TRIAXIAL SHEAR BEHAVIOR OF CEMENTED-TREATED SAND UNDER HIGH CONFINING PRESSURES

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Declaration Form

DECLARATION

I hereby, declare that this manuscript, entitled "Triaxial Shear Behavior of Cement-Treated Sand Under High Confining Pressures", is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Date: 04/05/2023

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List of Abbreviations & Symbols

OPC	Ordinary Portland Cement
CSA	Calcium Sulfoaluminate
CD	Consolidated Drained
CU	Consolidated undrained
UU	Unconsolidated undrained
SEM	Scanning Electron Microscope
Cc	Cement Content
σ'_3	Confining Pressure (Effective Principal Stress)
q_{peak}	Peak Deviator Stress
p'_{peak}	Mean Effective Stress,
φ'_{peak}	Peak Friction Angle
c'_{peak}	Cohesion Intercept
ε_a	Axial Strain
εa	Volumetric strain

Abstract

Over the years, stabilizing materials like biopolymer, fly ash, bitumen, lime, and Portland cement have stabilized and improved the engineering soil's properties. However, because of the environmental problems associated with OPC use, substituting it with calcium sulfoaluminate (CSA) cement offers excellent promise for ground improvement because it is less harmful to the environment. Nevertheless, previous studies have examined the effects of CSA cement on the mechanical behavior of cemented sand; researchers have yet to make an effort to study the behavior of CSA cement-treated sand under high confining pressure. To this end, a consolidated-drained (CD) triaxial test was conducted at high confining pressure to examine CSA treated sand's shear strength and mechanical characteristics. In addition, SEM analysis was performed to learn more about the substructure of the tested samples. Experimental conditions, including effective stresses of 500, 1000, and 1500 kPa, and 3, 5, and 7% CSA cement content were employed in this research. In conclusion, the test results revealed that the effective stresses and the percentage of CSA cement present in the samples significantly impact the mechanical behavior of CSA-treated sand under high confining pressures.

Keywords: calcium sulfoaluminate; high pressure; consolidated drained triaxial test; shear strength, volume change

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Chapter 1 – Introduction

1.1 Introduction

The strength of soil can be improved through soil stabilization by enhancing its compressibility, rate of settlement, bearing capability, and stability. Cementing agents such as fly ash, biopolymer, Portland cement, and lime have all been studied to develop a more potent soil-stabilizing material [1-6]. In addition, several publications have emphasized the need to investigate how cement content influences the strength and mechanical properties of soils treated with cementatious binders [7-10].

Although OPC is a durable and resilient material, it is losing favor for use in building and geotechnical uses due to its substantial carbon footprint. The mean world temperature has continuously risen, and geotechnical applications account for roughly 7% of carbon dioxide emissions from cement production [11]. Given the yearly increase in cement usage and the environmental concerns associated with Portland cement, there is an urgent need for a sustainable binder that does not compromise the improved soil's engineering properties[12].Compared to OPC, calcium sulfoaluminate (CSA) cement, whose primary component is ye'elimite, generates a smaller carbon footprint [13]. Furthermore, many researchers have examined CSA cement as one of the options for soil stabilization and improvement [14-23] due to its admirable properties, such as good resistance to freeze-thaw cycles, rapid strength gain, and emits lesser carbon compared to OPC.

Only a few studies [9, 24-27] have examined the impacts of high-containing pressures on soils treated with cement, despite many more investigating the mechanical behavior of soils under low to intermediate effective stresses. Since most engineering issues arise at low confining pressures, understanding soil behavior under high pressure is crucial for offshore piling and deep pile foundations, among others [8].

Hence, a CD triaxial test under high effective stresses were utilized to examine the shear strength, and mechanical characteristics of CSA cemented sand. To replicate in situ stresses, various confining pressures between 500 to 1500 kPa were used. The behavior of the cemented sample under stress-strain and volumetric change during the CD triaxial test was also discussed.

1.2 Definition of the problem

Geotechnical engineering has been essential in developing the world's infrastructure while assuring its durability and sustainability. However, the increasing incidence of foundation failures in construction projects due to problematic, compressible, and weak soil, among other factors, has become a recurrent disaster that negatively impacts this development. Hence, there is a need to enhance soil's engineering properties of problematic and weak soil for construction activities.

Furthermore, with the increasing rate of carbon emissions into the environment from geotechnical and construction activities, it is crucial to decrease the percentage of carbon oxide in the atmosphere by replacing Ordinary Portland Cement (OPC) with an eco-friendly binder. Therefore, lowering the likelihood of global warming and its consequences due to the amounts of CO_2 present in the atmosphere present is crucial.

1.3 Aim and Objective

This study aims to use an Environmental Triaxial Automated System to examine the CSA-cemented sand's shear strength and mechanical properties under high constraining pressure.

The objectives of the study are listed below to achieve the study's aim;

- To conduct a series of consolidated drained (CD) triaxial tests on a CSA cement-treated sand with high confining pressure.
- To determine the substructure of the sheared CSA cemented sand samples from the triaxial test using an SEM analysis.

Research Scope

Laboratory study of a CSA-treated sand's shear strength and mechanical characteristics using an Environmental Triaxial Automated System under high confining pressure. In this study, three different degrees of cementation (3%, 5%, and 7%) were utilized in conjunction with three effective stresses (500, 1000, and 1500 kPa).

Chapter 2 – Literature review

2.1 Introduction

This literature review aims to identify high-quality research articles on soil stabilization using mechanical and chemical methods. Triaxial investigations of sand treated with different binders are also discussed. This chapter also describes previous studies on soil improvement related to cement-treated sand under confining pressure.

2.2 Principles of Soil Stabilization

There are numerous methods and techniques for stabilizing soil. However, these techniques are usually divided into chemical and mechanical stabilization. Soil can be mechanically stabilized by applying vibration, compaction, impact, and kneading forces. Additionally, adding stabilizers ranging from lime, blast furnace slag, fly ash, and cement to weak soil can enhance the engineering properties of problematic and weak soils [28].

2.3 Methods of Soil Stabilization

There are several kinds of techniques and methods for stabilizing soil. However, these techniques are typically categorized as either chemical or mechanical stabilization.

2.3.1 Mechanical Stabilization

Stabilization by mechanical means is a form of soil stabilization in which soil particles are packed more closely together. It can be achieved by densifying the soil and reducing air voids in the soil. In mechanical stabilization, soil's engineering properties are enhanced by applying static weight in the form of vibration and compaction [29]. Several different machines and equipment can be used for the mechanical stabilization of soil. Some of this equipment includes vibrating compactors, rollers, boards, and clamps, among others. Properly selecting compaction equipment is essential in getting the best-desired results while saving costs.

2.3.2 Chemical Stabilization

In civil engineering, chemical soil stabilization is a technique employed to improve soil's engineering and physical properties before construction activities by adding chemicals. Soil stabilization is often carried out to minimize the amount of water entering the soil and prevent erosion. In the chemical stabilization of soil, chemicals such as CSA, lime, and fly ash, among others, increase the bearing capacity and soil shear strength and reduces settlement and compressibility.

2.4 Stabilization of soil with CSA cement

CSA cement is more environmentally friendly than Ordinary Portland Cement (OPC). Due to the environmental concerns connected with OPC, it has recently been used in the construction industry as an alternative binder in soil stabilization. Several studies have examined the possibility of using CSA cement for ground improvement. This section covers studies on the effectiveness of using CSA cement as a stabilizing material.

The stabilizing mechanism of an expansive soil treated with Calcium Sulfoaluminate (CSA) cement was studied by Pooni, et al. [17]. The research determined the hydration product and microstructural characteristics of cemented samples treated with. 1, 3, 5, 7, and 10% CSA cement by dry unit weight were used to remediate the expanding soil. The test samples were prepared and cured at different curing days ranging from 1 to 28 days. The researchers used UCS laboratory testing to examined the treated samples' strength increase. In addition, FTIR, XRD, TG, and SEM analysis tests were used to ascertain the microstructural behavior of the examined samples. The study showed that treating the expansive earth with CSA cement increased its strength. Furthermore, the strength increased even more with a rise in CSA cement concentration. Similarly, the Microstructural test findings show that the CSA-treated samples developed hydration products.

Jumassultan, et al. [16] studied the aftermath of freeze and thawed on the development of strength in sand treated with CSA cement. Experimental procedures like UCS and UPV were performed on test samples treated with 2, 5, 7, and 10% of CSA cement by dry weight of sand. The test samples underwent 0, 1, 3, 5, and 7 rounds of freezing-thawing, and cured for seven and fourteen days, respectively. According to the research, an increased in freeze-thaw cycles decreased the strength of samples treated with CSA cement. Nevertheless, the strength of the test samples increased as the cement concentration increased. Finally, the researchers concluded that CSA would be the best substitute binder for stabilizing sandy soil in cold areas to attain adequate strength and endurance against freeze-thaw action because it is an eco-friendlier binder compared to OPC.

