Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Evaluation of Sustainable and Environmentally Friendly Stabilization of Cohesionless Sandy Soil for Transportation Infrastructure

Project No. 20GTTAMU21

Lead University: Texas A&M University

Final Report

January 2022

Disclaimer

Acknowledgements

The authors would like to acknowledge and thank the discussions and feedback by the Louisiana Department of Transportation and Development and Texas Department of Transportation.

TECHNICAL DOCUMENTATION PAGE

<table>
<tr><td colspan="2">1. Project No.
20GTTAMU21</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="4" rowspan="2">4. Title and Subtitle

Evaluation of Sustainable and Environmentally Friendly Stabilization of Cohesionless Sandy Soil for Transportation Infrastructure</td><td colspan="2">5. Report Date
January 2021</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="4">7. Author(s)
PI: Miladin Radovic https://orcid.org/0000-0003-4571-2848
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<tr><td colspan="4" rowspan="2">9. Performing Organization Name and Address
Transportation Consortium of South-Central States (Tran-SET)
University Transportation Center for Region 6
3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
69A3551747106</td></tr>
<tr><td colspan="4" rowspan="2">12. Sponsoring Agency Name and Address
United States of America
Department of Transportation
Research and Innovative Technology Administration</td><td colspan="2">13. Type of Report and Period Covered
Final Research Report
Sept. 2020 – Aug. 2021</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="6">15. Supplementary Notes
Report uploaded and accessible at Tran-SET's website (http://transet.lsu.edu/).</td></tr>
<tr><td colspan="6">16. Abstract
Ordinary Portland cement (OPC) is generally used to stabilize cohesionless sandy soils that are often found in coastal areas. Due to its high carbon footprint, many studies are being conducted to identify a suitable green alternative for stabilizing cohesionless soils. Previous studies have shown that partially replacing OPC with waste materials such as nano-silica and coal waste reduces the overall carbon footprint without significantly impacting the performance. Geopolymer (GP) received a lot of attention in the past few decades owing to its similar properties to that of OPC yet with a lower carbon footprint. This study investigated the feasibility of stabilizing cohesionless sandy soils with metakaolin-based GP. Engineering and characterization tests such as shrinkage, strength, pH, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS) were performed to evaluate various characteristics of the stabilized mixes with different dosages of geopolymer and relate them to microstructural changes. Notably, GP-treated soils did not deteriorate during the durability tests, whereas the OPC-treated soil only retained about 75% of its strength. This is an indication that GP could be a better choice than OPC in coastal areas where cohesionless soils often experience heavy rainfall and flooding. Overall, an optimum dosage of GP improved both the mechanical properties and durability of cohesionless soils.</td></tr>
<tr><td colspan="3">17. Key Words
Geopolymer, cohesionless soils, pavements, sustainability, infrastructure, stabilization</td><td colspan="3">18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td colspan="2">20. Security Classif. (of this page)
Unclassified</td><td colspan="2">21. No. of Pages
32</td><td>22. Price</td></tr>
</table>

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CMTDS	Copper Mine Tailing Dam Sediments
EDS	Energy-Dispersive X-ray Spectroscopy
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
GP	Geopolymer
LVDT	Linear Variable Differential Transducer
M	Molar (solution concentration)
MDD	Maximum Dry Density
MK	Metakaolin
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
PSD	Position Sensitive Detector
RH	Relative Humidity
RLTT	Repeated Load Triaxial Test
RPM	Revolutions Per Minute
SEM	Scanning Electron Microscopy
SM	Silty Sand
SP	Poorly Graded Sand
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
VA	Volcanic Ash
XRD	X-ray Powder Diffraction
XRF	X-ray Fluorescence

EXECUTIVE SUMMARY

Cohesionless soils distributed in coastal areas are problematic and pose challenges for construction. They often require treatments to meet the engineering specifications of construction projects. Currently, these soils are stabilized with ordinary Portland cement (OPC), which is effective in adequately improving the engineering properties at low dosages. However, due to the high carbon footprint of the cement manufacturing process, many research efforts are focusing on identifying greener alternatives. Geopolymer (GP) is one of the materials that has received much attention as a green alternative to OPC for several applications in transportation infrastructure fields such as soil stabilization, pavements, bridges, etc. One of the main reasons for a lower carbon footprint of GP than OPC is that it can be synthesized using waste and natural materials (such as fly ash and clay). Furthermore, studies have shown that mixes having sufficient dosages of GP have exhibited performance comparable to OPC, which makes it a viable option for stabilizing problematic cohesionless soils. Although significant research efforts have been conducted to replace OPC with GP in various civil infrastructure applications, there are only a handful of studies on GP's applicability for stabilizing cohesionless soils.

A collaborative research study was performed to investigate the feasibility of stabilizing cohesionless sandy soils using metakaolin (MK)-based GPs. It is important to note here that MK was used over fly ash (FA) since MK is relatively a pure aluminosilicate source while FA can contain various types of impurities based on its source. Hence, even though FA-based GP has a lower carbon footprint than MK-based GP, it is in the interest of this study that MK was used to gain a better understanding of the interaction between GP and cohesionless soils. The influence of stabilizer dosage and curing period on overall performance and engineering properties of GP-stabilized sandy soils was studied to optimize the use of GP for transportation infrastructure in Region 6. Extensive laboratory tests including linear shrinkage bar tests, unconfined compressive strength tests (UCS), repeated load triaxial tests (RLTT), pH tests, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS) were performed on sandy soils treated with both OPC and GP. The performance of the two treatments was compared to determine the effectiveness of GP over OPC. Overall, the results show that higher dosages of GP can be effective in treating cohesionless sandy soils compared to OPC.

1. INTRODUCTION

The establishment of transportation infrastructure using natively available materials is often the most economical solution. The presence of cohesionless geomaterials, especially around the coastal areas, often hinders the use of native soils in their original form. Generally, problematic soils are mechanically or chemically stabilized using fibers and cementitious materials, respectively, to enhance the mechanical properties and satisfy the construction design requirements *(1-6)*. However, traditional calcium-based stabilizers have a high carbon footprint. Also, during natural disasters, like flooding and hurricanes, these pavements may undergo significant damages. Therefore, an alternative stabilizer with a lower carbon footprint and better durability is desirable to improve the current pavement infrastructure.

Recently, a new class of alumino-silicate polymer, commonly referred to as geopolymer (GP), has received much attention for its eco-friendly and sustainable nature in enhancing the performance characteristics of treated geomaterials. Unlike traditional calcium-based stabilizers, GPs have a significantly lower carbon footprint and still have comparable engineering properties as traditional stabilizers *(7)*. The stabilization of various soils using GP has been studied in previous studies *(8-11)*. The GP-stabilized soils were observed to improve unconfined compressive strength (UCS), volumetric changes, and durability. Based on the results obtained from the previous studies, this study utilized a similar GP composition to explore its effectiveness to stabilize and improve the engineering properties of cohesionless soils native to Region 6. The following section presents the project objectives along with the tasks performed to achieve the objectives.

2. OBJECTIVE

The overall objective of this study was to study the feasibility of stabilizing coastal soils using GP. The task plan adopted to achieve the objective is as follows: the first task involved an extensive literature review on the stabilization of cohesionless soils using both traditional stabilizers and geopolymers. The GP composition, dosage, curing time, and targeted unconfined compressive strength (UCS) of stabilized soils were especially noted during the literature review. The second task involved the selection of a native cohesionless soil that is representative of the coast of Region 6. Sandy soil with traces of silt, classified as silty sand (SM) according to the Unified Soil Classification System (USCS), was selected for this study. The third task focused on the development and characterization of different GP compositions. The GP was potassium-based and synthesized from metakaolin and silica fume. The composition with the most optimal balance between UCS and workability was selected to stabilize the SM selected in Task 2. The characteristics of different GP types were investigated using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). The fourth task focused on characterizing the engineering properties of GP-stabilized cohesionless soil and comparing its performance to traditional calcium-based stabilizers (i.e., Portland cement). Various engineering tests such as UCS tests, linear bar shrinkage tests, RLTTs, pH tests, and durability tests were conducted to study the effectiveness of GP in stabilizing cohesionless soil. In addition, SEM-EDS and XRD studies were performed on GP- and OPC-treated soil specimens to understand the microstructural characteristics of the treated soils and their influence on the macro-scale behavior.

