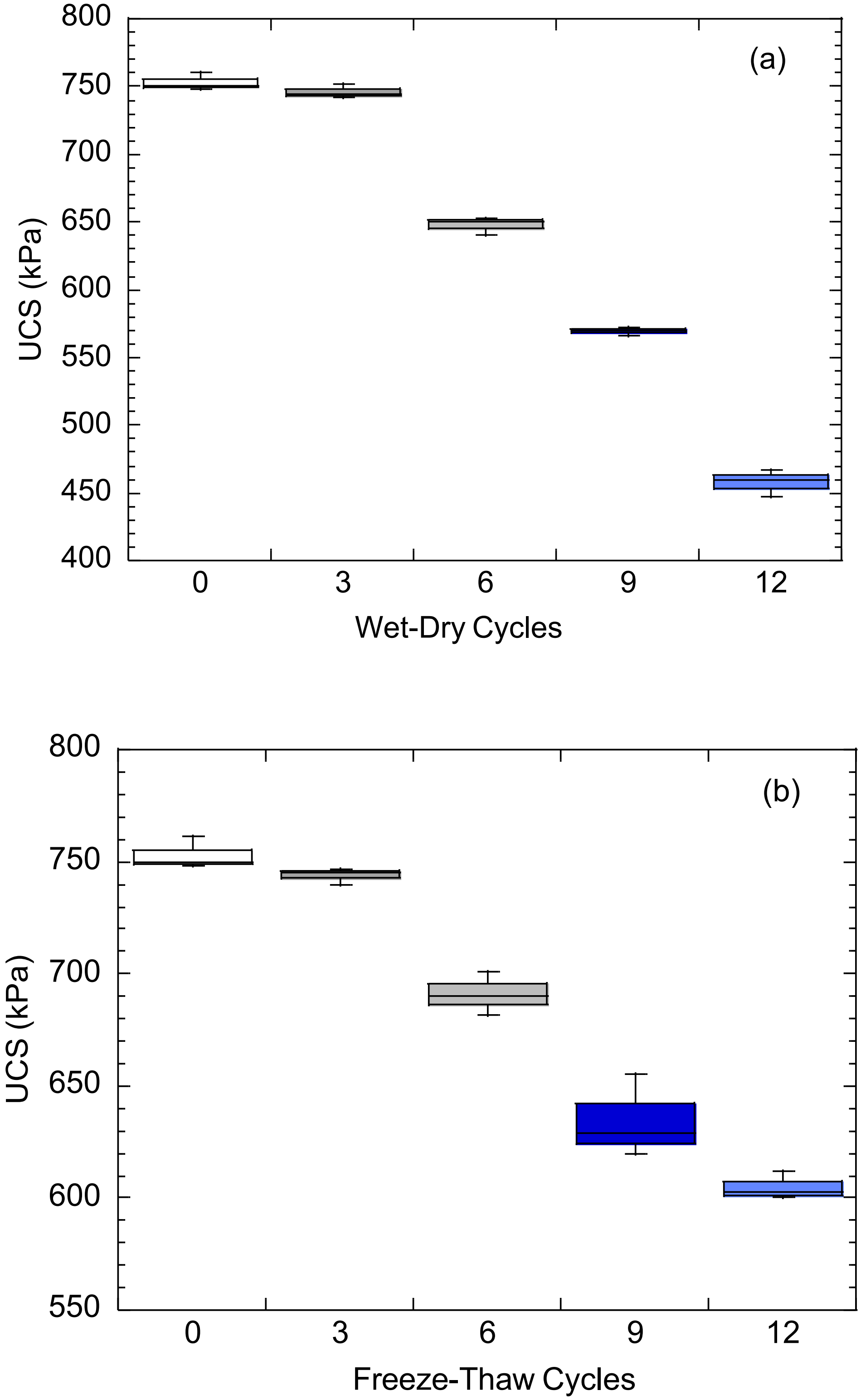

Fig. 17 The effect of (a) wet-dry and (b) freeze-thaw cycles on unconfined compressive strength of hydrogel-impregnated clay.

3.2.4 Shear strength parameters on hydrogel-impregnated clay

The consolidated and undrained triaxial tests were conducted under three different cell pressure conditions 50 KPa, 100 KPa, and 200 KPa (Fig.19) to obtain the soil shear strength and the difference in the physical soil properties using various hydrogel content.