OPC is frequently utilized as a binder in geological applications and building industries. But there is a pressing need to identify a potential substitute because OPC raises environmental concerns. Subramanian, et al. [30] examined the viability of using CSA cement instead of OPC cement for geological uses. CSA is an eco-friendly binder that emits less carbon than OPC. The research studied the ideal gypsum content to achieve a greater early strength increase value for CSA-stabilized sand. 3, 5, and 7% by weight of sand was used to treat the test samples. The samples were aged for one and twenty-eight days before testing. Furthermore, the research indicated that replacing 30% CSA cement with gypsum would yield a high initial strength development. In addition, CSA-treated test samples showed greater strength gains than OPC-treated samples.

Moon, et al. [31] studied how small particles impact the mechanical properties of cemented sand. In this research, the test samples were treated with CSA and OPC at 3%, 5%, and 7% by the total mass of dry sand. In addition, 0, 1, 3, and 5% kaolin powder was added to the cemented sand mixture. Finally, laboratory tests like UPV, UCS, and shear wave velocity were employed to determine the strength the cement samples got over time. The shear velocity of the test samples were determine in accordance to the method proposed by Khan, et al. [32] . According to the experiment's findings, fine particles significantly impact the treated sand samples' mechanical characteristics. Furthermore, the early stiffness and strength of the test samples treated with CSA and OPC also increased with a rise in fine particles. The study's conclusions showed that adding kaolin powder increased the treated samples' density, which caused a rise in strength. The researchers concluded that the choice of stabilizing materials for the treatment of the sand affects the impact of small particle sand treated with CSA and OPC.

The efficacy of using CSA cement as an alternative binder in a geotechnical application was examined by Subramanian, et al. [18]. UCS was used to determine the strength of cemented sand treated with both CSA and OPC by the researchers. The test samples were subjected to CSA and OPC treatments of 2, 3, 5, and 7%. The curing period for the cemented samples ranges from 1 to 28 days. Furthermore, this research used both wet and dry curing conditions. The research's conclusions revealed that test samples cured under wet conditions had less strength than those cured under drier conditions, with more significant strength growth. Nonetheless, the test samples treated with CSA cement had better strength development than those treated with OPC, even though they were both cured using the wet condition. Additionally, test samples treated with CSA under dry curing conditions exhibited higher early strength gain growth than those with OPC because of the presence of ettringite in CSA.However, samples treated with OPC had slightly high ultimate strength. The authors concluded that CSA cement is more environmentally friendly than OPC. Hence it could be used as an alternative binder for geotechnical uses.

Vinoth, et al. [33] examined the viability of employing CSA for rapid and durable soil treatment. Using UPV and UCS laboratory experiments, the strength growth in soil treated with CSA was examined. The test samples were produced using 5, 7, and 10% CSA and OPC by the total mass of sand. The test samples were allowed to cure for 1 to 28 days respectively. The study's conclusions indicated that samples treated with CSA developed their strength more quickly than samples treated with OPC after one day of curing. Finally, the authors concluded that cement content, as well as cement variety, affects the UPV development rate.

2.5 Triaxial Behavior of cemented treated-sand

A triaxial test is utilized to measure the shear strength and stiffness of a cylindrical core (soil or rock) sample. Triaxial test is divided into three (3): UU, CU, and CD triaxial tests. The confining pressure (stress conditions) during the consolidation phase of the test is used to simulate the in-situ stresses on site. The three directions are important because they indicate how much stress has been applied to the soil and how much it will take before failure. A triaxial test can be performed on concrete-encased, cemented, sandy, and clayey soil. This section covers research on the triaxial behavior of cemented-treated sand.

The effect of cementation and confining pressure on the mechanical behavior of cemented sand under triaxial testing was investigated by Marri, et al. [8]. This research analyzed the stress-strain behavior, stress-dilatancy relationship, and volumetric change behavior of the treated sand samples using a CD triaxial test with a high mean effective stress. The test samples were different OPC content ranging from 5% to 15 % by the total mass of sand. Different confining pressures ranging from 0.05 to 12 MPa were utilized during experiments. The findings from the study revealed that the impact of the cement concentration was more significant at low mean effective stress and more minor at high effective stress. The researchers state that at high confining pressure, the effect of the void ratio on the mechanical behavior of test samples is insignificant. Confining pressure and cementation significantly impact the cemented samples' stress-strain and volumetric strain relationships. The cemented sample's maximal deviator stress and stiffness increase as the cement content increases. Similarly, as the effective stress increases, so do the maximal deviator stress and the degree of compression during the shearing of the test samples.

Kutanaei and Choobbasti [34] studied the impact of OPC, Polypropylene (PP) fiber, and confining pressure on cemented sand. OPC was used as the stabilizing agent at 0% and 5% by the total mass of sand alongside fibers of 18 mm long and 0.023 mm diameter. Both treated and untreated test materials were subjected to CD triaxial testing at effective stresses of 100, 250, 500, and 1000 kPa. The research showed that treated samples' shear strength and maximal axial strain increase as the proportion of polypropylene (PP) fiber increases. In addition, the study indicated that the initial stiffness, maximal strength, and elastic modulus increase as the cementation level rises. The study concluded that adding cement, fiber, and fiber–cement to sand significantly improved the treated sand samples' mechanical properties and triaxial behavior. The introduction of OPC enhanced the strength and elasticity modulus of tested samples. Likewise, cohesion and the internal angle of friction rose with fiber content.

Amini and Hamidi [25] investigated the mechanical characteristics of a sand-gravel soil mixture treated with cement. Under triaxial conditions, the effects of particle size distribution, cementation, and mean effective stresses were investigated. Various CD and CU triaxial experiments were conducted on cemented and uncemented test samples. In this study, the cementation degree varied from 0% to 3% by mass of the sand-gravel mixture, and the mean effective stress varied across 0.05 MPa to 0.15 MPa. A summary of the study's findings, the energy absorbing potential was lower under undrained conditions and more significant under drained conditions. Nevertheless, there was an increase in energy absorption for both undrained and drained conditions when the cement content was increased. In addition, the treated samples were more brittle during the CD triaxial test than during the CU test. Furthermore, the failure envelopes of the samples analyzed were greater in the undrained state than in the drained state.

Employing triaxial testing, Ajorloo, et al. [35] examined the impact of cementation on the mechanical behavior of a sand sample treated with cement. The shear strength of treated sand was studied, along with the underlying process by which an increase in cement content increases shear strength under confined conditions. Therefore, several CD triaxial experiments were performed to determine the mechanical properties of samples treated with various cement (OPC and lime) contents under diverse effective stresses of 0, 100, 200, and 400 kPa. The test findings revealed that the effective confining pressure and degree of cementation substantially impact the stress-strain behavior of the examined cemented sand. Similarly, the initial rigidity and strength of the samples increased as the cement content increased, as indicated by the research findings.

Mola-Abasi, et al. [36] studied the triaxial behavior of zeolite treated with cement. Zeolite, degree of cementation, and effective stress were the most significant variables in this study. CU triaxial experiments were conducted on the treated samples at different effective stresses ranging from 50 to 400 kPa to ascertain the mechanical characteristics of the cemented samples. In accordance with the study's results, as confining pressure and cement content increased, so did the maximal strength and rigidity of the examined samples. However, samples treated with cement and zeolite were stiffer than those treated with cement alone. Additionally, introducing zeolite increases cemented samples' energy capacity and frictional angle. Furthermore, as cement content increases, the frictional angle and the cohesion intercept increase. The researchers concluded that the effect of zeolite on test samples is significantly more significant at high confining pressure than at low pressure.

Schnaid, et al. [9] investigated the stress-strain behavior of a sand sample treated with cement. The researchers used CD triaxial testing, UCS, and SEM to investigate the mechanical characteristics of treated sand samples. This study examined two parameters: effective stress and cement content. The test was conducted on samples containing 1, 3, and 5% OPC by dry sand weight at 20, 60, and 100 kPa confining pressure. The research revealed that the unconfined compressive strength in a triaxial test is directly proportional to the cement content. In addition, cement content increases the maximum deviator stress and the initial Additionally, the shear strength of the cemented sand significantly increased as the effective stress increased. The authors concluded that the untreated sand's UCS and friction angle could be utilized to calculate the shear strength of the cemented sand samples.

Hamidi and Haeri [37] examined cemented gravely sand's stiffness properties and deformation behavior. Adding 1,5%, 3%, 4.5%, and 6% gypsum plaster to the gravely sand's dry weight produced the test samples. To study the mechanical characteristics of the cement-treated gravely sand, the researchers conducted CD and CU triaxial experiments with effective stresses ranging from 25 to 500 kPa. This study studied the influence of bonding as a function of cementation degree and test sample yield strength. Numerous treated samples were subjected to triaxial testing under variable confining pressures to investigate comprehensively cemented gravely sand samples' stiffness characteristics and deformation behavior. Both undrained and drained triaxial test findings show that the tangent stiffness of the cemented samples decreases with increasing constraining pressure. A further observation was that axial stiffness improved with a rise in cement content.