3. LITERATURE REVIEW

3.1. Cement-treated Sandy Soil

Natural cohesionless geomaterials are prevalent in the southeastern region of the US, and these geomaterials often experience issues such as low relative density, high erosion potential, low strength, and low stiffness. This causes a problem to the pavement infrastructure on the coasts of the southeastern US since many of these routes were built using these natively available materials. They pose high risks during tropical storm seasons *(12)*. Therefore, major research efforts have been conducted to stabilize cohesionless soil to improve mechanical properties and durability. Currently, stabilizers such as OPC *(1; 13; 14)* and polymer fibers *(2; 4; 5)* are popular choices to improve cohesionless geomaterials and satisfy the design requirements for pavements.

Calcium-based stabilizers such as OPC and lime are widely used as soil stabilizers due to their low cost, ease of use, and effectiveness at low dosages *(13)*. Aiban et al. *(1)* investigated the effectiveness of using type V OPC to stabilize the coastal soil classified as poorly graded sand (SP) from Saudi Arabia. They reported that the treatment with 4 wt% of OPC, under suitable curing conditions, significantly improved the mechanical properties of SP. Da Fonseca et al. *(14)* used type III OPC to stabilize SM and SP, and showed that they require 3-5% and 7% of OPC, respectively, to reach a UCS of 1 MPa after 7 days of curing. Figure 1 shows the relationship between UCS, void/cement ratio, and cement dosage obtained by Da Fonseca et al. As cement dosage increases, the UCS increases and at the same time the void/cement ratio decreases. Overall, these two studies demonstrated the effectiveness of OPC to stabilize SP and improve UCS.

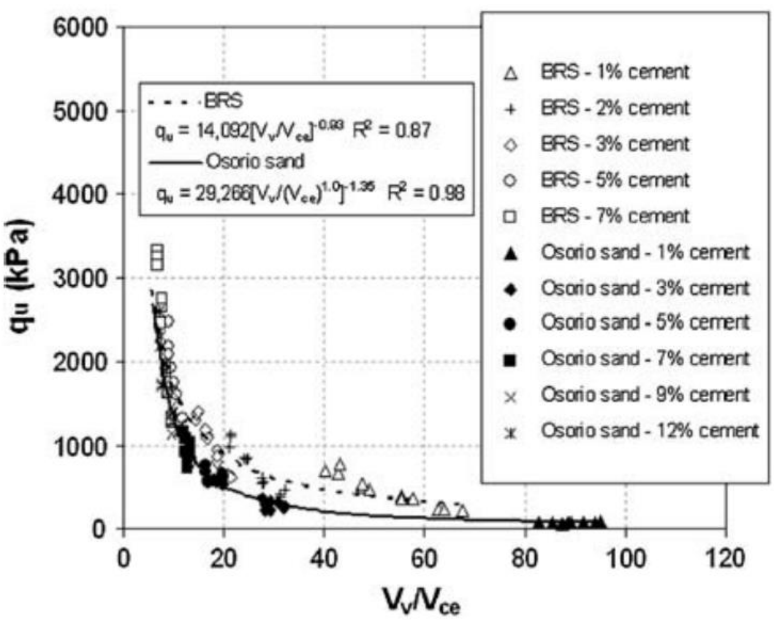
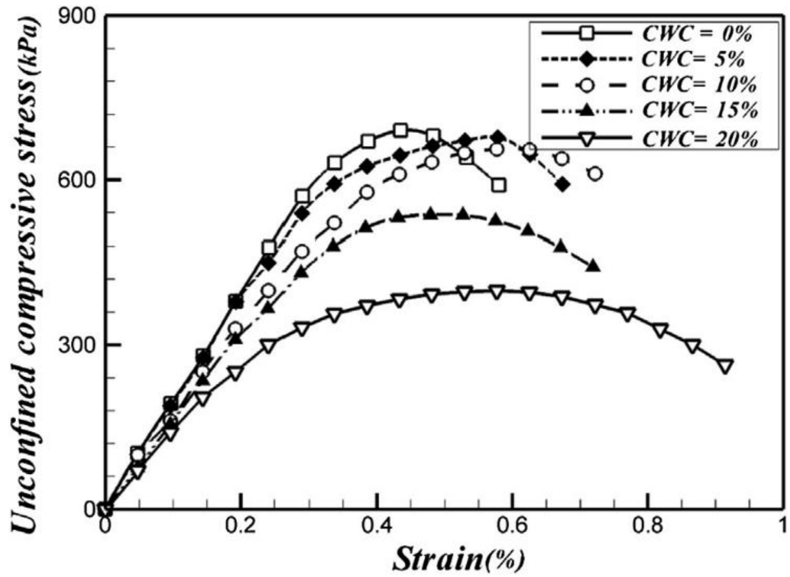


Figure 1. Relationship between UCS and void/cement ratio for various cement dosages *(14)*

Since OPC has a high carbon footprint, many recent studies focused on substituting a portion of OPC with waste materials such as nano-silica *(15)* and coal waste *(16)* to reduce the overall carbon footprint. An appropriate supplementary material should not compromise the properties and ideally should work synergistically with the main material. In the study done by Choobbasti et al.

(15), OPC was mixed with 20% of nano-silica to stabilize coastal sandy soils from Iran. The UCS results show that replacing 10% of OPC with nano-silica improved the UCS by 10 to 40%. On the other hand, coal waste does not perform as well as nano-silica when used to replace OPC. Afrakoti et al. *(16)* reported that the usage of coal waste does not contribute much to the improvement in UCS of the cement-treated soil. As it can be observed in Figure 2, any partial replacement of OPC with coal waste reduces the early UCS (<14 days). However, the UCS of mixtures with less than 15% of coal waste partial replacement after 28 days of curing is comparable to that of OPC-treated mixture without coal waste. Overall, both nanosilica and coal waste seem to be viable supplementary materials for OPC when used to treat sandy soils at their respective optimal dosages.



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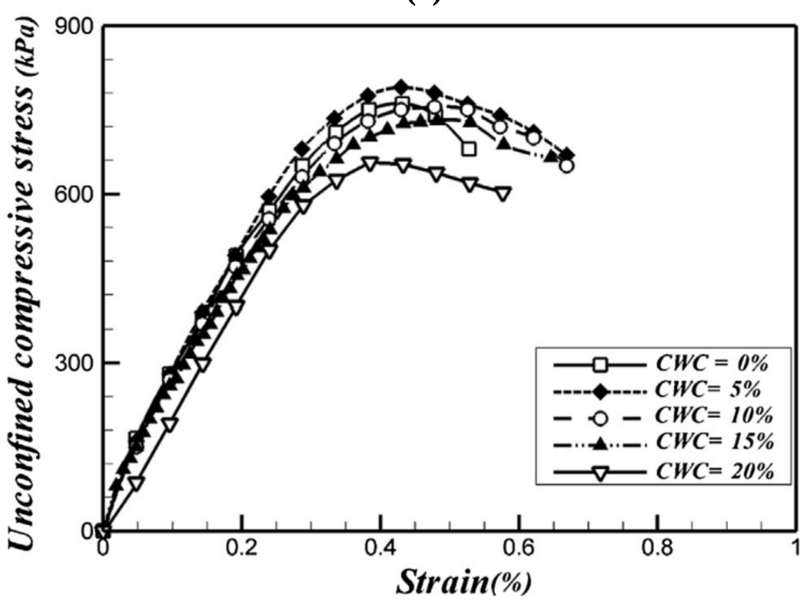


(b)

Figure 2. The effect of partially replacing OPC with coal waste as soil stabilizer for sandy soil after (a) 14 days and (b) 28 days of curing *(16)*

Finding an alternative material is one of the effective ways to address OPC's problem of high carbon footprint. In a comprehensive study by Santoni et al. *(17)*, various non-traditional stabilizers such as acid, lignosulfonate, enzyme, polymer, petroleum emulsion, and tree resin were evaluated as stabilizers for SM and compared against traditional stabilizers such as OPC and lime. Out of the three traditional stabilizers, it was found that the OPC worked the best for SM, which is consistent with the previous studies. Furthermore, out of all the different types of non-traditional stabilizers, polymers were found to be the most promising candidate to improve UCS and have good waterproofing potential. The UCS performance of OPC and polymer were summarized and presented in Figure 3. While the specimens are wet, OPC stabilizers improved the UCS by 8 times, and the polymer-based treatments improved the UCS by ~4 times. Rapid UCS development is one of the main advantages of polymer stabilizers over traditional stabilizers as it leads to shorter curing and construction times.