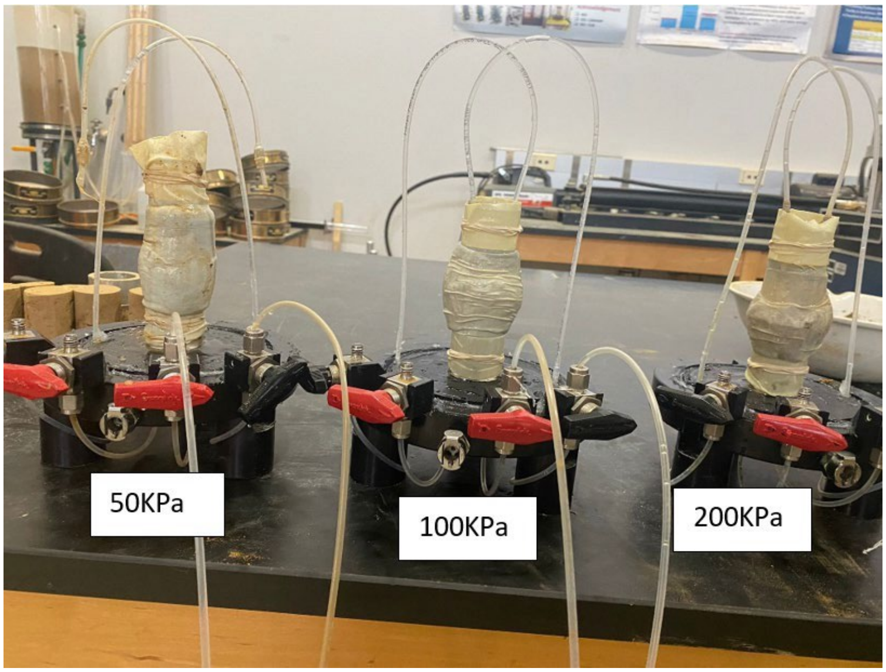

Fig. 18 Failed clay soil samples after triaxial tests.

Fig. 19 shows the Mohr circle curves and failure envelopes obtained from triaxial compression strength tests on hydrogel-impregnated clay soil samples. The test results show that the friction angle of hydrogel impregnated clay with 0%, 0.3%, and 0.4% sodium alginate were 25 °, 31 °, and 34 ° respectively. The gelation connection provided by hydrogel enhanced the connection between clay soil particles and improved the friction of soil. However, the cohesion of hydrogel impregnated clay with 0%, 0.3%, and 0.4% sodium alginate were 56 MPa, 39 MPa, and 32 MPa, respectively, which decrease along with higher sodium alginate content.