Pillai, et al. [38] examined the mechanical properties of marine clay treated with cement under confining pressure. Various CU triaxial tests were performed on the test samples to evaluate the triaxial behavior under undrained triaxial conditions. The test sample was prepared by adding 5% OPC by dry unit weight of marine clay. The triaxial test was conducted with various mean effective stress ranging from 100 to 600 kPa under undrained conditions. Due to the cementation bonding process, the cemented clay exhibits a very high pre-consolidation pressure, according to the research findings.

Previous research has shown that the maximum deviator stress and cemented samples' initial stiffness rise under the triaxial condition. In addition, the maximum deviator stress and the degree of compression during shearing also rise, along with increased mean effective stress.

Table 2.1 Reviewed journal based on the triaxial behavior of cemented sand

Authors	Stabilizing agent	Effective stress	Curing time
[8] CD triaxial test	5, 10, and 15 % of OPC	0.05 MPa, to 12 MPa	14 days
[34] CD and CU triaxial test	0, and 5 % OPC and fibers of 0.023 mm diameter and 18 mm long	100 kPa, 250 kPa, 500 kPa, and 1 MPa	7 days
[25] CD triaxial test	0, 1, 2, and 3% of Portland cement	50, 100, and 150 kPa.	7 and 28 days
[35] CD triaxial test	Different content of cement and lime ranging from 20 to 200%	0 kPa, 100 kPa, 200 kPa, and 400 kPa	28 and 180 days
[36] CU triaxial test	4 and 8% of cement and zeolite	50, 100, 200, and 400 kPa	42 days
[9] CD triaxial test	1, 3, and 5% OPC	20, 60, and 100 kPa	7 days
[37] CD and CU triaxial tests	1.5%, 3%, 4.5%, and 6% of gypsum plaster	25 kPa to 500 kPa	7 days
[38] CU triaxial tests	5% of OPC	100 to 600 kPa	28 days

Chapter 3 – Materials and Methodology

3.1 Materials used

For this study, quartz sand was utilized, and according to the Unified Soil Classification System, it was classified as "SP" (poorly graded). Table 1 provides an overview of the index characteristics of the sand, while Figure 3.1 illustrates the grain distribution curve for quartz sand. CSA cement and gypsum were also used to prepare test samples. The CSA cement employed for this research primarily contains ye'elimite (C_4A_3S or $4CaO_3Al_2O_3$), belite, and gehlinite. The ye'elimite in the CSA allows for an environmentally friendly manufacturing process during production [16, 39]. According to [30, 40], the amount of gypsum in a binder has been shown to impact the hydration process of CSA cement significantly. The reaction demonstrates the hydration of ye'elimite due to adding gypsum [16].

$$4CaO \cdot 3Al_2O_3 \cdot SO_3 + 2CaSO_4 \cdot 2H_2O + 32H_2O \rightarrow 6CaO \cdot Al_2O_3 \cdot 3SO_3 \cdot 32H_2O + 4Al(OH)_3 \quad 3.1$$

The end product of the hydration process is ettringite, and its chemical formula is $6CaO \cdot Al_2O3 \cdot 3SO3 \cdot 32H_2O$ or $C_3A \cdot 3CS \cdot 32H$.

When thirty percent of CSA cement was replaced with gypsum, Subramanian et al. [18] discovered a substantial increase in initial and sustained increase in strength. Therefore, this investigation used the optimal gypsum content of thirty percent to substitute for a certain amount of the CSA content.

Table 3.1 Quartz sand physical properties

Properties	Value
Effective grain size (D_{10}) (mm)	0.65
Effective grain size (D_{60}) (mm)	0.95
Uniformity coefficient, C_u	1.46
Coefficient of curvature, C_c	0.96
USCS	SP
Specific gravity, Gs	2.64

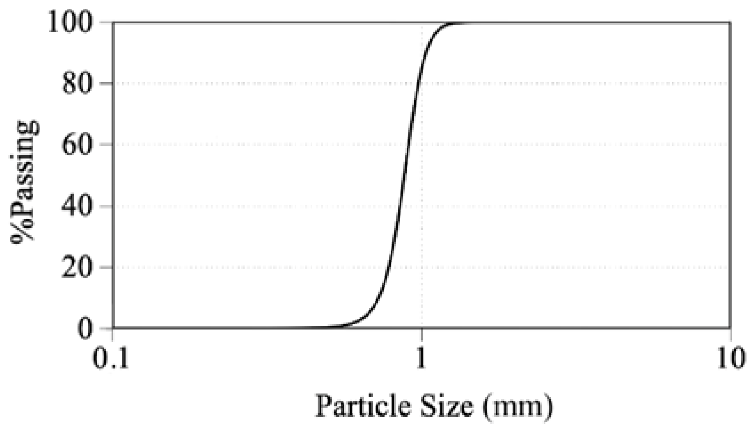


Figure 3. 1 Particle distribution curve of quartz sand


Figure 3. 2 The Quartz Sand
(0.4 to 0.9 mm)


Figure 3. 3 CSA cement

Figures 3.2 and 3.3 show the photograph of the quartz sand and CSA cement used for the research.

3.2 Sample preparation

Samples were prepared through a mixture of dry sand with varying percentages of cement (3, 5, and 7%) and gypsum. The CSA-sand mix was blended using an automatic mixer for 5 minutes until a uniform appearance was reached. Following the standard compaction test [41], water was added, and the mixture was mixed for ten minutes. The optimal moisture content (OMC) for the quartz sand treated with 0, 3, 5, and 7% of CSA can be seen in Table 3.2. The OMC for the treated samples is 19%, 17.25%, 16.75%, and 15.75%, respectively, for the different CSA content.

The compaction curve of CSA-treated sand is illustrated in Figure 3.4. Following mixing, the CSA-sand mixture was then compacted in three separate layers in a 38-mm-diameter, and 76-mm-height cylindrical mould. For an easier test samples extrusion process, oil was applied to the interior surfaces of the cylindrical steel moulds. Twenty-five blows with the rammer were used to compact each of the three layers. The tops of the initial and second layers were sacrificed to prevent problems with smooth compaction surfaces and guarantee appropriate surface-to-surface contact before the placement and compaction of the subsequent layer [42]. The samples were extruded after three days, enclosed in an elastic covering to prevent moisture loss, and placed in a humidified room. Because of the significant increase in strength of CSA cemented soils, the curing period was set for 7 and 14 days.

Table 3.2 Standard Proctor Test results for CSA-treated sand

CSA content (%)	Optimum Moisture Content (OMC) (%)	Maximum Dry Density (MDD) (kN/m^3)
0	19.00	1.56
3	17.30	1.59
5	16.80	1.61
7	15.80	1.65

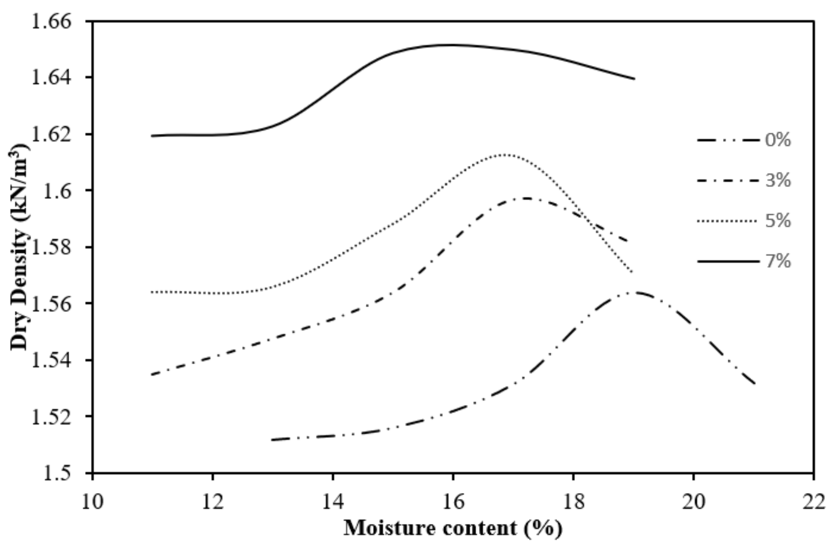
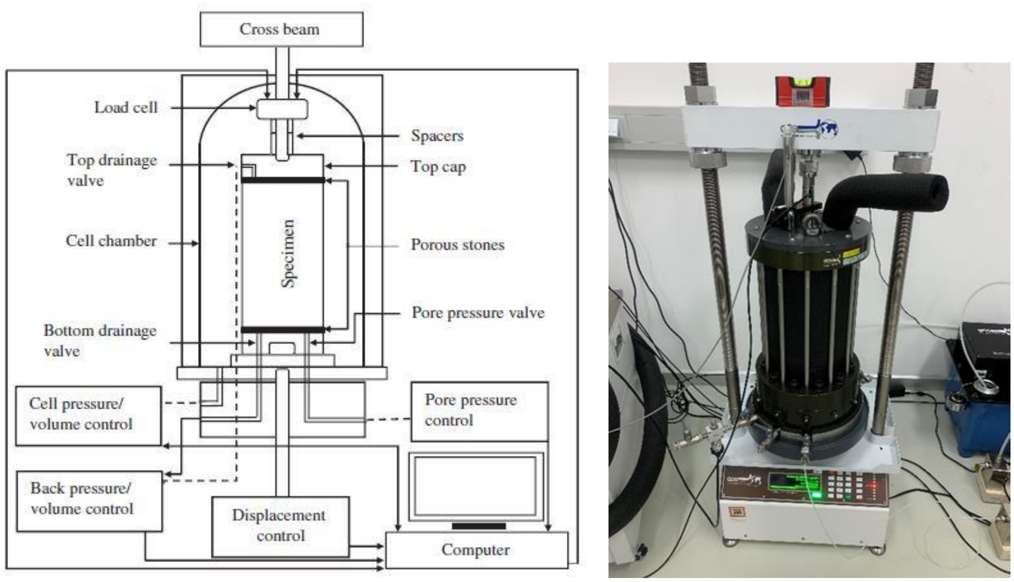