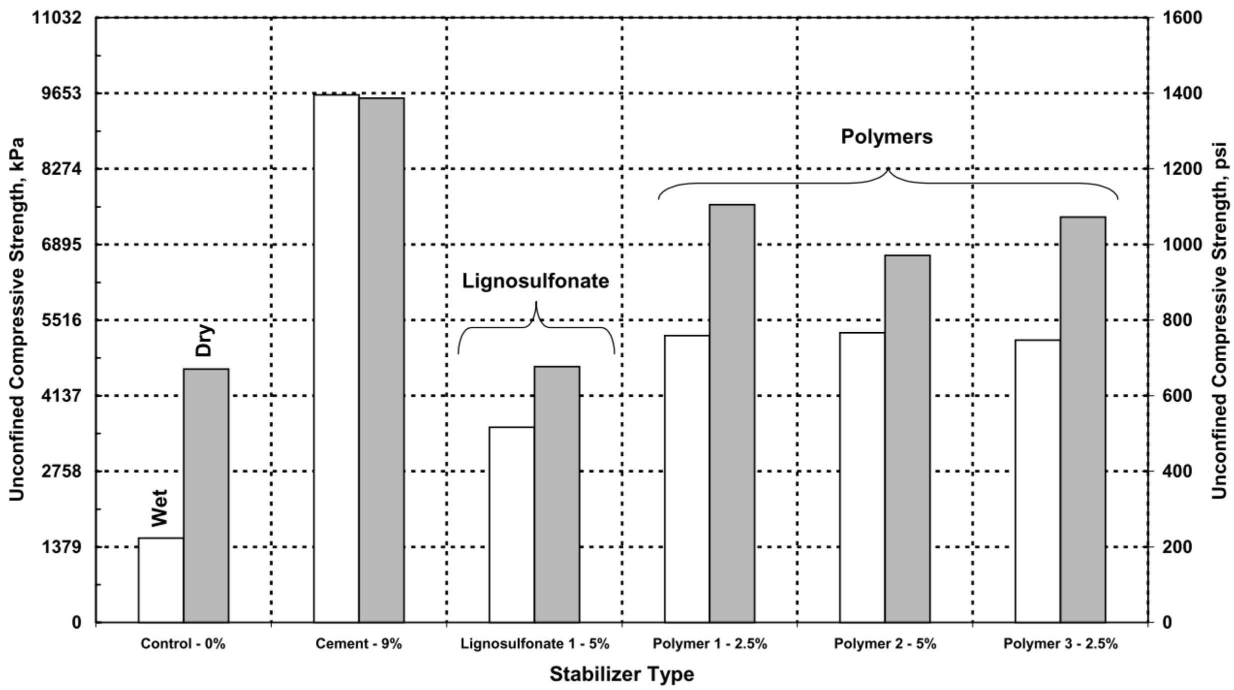


Figure 3. UCS comparison of cement and various non-traditional stabilizers for sandy soils *(17)*

3.2. Geopolymers

GP has recently become popular as a soil stabilizer since it is effective in enhancing the engineering properties of various problematic soils *(18-20)*. GP is synthesized by mixing an alkali activator solution with a source of aluminosilicate *(21; 22)*. The alkali activator solution could be a mixture of sodium hydroxide, potassium hydroxide, sodium silicate, potassium silicate, and silica fume. Meanwhile, popular choices for the source of aluminosilicate include FA, ground granulated blast furnace slag (GGBFS), and MK *(23-25)*. GP treatment can improve the engineering properties of problematic soils, including UCS, stiffness, tensile strength, California bearing ratio (CBR), and durability *(26-30)*. The extent of improvement depends on the GP composition, dosage, viscosity of the activator solution, water content, curing time and temperature, and soil type.

During the geopolymerization process (see

), the source of aluminosilicate is dissolved into monomeric and oligomeric species due to the highly alkaline conditions created by the alkali activator solution. After dissolution, the species begin to chain back together through polycondensation where excess water is released. As polycondensation continues, the chains will continue to grow and crosslink until an amorphous gel with a complex three-dimensional structure is formed. The final GP structure can be described as an amorphous and three-dimensional framework of corner-sharing $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedra in IV coordination, where the IV-coordinated aluminum is what distinguishes GP from other aluminosilicate materials. The negatively charged aluminum is charge balanced by the alkali cations that were used during the synthesis *(7; 31)*. The utilization of potassium hydroxide instead of sodium hydroxide results in enhanced workability at the same water molar amount since sodium has a smaller cation radius; therefore, it would have a substantial ionic potential *(32)*.

Figure 4. Reaction mechanism of geopolymerization.

Another study also showed that sodium-based GP retains more capillary water than potassium-based GP for numerous compositions cured for 28 days *(33)*. This implies that potassium-based GP is preferred over sodium-based GP as a soil stabilizer since potassium-based GP would attract less water during wet/dry cycles, leading to smaller volumetric fluctuations. The water content or water to solid ratio also influences the mechanical and workability properties of GP similar to other cementitious materials *(34)*; therefore, it is vital to find a balance between mechanical properties and workability when implementing GP as a soil stabilizer. This would then allow GP to properly disperse into the soil during the mixing process, which is crucial for the strength development.

The presence of excess water results in incomplete chemical reactions and can break the geopolymer-soil bonds *(35)*. GP stabilization results in the enhancement of engineering properties of the treated material that depends on the curing time and temperature *(28)*. The time-dependent strength gain has been observed to continue for over one year, and the long-term strength has been reported to be as high as three times the strength gained in a month. Even though the geopolymerization process is accelerated at elevated temperature conditions, the use of high-temperature curing is energy-intensive and is not feasible for most field applications *(36)*.

3.3. Geopolymer-treated Sandy Soil

Rios et al. *(37)* investigated the feasibility of stabilizing SM from Portugal with FA-based GP (FA-GP) and compared its performance with lime stabilization. They tested five different mixtures for both UCS and stiffness: 1) untreated SM, 2) SM+FA-GP, 3) SM+lime, and SM+lime+FA at two different dosages. They used an alkali activator solution prepared by mixing sodium hydroxide and sodium silicate. From the UCS results (see Figure 5), it was observed that 3% lime improved the strength by 6 times when compared to the untreated soil, and the addition of 10-20% FA to 3% lime improved the strength by 7 to 8 times depending on the dosage. Furthermore, the usage of FA-based GP improved the strength by 66 times.

It is important to note that Figure 5 does not include the UCS value of the GP-treated soil since the value is too high and would overshadow the values of the other stabilizers. A significant difference in value was also observed in the stiffness measurements. Even though this study demonstrates the superior performance of FA-based GP compared to the other stabilizers, it was observed that cohesionless geomaterials such as SM soils are typically stabilized with OPC over lime *(13; 17)*. Therefore, it would have provided a better comparison if Rios et al. had done the study with OPC instead of lime. Additionally, it would also be interesting to observe the effect of FA-based GP dosages on the mixture performance as the single composition considered by Rios et al. exhibited higher strength than the other compositions with lime.