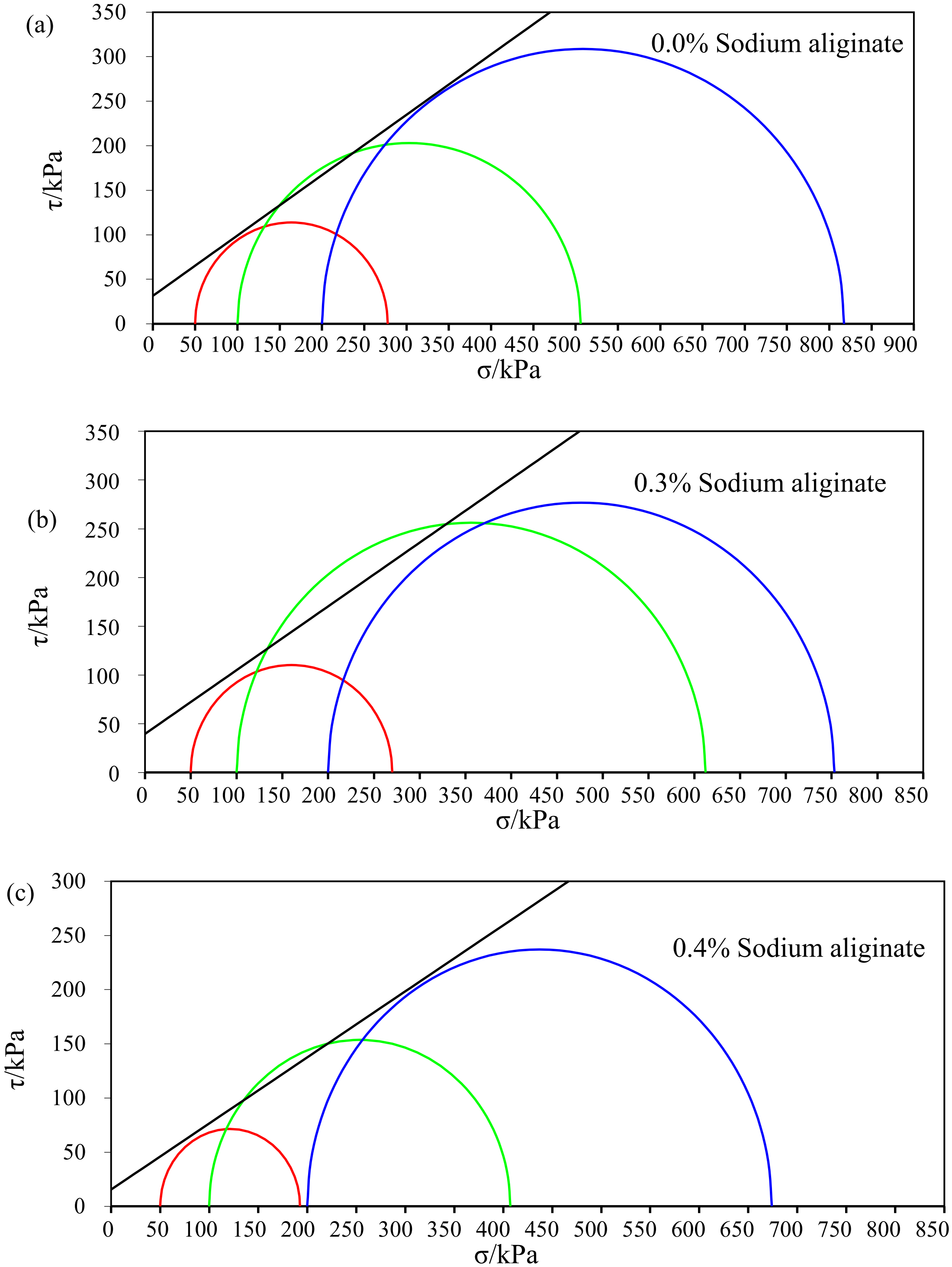

Fig. 19 Mohr circle and failure envelope of hydrogel-impregnated clay with a) 0%; b) 0.3%; and c) 0.4% sodium alginate.

4. Impacts/Benefits of Implementation (actual, not anticipated)

Many marine transportation projects located in the coastal area have to be built on top of cohesionless soil such as sandy soil or silty soil. These sites are long in suffering the coastal erosion that is caused by natural effects and human activities. The results of this study bring an important conclusion that the hydrogel-impregnated sand achieved a relatively high strength even at low concentrations. The cohesion of treated sand improved from 0 to 150 kPa which had great potential to against the coastal erosion induced by hurricanes or flooding. But when this method was applied to clay, the addition of sodium alginate reduced the strength of clay samples, however, the ductility of clay soil was enhanced significantly. The Ca-alginate hydrogel could also reduce the swelling deformation of expansive clay soil. The swelling behavior of expansive soil can cause significant soil movement in the subbase of the maritime transportation infrastructures which results in crack damage on the surface. With the stabilization of Ca-alginate hydrogel, it will create more stable and safe subbase materials for the infrastructures. Moreover, the results of the durability test for both the hydrogel-impregnated sand and clay indicated that the Ca-alginate hydrogel has a good durability performance against wet-dry and freeze-thaw cycles.

5. Recommendations and Conclusions

Generally, the hydrogel-treated soil could help to stabilize the maritime transportation facilities constructed on the problem soil, especially the cohesionless soil. For sand, the effects of reaction time, sodium alginate content, and curing temperature on mechanical behaviors of hydrogel-impregnated sand were studied through unconfined compression tests, falling head permeability tests, consolidated and undrained triaxial tests, scanning electron microscopy, and durability tests. The optimum reaction time and curing temperature of hydrogel-impregnated sand were found to be 3 days and 50°C, respectively. The UCS tended to increase with the increase of sodium alginate content, but hydraulic conductivity decreased with the increase of sodium alginate content. The UCS of hydrogel-impregnated sand at 0.4% sodium alginate content can reach 430 kPa. Meanwhile, the hydrogel-impregnated sand showed a significant improvement in cohesion. The results showed that the cohesion and friction angle of hydrogel-impregnated sand is 150 kPa and 16º respectively. These would help bond the sand particles as a whole and improve their strength performance. In addition, the stress-strain curves of hydrogel-impregnated sand indicated that the ductility of hydrogel-impregnated sand was significantly improved compared with the traditional cementitious method. Moreover, the results of durability tests indicated that approximately 60% of the original UCS of hydrogel-impregnated sand remained after 12 wet-dry and freeze-thaw cycles.

There are some challenges when the hydrogel is applied to clayey soil. The strength of clay samples without sodium alginate (3200 kPa) was the highest, which was about 4.3 times of clay samples with 0.4% sodium alginate content (750 kPa). But the strain of hydrogel-impregnated clay samples increased along with higher sodium alginate content, and the hydrogel-impregnated clay with 0.4% sodium alginate content had a residual strength of 750 kPa. And higher sodium alginate content gave more help to reduce the swelling deformation of clay soil. The expansive behavior was mitigated through the addition of sodium alginate. With the addition of 0.4% sodium alginate, the swelling deformation decreased from 0.8 mm to 0.5mm, giving a reduction of the swelling deformation of 38.7%. From the triaxial tests, it has been found that higher sodium alginate content resulted in higher friction angles. However, the cohesion decreased along with higher sodium alginate content. After 12 wet-dry and freeze-thaw cycles, 60% and 80% of the original UCS of hydrogel-impregnated clay remained. The results indicated that the Ca-alginate hydrogel has a good durability performance against wet-dry and freeze-thaw cycles.

Based on these conclusions above, sodium alginate was highly recommended for the application of reinforcement of cohesionless soil in maritime transportation infrastructure projects. It can significantly improve the strength and ductility performance of cohesionless soil. It can also create a relatively high cohesion strength for sandy or silty soil which could significantly enhance the subgrade of maritime transportation infrastructure against coastal erosion. The sodium alginate does not show any improvement in the strength behavior of treated clay soil. However, it helps to mitigate the swelling behavior of the expansive clay which may benefit to mitigate the cracks damage on the maritime transport infrastructure. Further study on erosion resistance of hydrogel-treated sandy soil and cracks mitigation observation tests were highly recommended to better understand the feasibility of applying the hydrogel in the subbase of maritime transportation infrastructure.

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