Figure 3. 4 Compaction curve of CSA-treated soil

3.3 Testing system

The GDS Instruments Environmental Triaxial Automated System (ETAS) was used to conduct the tests. A picture of the completed high-pressure triaxial cell is shown in Figure 3.5, along with the testing setup. GDSlab control software, datalogger, velocity-controlled load frames, pressure/volume controllers, velocity-controlled load frames, PWP/axial displacement sensor, top cap, back and cell pressure/volume controllers (ADVDPC) and the triaxial cell are some the parts of the ETAS system. The two computerized pressure/volume regulators apply and control cell and back pressure. The load was transferred to the system from the base of a loading frame using a digital hydraulic force actuator. The pore water pressure sensor measured the PWP at the sample's base. The pore water pressure sensor measured the PWP at the sample's base. The ADVDPC used in this research has a pressure capacity of 4 MPa, the weight cell has a capacity of 50 kN, and the triaxial cell has a pressure capacity of 4 MPa.



(a) (b)

Figure 3. 5 (a) Schematic diagram of the ETAS (b) Picture of the High-pressure triaxial cell within the loading frame

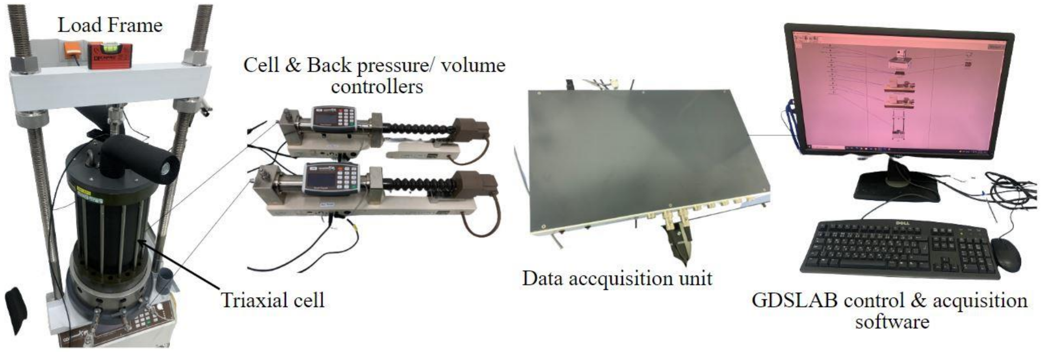


Figure 3. 6 Components of the Environmental Triaxial Automated System (ETAS)

3.4 Test procedure

Upon completion of the curing period, the test sample was positioned on the top of the pedestal of the ETAS triaxial cell's base. The sample was then covered with a rubber membrane to isolate it from the chamber oil, and two filter papers and porous stones were positioned underneath and on top of it. A pair of o-rings were installed between the test sample and the base pedestal to keep cell oil out. The high-pressure chamber was subsequently assembled and then filled with silicon oil. To achieve saturation, the sample was flushed with water that had been de-aired from the top down for two hours, with the back pressure being ten kPa lower than the mean effective stress (confining pressure). After that, both pressures were increased simultaneously until the B-value was higher or equal to 0.90 [9, 43]. Subsequently, it was sheared under drained circumstances after being consolidated to the necessary confining pressure of 500, 1000, and 1500 kPa, respectively. Finally, shearing was carried out on the test materials by applying an axial tension at a steady rate of 0.1mm/min. The CD triaxial test was performed in compliance with ASTM/D7181-20.