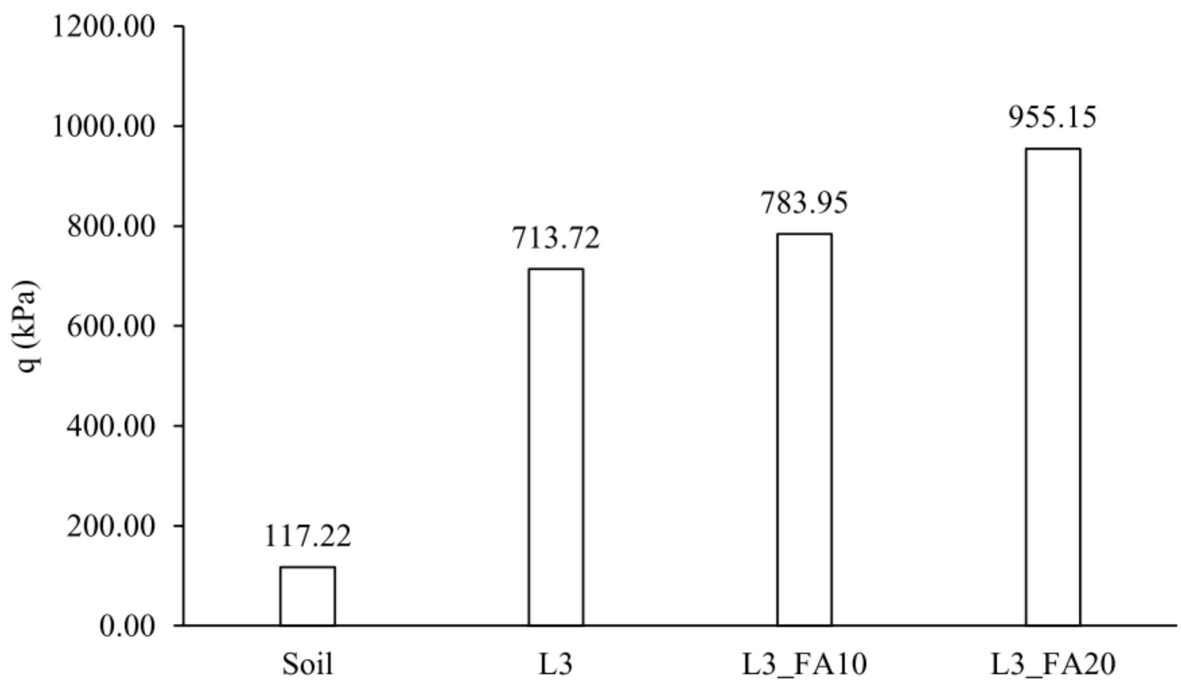


Figure 5. Comparison of UCS values for various stabilized SM mixes *(37)*

Dungca et al. *(38)* studied the effectiveness of stabilizing SM from the Philippines using FA-based GP. The FA-based GP was synthesized first by dry mixing the sodium hydroxide pellets, sodium silicate powder, and fly ash. Then the dry mixture was added into water and mixed for 10 minutes until the paste was homogeneous. The GP paste used by Dungca et al. has a sodium silicate to sodium hydroxide ratio of 2, activator to FA ratio of 0.4, and NaOH concentration of 14 M. The GP paste was then added to the soil at 10, 20, and 30%.

The 28-days UCS results showed that the untreated SM was too weak to be tested, 10%, 20%, and 30% FA-GP improved the strength to 78 kPa, 247 kPa, and 1350 kPa, respectively. Thus, even though the study showed that GP could be an effective stabilizer for SM, a very high dosage (> 20%) was needed to reach a reasonable UCS value. Furthermore, it would have been helpful if the study had compared GP based mixes with traditional stabilizers such as OPC. Figure 6 shows the specimens of 30% GP-treated sandy soil by Dungca et al. *(38)* after UCS tests. It can be observed that the treatment was successful as indicated by high UCS values and brittle failure.

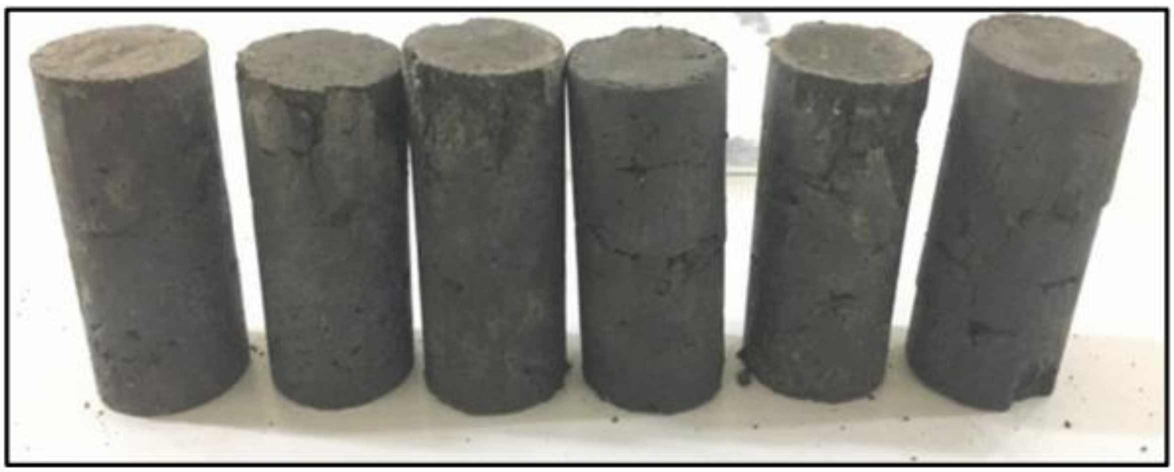


Figure 6. Failed specimens of 30% GP-treated sandy soil after UCS test *(38)*

Shariatmadari et al. *(39)* investigated the application of volcanic ash (VA)-based geopolymer-treated silty sands for controlling wind erosion. The VA-based GP-treated specimens were prepared with distilled water, silty sand, alkaline activator (8M NaOH). Figure 7 shows the effect of fines content on the UCS values of VA-based GP-treated specimens cured for 7 days at 60°C and 5% relative humidity. They focused on the effect of fines content by varying the ratio between sand and silt for the silty sand soil specimens. Although UCS values significantly decreased with an increase in fines content up to 30% and remained constant between 30% and 70% before slightly decreasing at 100% fines content. In summary, the UCS values decreased with an increase in the percentage of fines content in VA-based GP-treated specimens. It should be noted that Shariatmadari et al. *(39)* reported one of the highest values of UCS for GP-treated sandy soils because the samples were cured under elevated temperature instead of ambient conditions with high humidity.

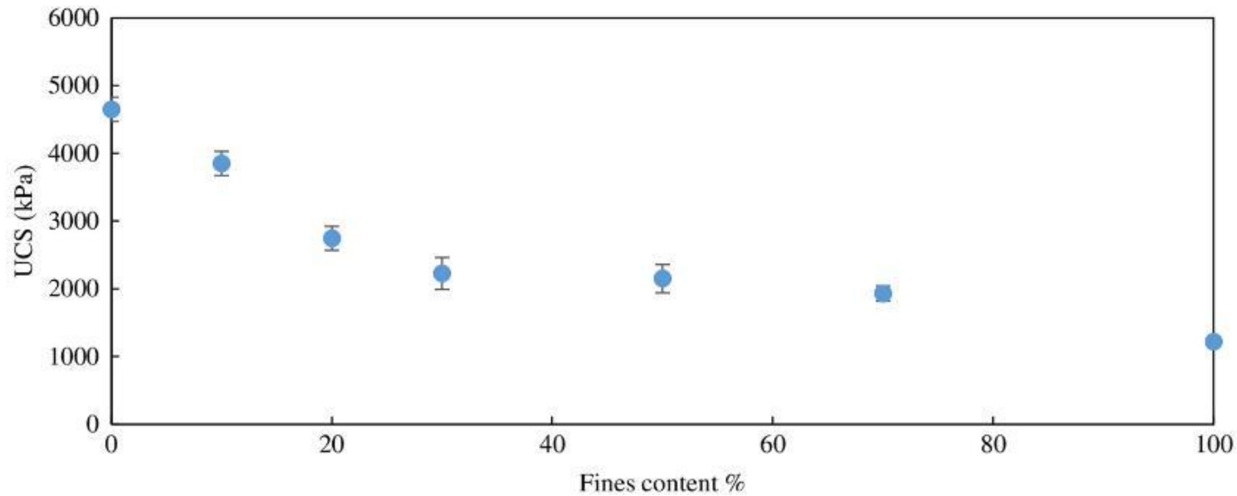


Figure 7. UCS values of GP stabilized silty sand specimens with different fines content ***(39)***