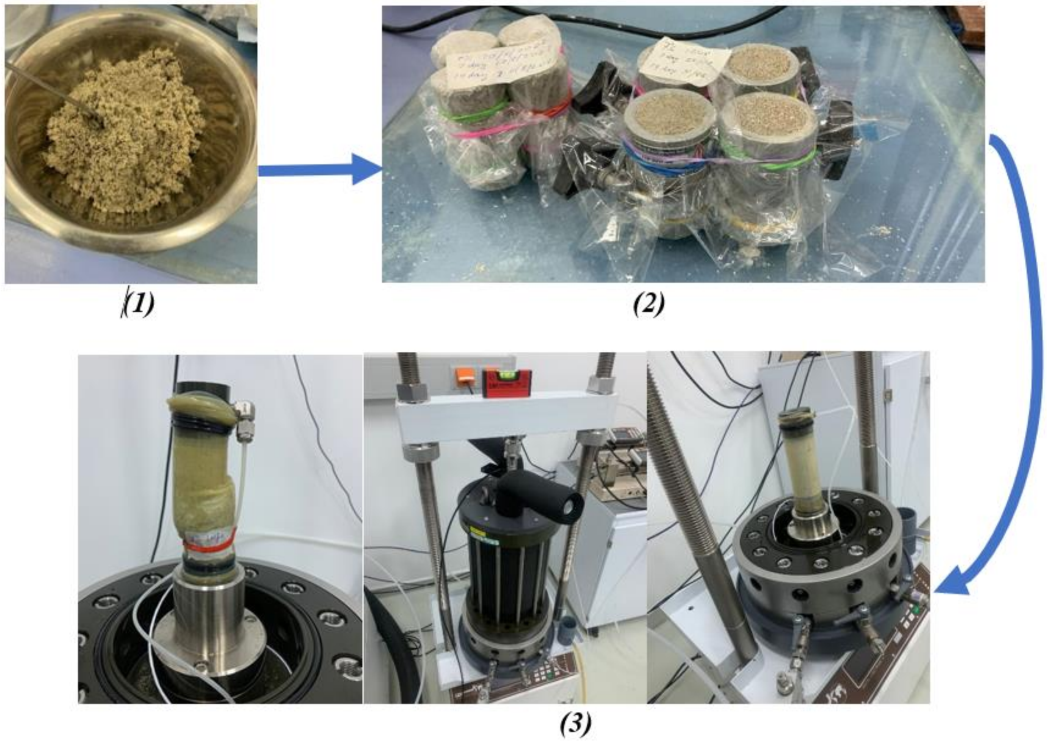


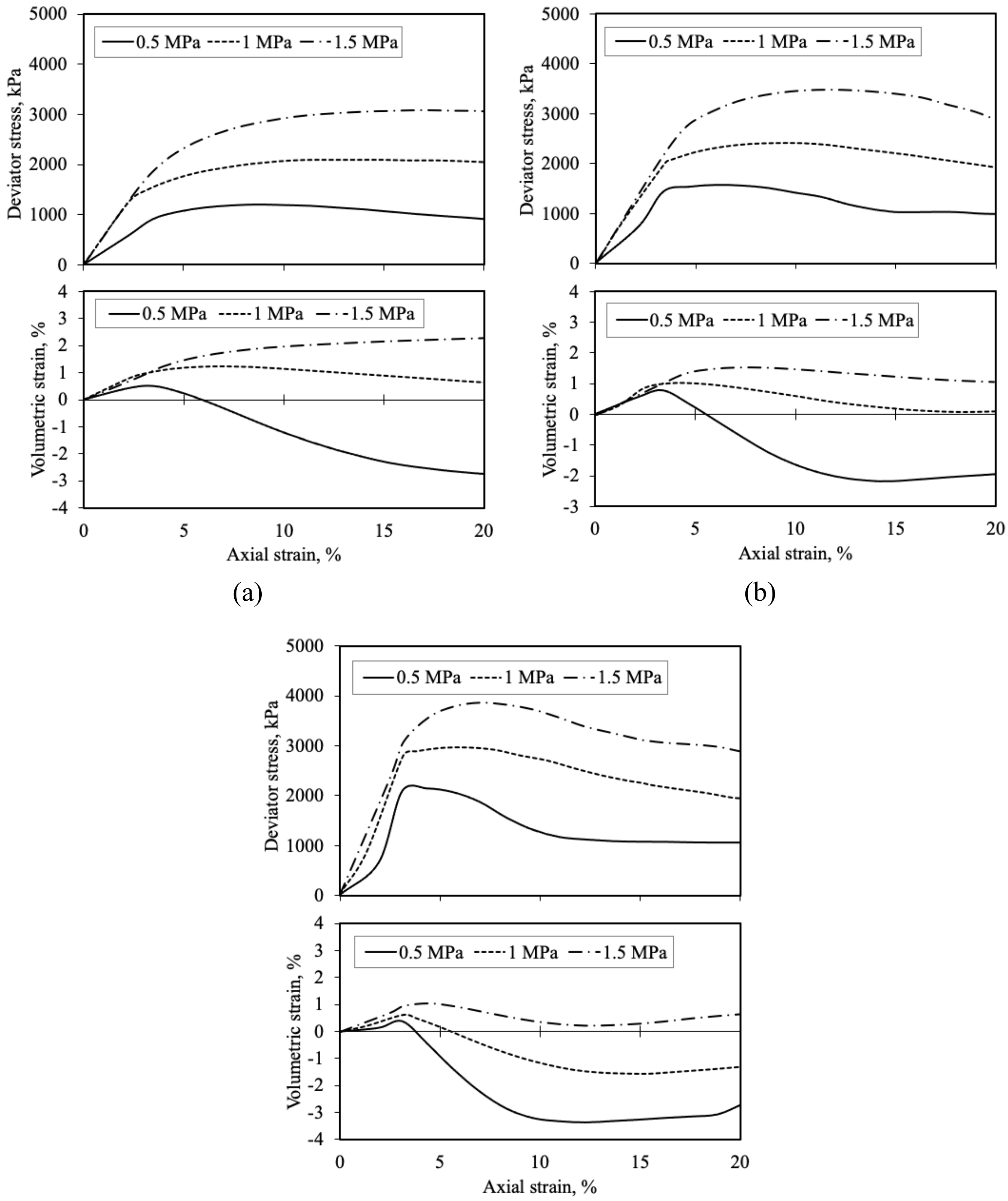
Figure 3. 7 (1) Sample Preparation (2) Curing of Test Samples

(3) Traxial Test using the ETAS

Chapter 4 – Results and Discussions

4.1 Stress-strain relationship of the CSA cemented sand

In this study, CD triaxial experiments were performed on both CSA-cemented and uncemented sand samples. Under drained conditions, the test samples were consolidated to a confining pressure of 500, 1000, and 1500 kPa while σ'_3 remained constant throughout the test. Figures 4.1 and 4.2 show the q-εa and εv-εa relationship for treated and untreated samples. Both Figure 4.1 and Figure 4.2 show that the CSA content and effective stress significantly impact the treated sand's behaviour. It can be seen from both figures that as the mean effective stress go up, so do the early stiffness and maximal deviator stress of the treated samples. Similarly, as the CSA content in the test samples rises, there is an increase in the maximal deviator stress and a decrease in peak axial strain. As the percentage of CSA cement rises, the q-εa curve of the samples becomes increasingly brittle. The q-εa graphs for samples treated with 5 and 7% CSA cement show a propensity to achieve a peak deviator stress within the curing intervals of 7 and 14 days, respectively. It is followed by strain-softening for all examined samples. The stress-strain graphs for samples treated with 5 and 7% CSA cement show a propensity to achieve a peak deviator stress within the curing intervals of 7 and 14 days, respectively. It is followed by strain-softening for all examined samples. However, the q-εa graph for samples treated with 3% CSA can achieve high deviator stress after fourteen days of curing, then follows strain-softening. However, depending on the confining pressure range, it shows a different trend for 7 days of curing as the strain-softening changed into a strain hardening for samples sheared at 1 and 1.5 MPa. Nevertheless, a strain-softening stress-strain behavior was observed for samples treated between 3% CSA under 0.5MPa and 5% CSA under 1MPa, and 7% CSA under 1.5 MPa. These differences were due to the CSA content, different confining pressure, and the effect of curing days. The effect of CSA cement on the mechanical behavior of the treated sand can be seen in Figures 4.1 and 4.2. Figure 4.3 compares the results of three experiments conducted at different cement levels under the same effective confining stress $\sigma_3' = 1.5$ MPa, to explain the impact of CSA cement on the q-εa and εv-εa relationship of the sand. Since the highest confining pressure used in this research was 1.5 MPa, the experiments performed at this pressure were used to elaborate on the impact of confining pressure on the treated samples. Understanding soil behaviour under high pressure in various contexts would be helpful, including deep pile foundations, tunnels, and others.



(c)

Figure 4. 1 Stress-strain and volumetric change behavior of treated sand with CSA: (a) 3% CSA; (b) 5% CSA; (c) 7% CSA; for 7 days of curing

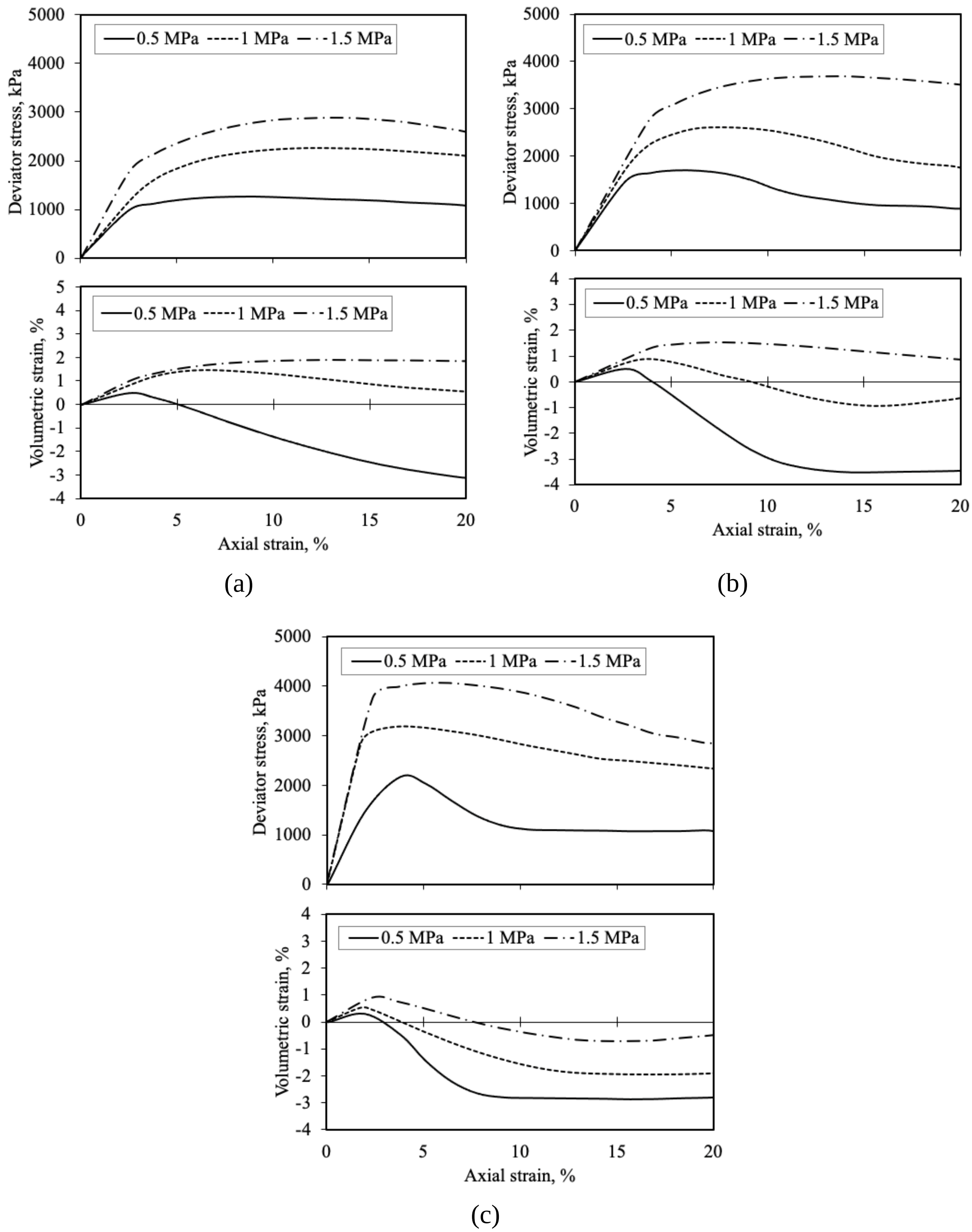


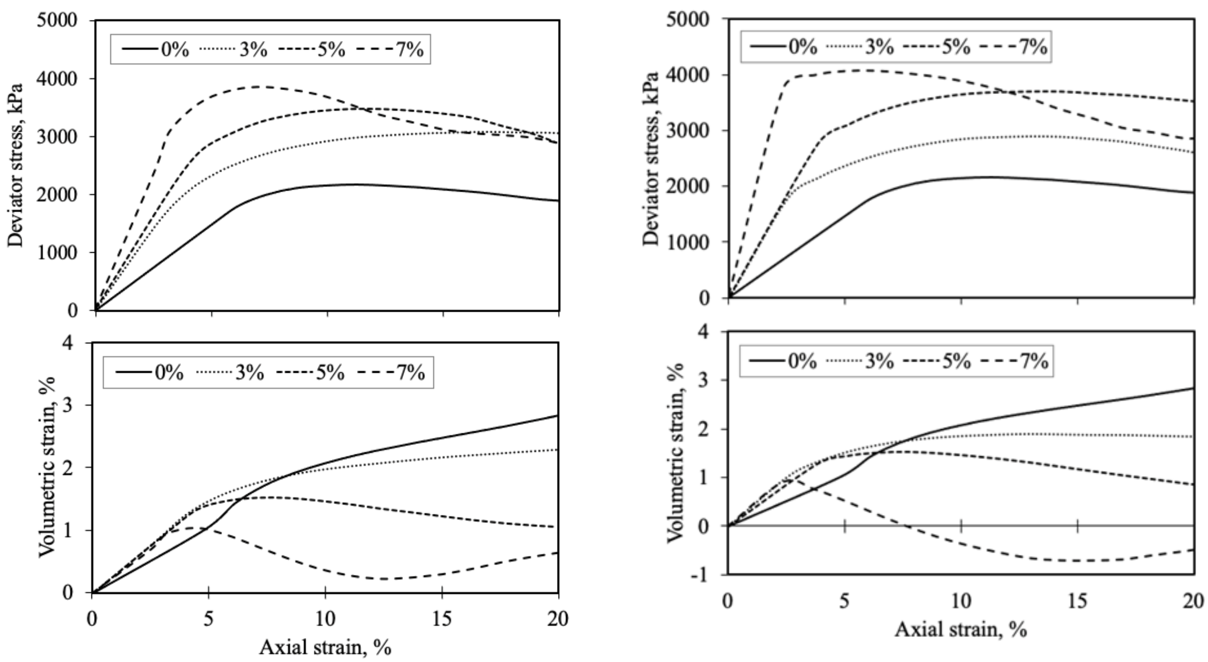
Figure 4. 2 Stress-strain and volumetric change behavior of treated sand with CSA: (a) 3% CSA; (b) 5% CSA; (c) 7% CSA; for 14 days curing

Table 4. 1 Summary of the CD triaxial tests results

Test ID	Initial state			Failure condition				Ultimate condition			
	σ'_3, kPa	t, days	cc, %	q_{peak}, kPa	p'_{peak}, kPa	φ'_{peak}, °	c'_{peak}, kPa	q_{ult}, kPa	p'_{ult}, kPa	φ'_{ult}, °	c'_{ult}, kPa
CD-0/0.5	500	-	0	1006.6	845.3	24.9	7.1	714.1	747.1	23.4	3.6
CD-0/1	1000	-	0	1738.4	1588.7	24.9	7.1	1607.4	1544.6	23.4	3.6
CD-0/1.5	1500	-	0	2174.8	2232.8	24.9	7.1	1871.4	2131.5	23.4	3.6
CD-3/0.5/7	500	7	3	1211.5	913.0	28.9	79.6	906.1	812.2	30.0	4.3
CD-3/1/7	1000	7	3	2104.6	1711.6	28.9	79.6	2052.0	1693.2	30.0	4.3
CD-3/1.5/7	1500	7	3	3087.0	2537.8	28.9	79.6	3038.5	2521.5	30.0	4.3
CD-3/0.5/14	500	14	3	1254.4	928.1	33.6	117.9	1063.3	864.8	26.7	9.3
CD-3/1/14	1000	14	3	2260.6	1762.6	33.6	117.9	1750.2	1593.2	26.7	9.3
CD-3/1.5/14	1500	14	3	2892.9	2474.2	33.6	117.9	2554.6	2361.4	26.7	9.3
CD-5/0.5/7	500	7	5	1580.6	1036.3	29.1	178.6	991.7	839.1	29.1	18.6
CD-5/1/7	1000	7	5	2424.3	1817.9	29.1	178.6	1916.3	1647.3	29.1	18.6
CD-5/1.5/7	1500	7	5	3483.4	2670.4	29.1	178.6	2894.6	2474.6	29.1	18.6
CD-5/0.5/14	500	14	5	1696.8	1075.8	30.0	194.3	880.8	801.5	28.5	31.4
CD-5/1/14	1000	14	5	2607.5	1879.3	30.0	194.3	1750.2	1593.2	28.5	31.4
CD-5/1.5/14	1500	14	5	3694.7	2740.9	30.0	194.3	3514.3	2680.8	28.5	31.4
CD-7/0.5/7	500	7	7	2152.4	1227.4	28.5	341.4	1065.8	863.7	28.3	42.1
CD-7/1/7	1000	7	7	2975.2	2000.9	28.5	341.4	1921.1	1648.4	28.3	42.1
CD-7/1.5/7	1500	7	7	3863.0	2796.8	28.5	341.4	2870.9	2465.3	28.3	42.1
CD-7/0.5/14	500	14	7	2186.4	1238.6	29.2	358.2	1057.1	861.5	28.2	42.9
CD-7/1/14	1000	14	7	3185.6	2072.9	29.2	358.2	2311.5	1778.6	28.2	42.9
CD-7/1.5/14	1500	14	7	4079.8	2869.8	29.2	358.2	2851.9	2459.8	28.2	42.9

Note: CD-A/B/C: "CD" is consolidated drained triaxial test. "A" is cement content, "B" is confining pressure in MPa and "C" is number of curing days.

As illustrated in Figure 4.3, the axial strain at failure for the sample under testing reduces with increasing cementation. In addition, the treated sand samples' initial stiffness and maximal deviator stress rise as the proportion of CSA cement in the treated sand samples rises. For example, the maximal deviator stress at a confining pressure of 1500 kPa rose from 3,477 to 3,856 kPa when the CSA content increased from 5 to 7%. This increase occurred when the CSA content was increased. Figures 4.1 and 4.2 also show the volumetric strain curves obtained from the experiments conducted on the CSA-treated sand samples. A volumetric compression was observed in experiments done for 3% and 5% at σ'_3 = 1000 kPa and 1500 kPa, and 1500 kPa for 7% samples for seven days of curing. In every test conducted at 500 kPa, an initial compression was followed by a subsequent dilatation. After 14 days of curing, the samples examined showed an initial volumetric compression, followed by a slow dilatation. The exception was the 3% and 5% samples that were sheared at σ'$_3$ = 1.5 MPa; these samples displayed a volumetric dilation. In addition, the volumetric strain curves reveal that the examined samples exhibit a more dilatant behavior during shearing as cement concentration rises. Thus, the compression of CSA-treated samples decreases as cement concentration increases in response to varying confining pressures. Figures 4.1 and 4.2 indicate that the εv-εa curves reached a stable value at the end of each test, as illustrated. Therefore, the ultimate condition obtained from stress-strain curves may be comparable to the critical state for the CSA-treated samples utilized in this study. Furthermore, the mean effective stress increases the peak deviator stresses, axial strain, and compression level during shearing. As a result, the q-εa behavior of the treated samples becomes ductile with increased confining pressure. However, the CSA cement concentration increases the peak deviator stresses while the axial strain is decreased. It also increases dilation during shearing. Therefore, the treated samples' q-εa behavior changes from ductile to brittle as the CSA cement content increases.



(a) (b)

Figure 4. 3 Stress-strain and volumetric change behavior of treated sand with CSA: for σ$_3$' = 1.5 MPa (a) 7 days curing (b) 14 days curing

The volumetric strain curves of the tests carried out on the CSA-treated sand samples at 1500 kPa confining pressure are also compared in Figure 4.3. It can be observed from Figure 4.3 (a) that all of the test samples exhibited compression at 1500 kPa effective stress. However, there was an exception for samples treated with 7% CSA and cured for 14 days, as the sample showed an initial compression followed by a gradual dilation. Hence, as the cement content increase, there is a reduction in the compression behavior of the sand at high effective stress. Additionally, peak deviator stress, the initial stiffness, and axial strain at failure all increased with the addition of different CSA cement content to the uncemented sand. Similarly, as the amount of CSA cement rises, the samples' stress-strain behavior transitions from flexibility to brittleness. Furthermore, the maximal deviator stress and degree of compression during shearing increased along with the mean effective stress. Therefore, CSA cement content and high confining pressure significantly impacted the q-εa and εv-εa behavior of the CSA-treated sand [e.g 8-10, 26, 43].