Chemical reactions in GP-treated soils are strongly affected by the type and presence of clay particles *(40)*. Shariatmadari et al. *(39)* also explained the effect of fines content on geopolymer-based soil stabilization in Figure 8. Both papers proposed that the main mechanism behinid geopolymer stabilization is through physical bonding for both sandy and clayey soils. The improvement in compressive strength with a decrease in fines content of GP-treated sandy soils can be attributed to the geopolymer coating on soil particles. Even though fine particles should theorectically improve the mechanical properties of the specimen by filling up the voids, it also increases the specific area for the specimen which reduces the effectiveness of GP treatment. As it can be observed in Figure 8, the treatment will result in more abundant coating for coarse-grained soils, which will then form stronger bonds between the particles and vice versa for fine-grained soils *(39)*.

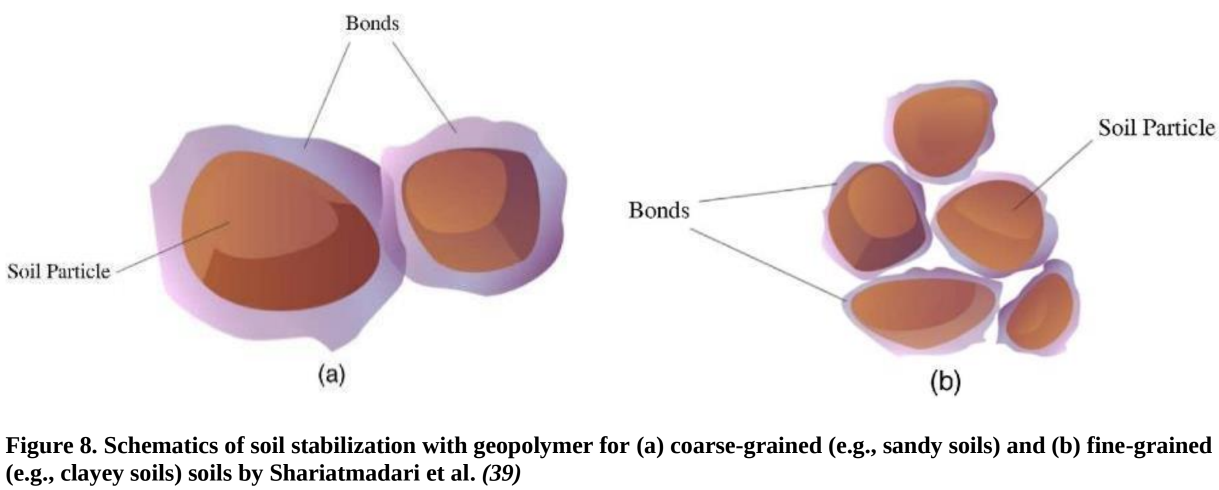


Figure 8. Schematics of soil stabilization with geopolymer for (a) coarse-grained (e.g., sandy soils) and (b) fine-grained (e.g., clayey soils) soils by Shariatmadari et al. ***(39)***

Lori et al. *(41)* applied copper mine tailing dam sediments (CMTDS) based GP to poorly-graded sand (SP) and compared them to OPC stabilized mixes. The CMTDS-GP were synthesized with at different molar (M) concentrations of KOH solution (1, 3, 7, and 10M) and different percentages of CMTDS (10, 15, and 20%). They reported that after 7 days of curing at ambient temperature, CMTDS-GP synthesized with 1M KOH solution was only able to improve the UCS up to ~50-60% that of 5% OPC mixes, regardless of the CMTDS dosage. However, when KOH solution with higher concentrations was used, 10% CMTDS-GP was able to improve the UCS up to 150-200% of the UCS of 5% OPC. Interestingly, using 10M KOH to synthesize CMTDS-GP instead of 3M KOH improved the soil by an additional 0.5 MPa regardless of CMTDS dosage. Figure 9 compared the UCS values between untreated (Soil), 5% OPC (5OPC), CMTDS-GP with 10M KOH at 10 (10M10C0S), 15 (10M15C0S), and 20% (10M20C0S). 5% OPC was able to improve the UCS of untreated soil by 300% after 7 days of curing, and 900% after 91 days of curing. Furthermore, all CMTDS-GP stabilized mixes with 10M KOH demonstrated higher UCS than 5% OPC. They justified using higher dosages of CMTDS than OPC by referring to the environmental and cost benefits of using CMTDS, which is a waste material. This study showed promising results in stabilizing SP with CMTDS-based GP. However, additional studies to further evaluate the behavior of mixes stabilized with lower dosages of CMTDS-GP will be beneficial in determining its equivalent dosage to OPC in terms of UCS.

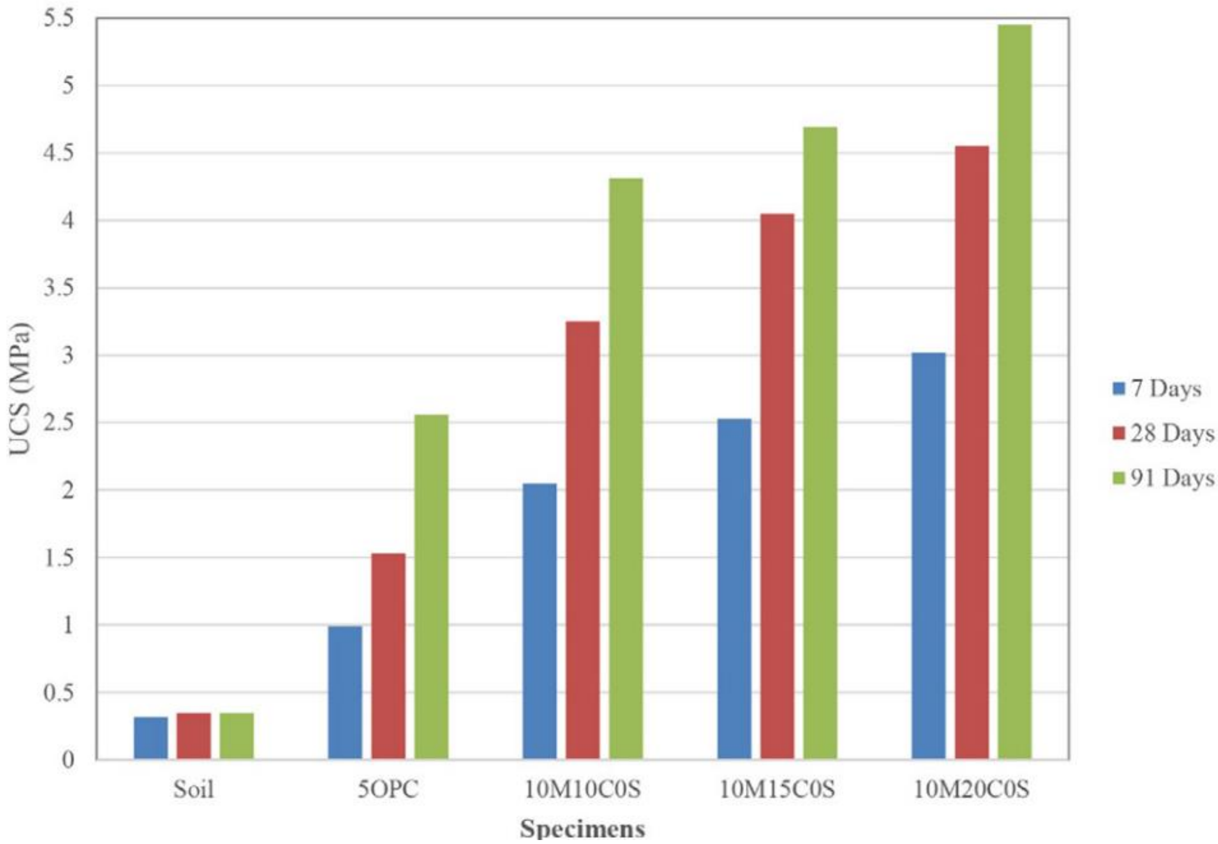


Figure 9. UCS of SP stabilized by OPC, and CMTDS-based GP at various dosages and curing periods ***(41)***