4.2 Failure characteristics

The cohesion intercept and angle of internal frictional considerably change the failure behavior of CSA-treated sand samples due to their cohesive-frictional character. Additionally, all the experiments performed for this research were done in drained conditions. Therefore, each test's peak state accurately captures the failing state of the treated sand samples. The failure states from all of the experiments carried out in this research are shown in Figure 4.4. The failure data from tests with CSA contents of 0%, 3%, 5%, and 7% were used to generate the best-fitting failure envelopes. Figure 4.4 demonstrates that the envelopes of failure of the tested sample are curved. Nevertheless, as the percentage of cement increases, the failure envelopes of the treated samples become increasingly curved. Furthermore, several researchers have presented curved envelopes for cemented soils, whereas the uncemented sandy gravel material was reported to be almost straight [8, 10, 44, 45]. In addition, Figure 4.4 demonstrates that an increase in the curvature of the failure envelope occurs along with a rise in the amount of CSA cement content. The failure envelopes shift to higher stress levels as the CSA content rises, indicating that the sand's cohesion and particle intercept cohesion increase as the CSA cement content rises. (Figure 4.4). The figure also shows that as the CSA cement concentration declines, the failure envelopes' slope transitions from linear to non-linear. Thus, at low-confining pressures, the influence of cementation on treated sand samples is much more pronounced than at high-confining pressures. However, this observation would be verified with higher confining pressures in the future study compared to confining pressures used in this study.

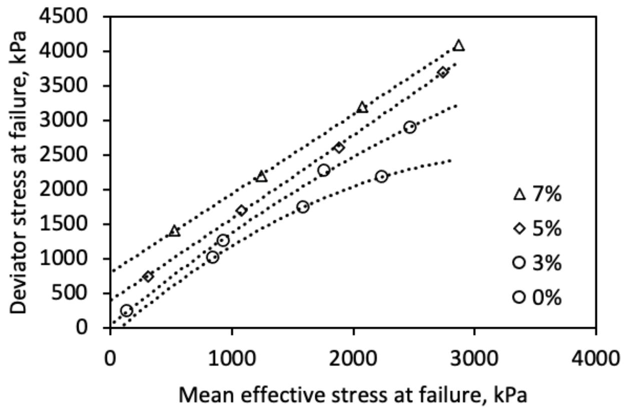


Figure 4. 4 Failure envelopes of CSA-treated and untreated samples

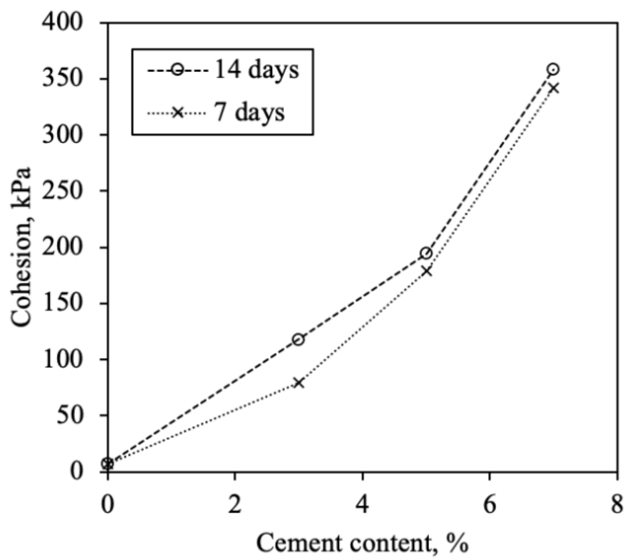


Figure 4. 5 Influence of CSA cement content on cohesion intercept

The shear strength of the tested samples can be defined as a function of the friction angle and the cohesion intercept when considering the cohesive-frictional properties. The frictional angle and cohesion intercepts were obtained by plotting the mohr-coulomb diagram for all tests carried out with various cement contents and sheared at different mean effective stress ranging from 0.5 to 1.5 MPa. Additionally, Figure 4.5 shows that the cohesion between the particles of the treated samples rises along with the cement concentration. Table 3 displays the friction angle and cohesion intercept derived from the mohr-coulomb graphs.

4.3 Stress-dilatancy relationship of the CSA-treated samples

The term "dilation" is commonly used to describe the rise in volume that occurs any time a dense sand sample is sheared in a triaxial test. It occurs because of the fabric's inherent geometrical limitations against the pressures applied during shearing. Nevertheless, as shown in Figures 4.6 to 4.8, at higher confining pressures, the volumetric behavior of sandy material is often suppressed during shearing. Hence, the dilatancy of the CSA-treated sample can be influenced by the presence of CSA cement, which strengthens the bond between the sand particles after treatment. Further, the volumetric strain curves of the examined samples show that a rise in confining pressure suppresses the dilation rate.

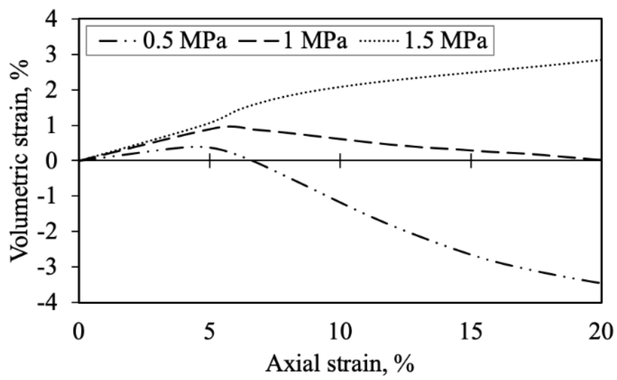


Figure 4. 6 Stress-dilatancy relationship for untreated sand.

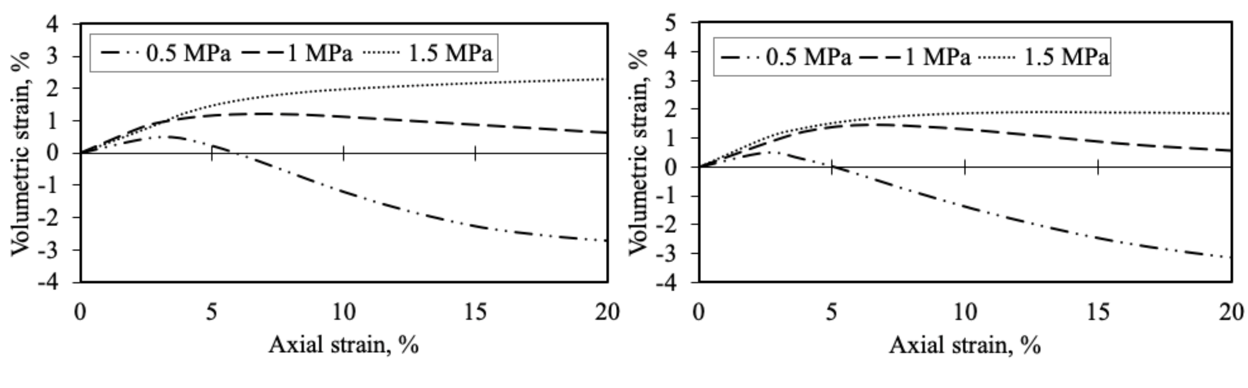
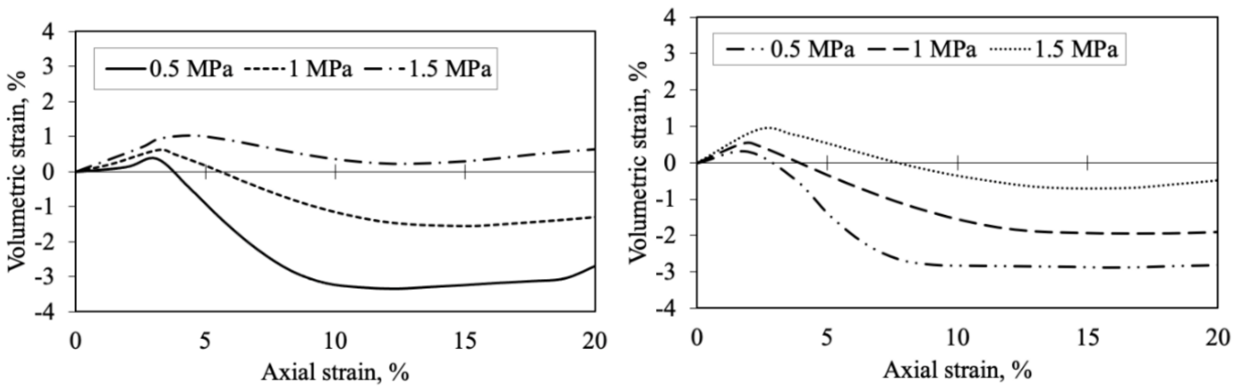


Figure 4. 7 Stress-dilatancy relationship for CSA-treated sand samples with 3% cement content at (a) 7 days (b) 14 days