4. METHODOLOGY

4.1. Soil Selection and Characterization

The soil used for this project was a natural sandy soil collected from Texas, USA. Basic soil characterization tests were performed following the American Society of Testing and Materials (ASTM) standards, and the results can be found below in Table 1. Figure 10 depicts the particle size distribution of the natural soil. The natural soil contains 82.0% sand, 16.2% silt, 1.4% clay, and is non-plastic. Therefore, the natural soil is classified as silty sand (SM) as per the Unified Soil Classification System (USCS). Based on these characteristics, this natural soil fits the requirement of "cohesionless sandy soils in coastal areas" and is ideal for this research study.

Table 1. Basic soil characterization test results.

Properties	Standard	Result
Specific Gravity, G_S	ASTM D854	2.67
Sand (%)	ASTM D6913	82.0
Silt (%)	ASTM D7928	16.2
Clay (%)	ASTM D7928	1.4
Liquid Limit, LL	ASTM D4318	-
Plastic Limit, PL	ASTM D4318	-
Plasticity Index, PI	ASTM D4318	Non-plastic
USCS Classification	ASTM D2487	SM
Optimum Moisture Content, OMC (%)	ASTM D698	12.4
Maximum Dry Density, MDD (g/cm^3)	ASTM D698	1.67

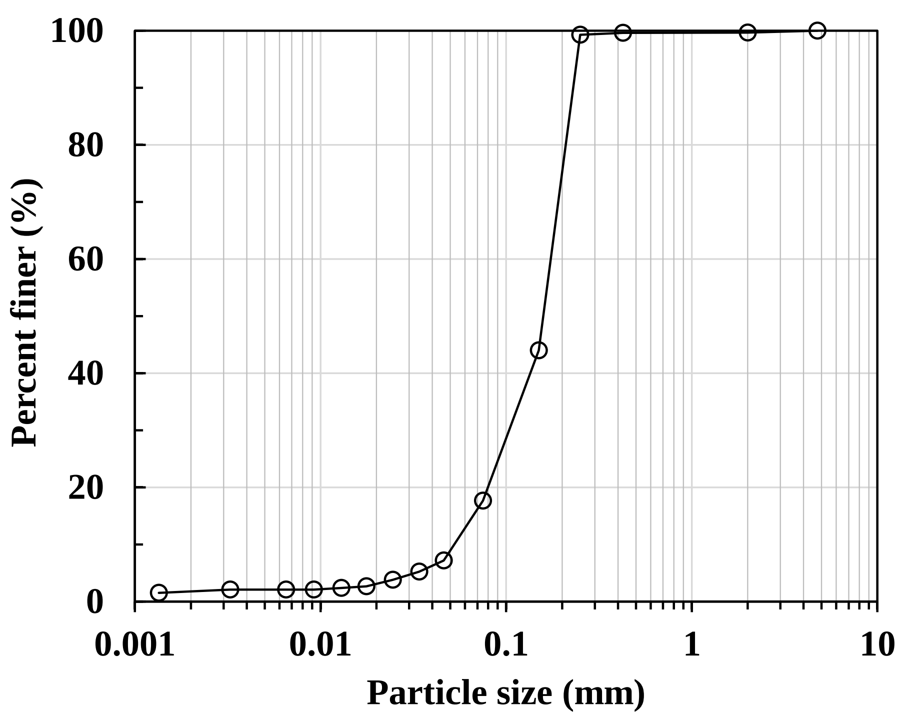


Figure 10. Particle size distribution of natural soil.

The chemical and phase compositions of the sandy soil were analyzed with X-ray fluorescence (XRF) and X-ray diffraction (XRD). XRF scan was done with Rigaku Supermini200 (Rigaku Corporation, Japan) and then analyzed using the internal database. The chemical composition of SM obtained from XRF is summarized in Table 2. XRD scanning was done with a Bruker-AXS D8 Advanced (Bruker Corporation, MA, USA) with Cu source (Cu Kα radiation, λ = 1.54178 Å) and a Lynxeye position sensitive detector (PSD). The XRD spectrum was analyzed with the Profex software. From the XRD spectrum shown in Figure 11, SM is composed of mostly quartz (SiO_2) with some other minor phases such as calcite ($CaCO_3$), anorthite ($CaAl_2Si_2O_6$), and microcline ($KAlSi_3O_8$) as summarized in Table 3.

Table 2. Chemical composition of the soil used for this project.

Chemical Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	TiO_2
wt%	76.02	8.50	2.16	8.62	1.36	1.98	0.76	0.05	0.55

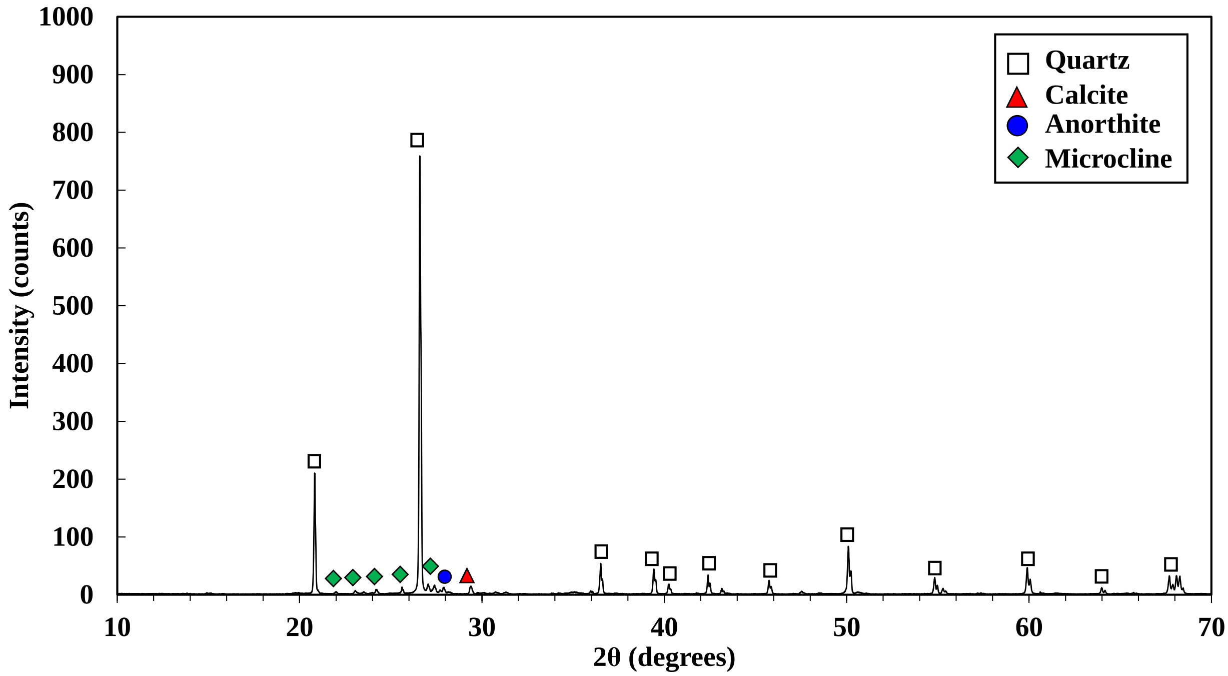


Figure 11. XRD spectrum of the soil used for this study.

Table 3. The phase composition of the sandy soils.

Phase	Quartz	Calcite	Anorthite	Microcline
wt%	85.0	3.6	5.4	6.0

4.2. Geopolymer Synthesis and Selection

The GP used in this study was synthesized using potassium hydroxide (Noah Technologies, TX), amorphous fumed silicon (IV) oxide (Alfa Aesar, MA) with a specific surface area of 350-410 m^2/g, MetaMax® (BASF Catalysts LLC, NJ) metakaolin (MK), and deionized water. Although FA is cheaper and more commonly used in previous research works, it was not used in this study due to its inconsistent composition and high concentration of impurities dependent upon its source. Hence, MK was chosen for this study because it is a clean source of aluminosilicate with a minimal amount of impurities.

The potassium hydroxide (KOH) was dissolved in deionized water to create a highly alkaline solution to process the alkali metal cations. The amorphous fumed silicon oxide was then added to adjust the SiO_2/Al_2O_3 ratio of the final product as needed to create the activating solution for the synthesis of GP. The activating solution was then mixed with MK in a high-sheared mixer for 6 minutes at 400 revolutions per minute (RPM) to create a homogenized mixture, known as GP.

Since the number of possible GP compositions is endless, it is necessary to narrow down the compositions using data from previous works for the scope of this work. Based on the previous studies *(10; 42; 43)*, K331 was selected as the composition due to its combination of high strength and suitable workability. It should be noted that GP compositions are labeled as KXYZ where the first letter denotes potassium (K) while XYZ numbers denote SiO_2/Al_2O_3 ratio, water to solid ratio used to prepare GP, and Na/Al or K/Al ratio, respectively. For example, GP sample K331 is prepared with K-activator, with SiO_2/Al_2O_3=3, water/solid ratio=3, and K/Al=1.

4.3 Chemical Stabilization of the Sandy Soil

The sandy soil was treated with three stabilizers for comparison – OPC, GP, and GP-OPC mixture. A total of six different mixtures were made for this study – untreated, 8% GP (8GP), 20% GP (20GP), 2% OPC (2C), 4% OPC (4C), and 8% GP + 2% OPC (8GP-2C). The soil specimens were compacted to 98% of the MDD and on the wet side of the OMC. The performance of the different mixtures was evaluated through linear shrinkage bar tests, UCS tests, RLTT, pH tests, and durability tests at three different curing periods – 0 days (6 hours), 3 days, and 14 days (Table 4). The details of the mixing proportions are presented below in Table 5. The details of the laboratory testing programs are summarized in Table 6.

Table 4. Target dry density and moisture contents for the preparation of soil specimens.

Specimen group	98% MDD (g/cm^3)	Moisture content at 98% MDD on wet side (%)	MDD (g/cm^3)	OMC (%)
Untreated	1.65	16.1	1.68	12.4
2C	1.68	15.4	1.71	12.2
4C	1.69	15.4	1.72	12.1
8GP	1.73	14.9	1.77	12.9
20GP	1.83	13.7	1.86	12.2
8GP-2C	1.75	15.1	1.79	13.2

Table 5. Mixture proportion of the different compositions.

Specimen group	Sandy soil (g)	K331 Paste (g)	OPC (g)	Water (g)
Untreated	1650	0	0	266
2C	1647	0	33	259
4C	1625	0	65	260
8GP	1602	191	0	195
20GP	1525	455	0	101
8GP-2C	1591	190	32	202

All stabilizers were mixed with soil differently to allow for proper reactions. For cement-treated soils, the OPC powder was first dry-mixed into the soil, and then water was added to reach the targeted moisture content. For GP-treated soil, the natural soil was first mixed with the water. Once the soil was wetted, GP paste was prepared separately on the side and then mixed into the moist soil. For GP-cement-treated soils, the preparation starts with dry mixing the OPC powder with natural soil, then GP was prepared on the side. Subsequently, water was added into the OPC-soil mixture before adding GP.

Table 6. Summary of the overall testing program.

Test	Test Standard/ Reference	Stabilizer Dosage	Number of Specimens
Linear Shrinkage Bar Test	Tex-107-E	Untreated	2 replicates
Linear Shrinkage Bar Test	Tex-107-E	2C 4C 8GP 20GP 8GP-2C	2 replicates x 1 curing
Unconfined Compressive Strength (UCS) Test	ASTM D5102 & ASTM D2850	Untreated	2 replicates
Unconfined Compressive Strength (UCS) Test	ASTM D5102 & ASTM D2850	2C 4C 8GP 20GP 8GP-2C	3 replicates x 3 curing
Repeated Loading Triaxial Test (RLTT)	AASHTO T-307	Untreated	2 replicates
Repeated Loading Triaxial Test (RLTT)	AASHTO T-307	2C 4C 8GP 20GP 8GP-2C	2 replicates x 3 curing
pH Test	Tex-128-E	Untreated	2 replicates
pH Test	Tex-128-E	2C 4C 8GP 20GP 8GP-2C	2 replicates x 3 curing
Durability Test	Protocols outlined in Little (1998) *(44)*	4C 20GP 8GP-2C	3 replicates x 2 curing

4.3.1. Linear Shrinkage Bar Tests

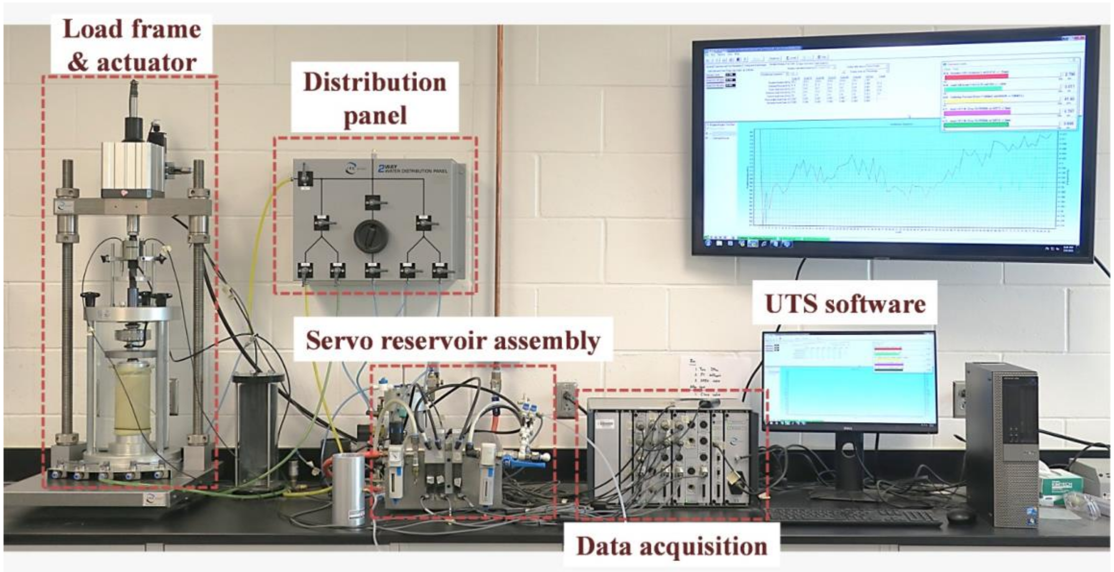
The linear shrinkage bar tests were performed according to TEX-107-E to study the shrinkage behavior of natural and treated soil mixtures. The inside of the 19 mm x 19 mm x 127 mm linear shrinkage bar mold was greased with petroleum jelly to prevent the adhesion of the soil to the mold. The soil slurry was evenly placed in the mold and gently shaken to remove any entrapped air bubbles. The soil surface was trimmed with a straightedge, and the wet soil in the mold was placed in an oven at 110 ± 5°C after a slight change in soil color. After 24 hours of oven-drying, the length of the dried soil mix was measured to determine the linear shrinkage. For each specimen group and curing period combination, the linear shrinkage bar tests were performed on duplicate specimens to ensure the reliability and repeatability of the test results. The experimental program was simplified to only testing 4C, 8GP, and 8GP-2C after 14 days of curing since the natural soil does not have any shrinkage; therefore, it seemed appropriate to only test "extreme" samples.