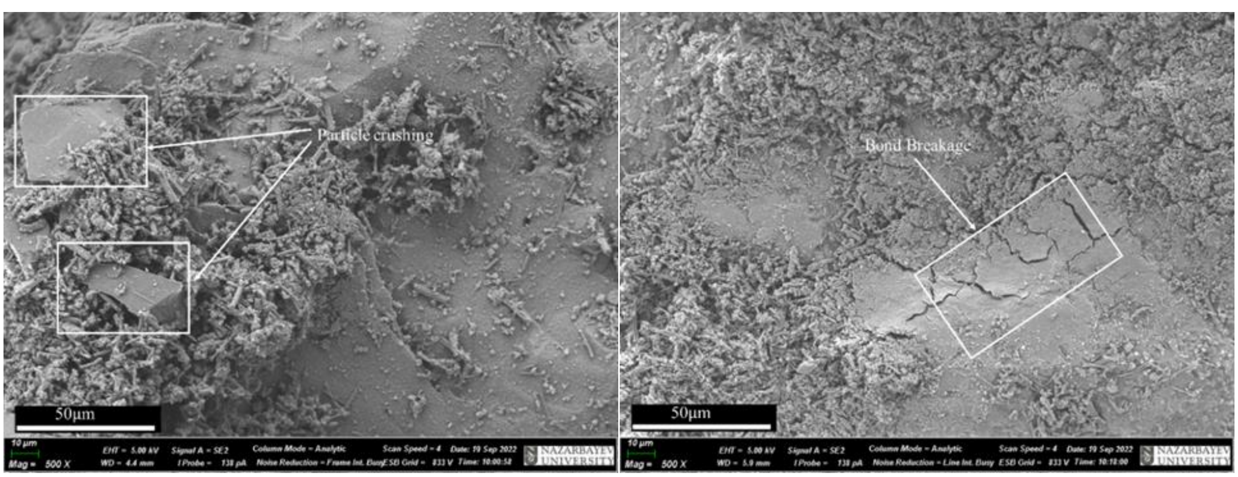


(a) (b)

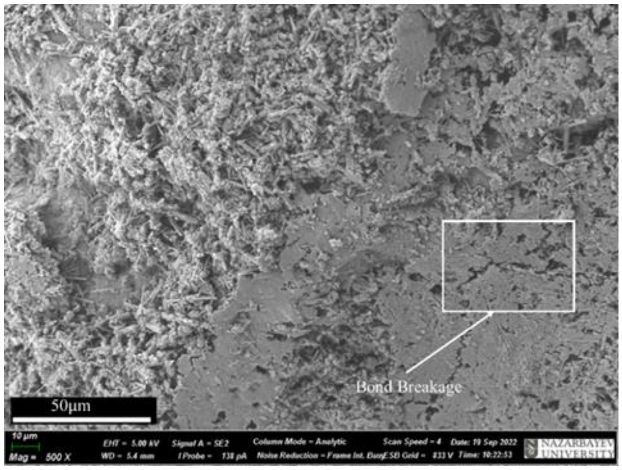
Figure 4. 8 Stress-dilatancy relationship for CSA-treated sand samples with 7% cement content at (a) 7 days (b) 14 days

4.4 SEM observation

After the triaxial testing, CSA-treated samples underwent scanning electron microscope (SEM) analysis to assess the material deformation, particle crushing, and cement bond breaking caused by shearing. Figures 4.9 and 4.10 show typical photomicrographs of samples sheared at various CSA cement contents and confining pressures, respectively. Figure 4.9a shows that particle crushing and bond breaking are comparatively big in the loose state and decline progressively with increasing relative density. (Figures 4.9b and 4.9c). It shows the influence of density on the bond-breaking and particle crushing of the CSA-treated samples.

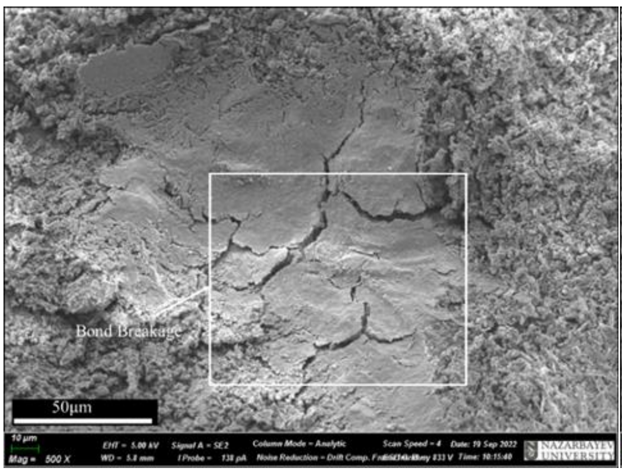


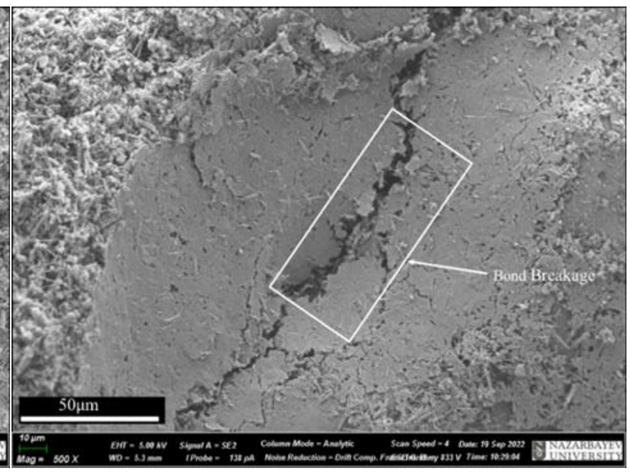
(a) (b)



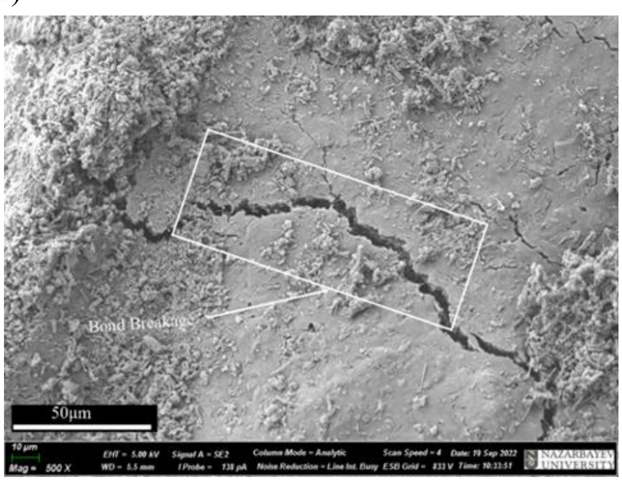
(c)

Figure 4. 9 SEM photographs of cemented sand samples (a) 3% (b) 5% (c) 7% after shearing at 1 MPa confining pressure.





(a) (b)



(c)

Figure 4. 10 SEM photographs of samples with 7% cement content after shearing (a) 500 kPa (b) 1000 kPa (c) 1500 kPa

Furthermore, as shown in Figure 4.9, the CSA-treated samples exhibit less particle disintegration at higher mean effective stress. As a result, an increase in CSA concentration reduces the amount of particle crushing and bonding breaking that occurs during shearing. Figure 4.10 shows that the particulate crushing and bonding damage of the CSA-treated samples rises with increasing confining pressure. This finding is in line with the results of the earlier experimental research that was carried out on cemented sand [8, 10].

Chapter 5 – Conclusions

This research examined CSA cement concentration's effect on the CSA-treated sand's shear strength and mechanical behavior under high confining pressure. CD triaxial experiments with high confining pressures were employed in this study. The influence of the CSA cement concentration and the confining pressure on the q-εa and εv-εa behavior during shearing and the failure characteristics were addressed. Based on the research results, the following conclusion was drawn.

1 The amount of cement in the CSA-treated sand samples and the mean effective stress significantly impact the sand samples' q-a and εv-εa behavior. As the percentage of CSA cement increases, there is an increased in maximal deviatoric stress and a reduction in compression during shearing. Nonetheless, as mean effective stress increases, the maximal deviator stress and amount of compression during shearing increase. Furthermore, with increased confining pressure, the treated samples exhibited a ductile behavior. With an increase in cement content, the test samples become brittle.

2 Additionally, the mean effective stress and CSA content influence the failure characteristic of sand. The failure envelopes shift to higher stresses as the CSA cement content rises, indicating that the cohesion intercept of the sand will increase. In addition, the slope of the failure envelopes decreases as mean effective stress increases, implying that mean effective stress influences the curvature of the failure envelopes.

3 The percentage of CSA in the treated samples and the confining pressure also influences the stress-dilatancy of samples. There was increased cohesion and bonding between sand particles at specific confining pressures when CSA cement was added. Consequently, the maximal deviatoric stress increases as the degree of CSA cement rises. In addition, the increase in confining pressure reduces the amount of dilation at specific CSA cement content.

4 Finally, a scanning electron microscope (SEM) showed a breakage in the cement bonding and crushing of the sand particles during shearing. Consequently, the degree of sand particle breaking during shearing increases as confining pressure increases and decreases as CSA cement content increases.

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