4.3.2. UCS Tests

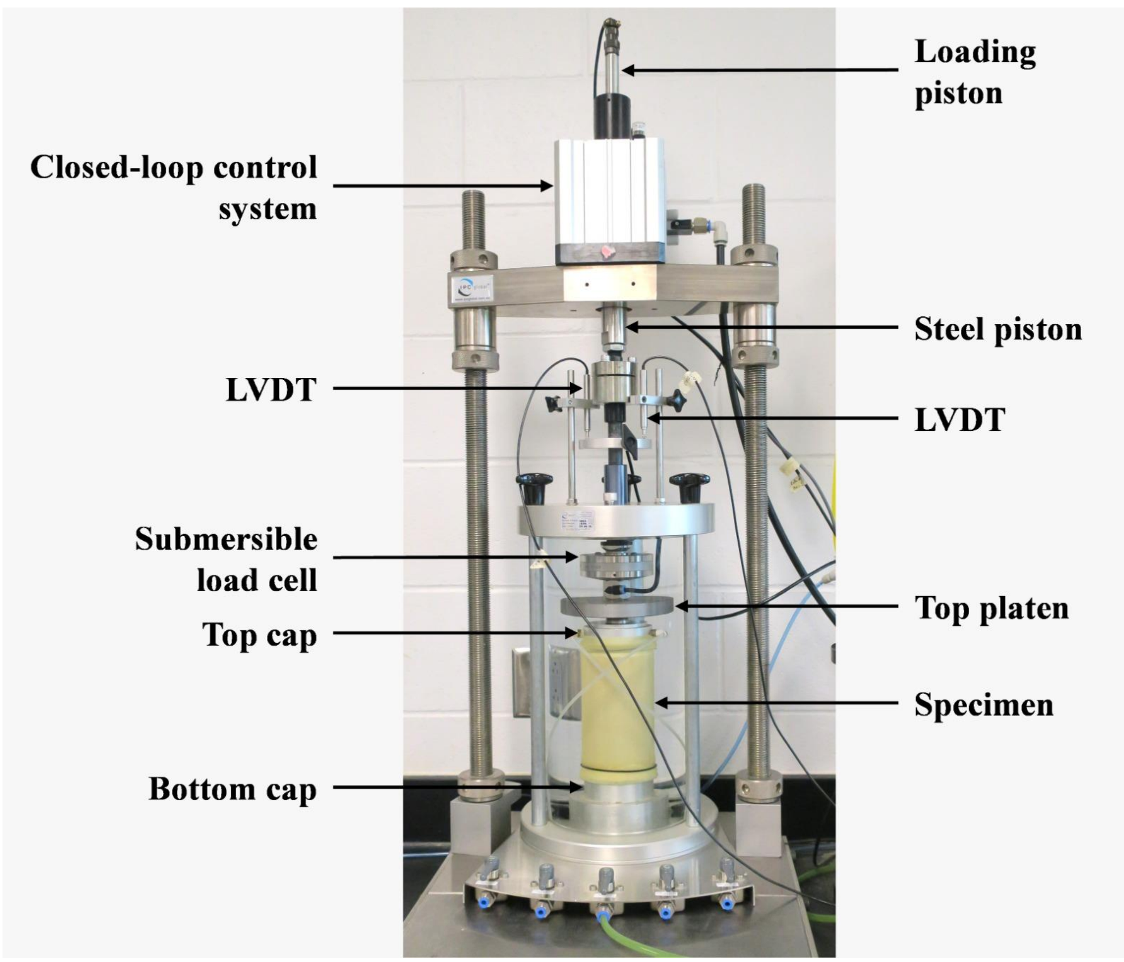
The UCS tests were performed following ASTM D5102 and ASTM D2850 to evaluate the improvements in the strength of the treated specimens. The soil specimens were compacted in three layers using Instron materials testing machine to make samples approximately 72 mm in diameter by 144 mm in height. The samples were cured under ≈ 100% Relative Humidity (RH) for each curing period. Then, the samples were tested using the universal testing systems (Instron) machine at a strain rate of 1%/minute.

4.3.3. RLTT

The repeated load triaxial tests (RLTT) were conducted by following the American Association of State Highway and Transportation Officials (AASHTO) T-307 standard to determine the resilient modulus (M_R) of subgrade soils. All RLTTs were conducted using a repeated load triaxial test apparatus shown in Figure 4a. The test consisted of a total of 15 testing sequences, in which five different deviatoric stresses (13.8, 27.6, 41.4, 55.2, and 68.9 kPa) were applied to the cylindrical specimens confined separately with three different confining pressures (41.4, 27.6, and 13.8 kPa) (Table 7). Before starting the entire 15 testing series, 500 load cycles were applied with confining stress of 41.4 kPa and cyclic stress of 24.8 kPa for the pre-conditioning of the specimen. The pre-conditioning sequence could ensure proper contact between the top platen, the top cap, and the top surface of the test specimen (Figure 4b). After completing the pre-conditioning stage, 15 testing sequences with 100 cycles at different deviatoric and confining stresses were applied to the test specimens. The cyclic deviator stress was applied as haversine-shaped loading with 0.1-second load duration, followed by a 0.9-second rest period. As a result, each cycle lasted for a total of 1 second. The load response and vertical deformation were measured using a submersible load cell and two linear variable differential transducers (LVDTs), respectively (Figure 12b).



(a)



(b)

Figure 12. Repeated load triaxial tests: (a) repeated triaxial apparatus, and (b) repeated load triaxial cell

Table 7. Summary of an RLTT testing program.

Sequence #	Confining pressure (kPa)	Contact stress (kPa)	Cyclic stress (kPa)	Max. axial stress (kPa)	No. of load cycles
Conditioning	41.4	2.8	24.8	27.6	500
1	41.4	1.4	12.4	13.8	100
2	41.4	2.8	24.8	27.6	100
3	41.4	4.1	37.3	41.4	100
4	41.4	5.5	49.7	55.2	100
5	41.4	6.9	62.0	68.9	100
6	27.6	1.4	12.4	13.8	100
7	27.6	2.8	24.8	27.6	100
8	27.6	4.1	37.3	41.4	100
9	27.6	5.5	49.7	55.2	100
10	27.6	6.9	62.0	68.9	100
11	13.8	1.4	12.4	13.8	100
12	13.8	2.8	24.8	27.6	100
13	13.8	4.1	37.3	41.4	100
14	13.8	5.5	49.7	55.2	100
15	13.8	6.9	62.0	68.9	100

4.3.4. pH Test

Soil pH is a measure of the degree of acidity or alkalinity of the soil. It is useful to determine the solubility of soil minerals and the mobility of ions in the soil. All pH tests in this study were measured as per Tex-128-E, using the Cole-Parmer P200 pH meter (Figure 13). The pH meter was calibrated before each test, followed by three-point calibration with three different pH standard buffer solutions (4.00, 7.00, 10.01 pH). First, 150±1 mL of deionized water in a glass beaker was heated at 45°C to 60°C for the leaching of the soil. Then, 30±0.1 g of dried soil, passing sieve No. 4 (4.75 mm), was mixed with the water (i.e., water/soil ratio = 5 mL/g). Subsequently, the soil-water slurry was mixed using a stirring bar on a magnetic mixer for 20 seconds every 15 minutes in an hour. After one hour, the soil pH was measured by submersing a calibrated electrode in the soil-water mixture.

Since the first step of geopolymerization is to ensure that the precursor material (metakaolin in this study) properly dissolves into Al and Si monomeric and oligomeric species, a highly alkaline environment is needed for the occurrence of hydroxyl-promoted dissolution *(45)*. Therefore, the soil pH tests were conducted on both untreated and treated soils after different curing periods to ensure the presence of an alkaline environment needed for the chemical reactions. This provides an understanding of the long-term effects of cement and GP treatments.

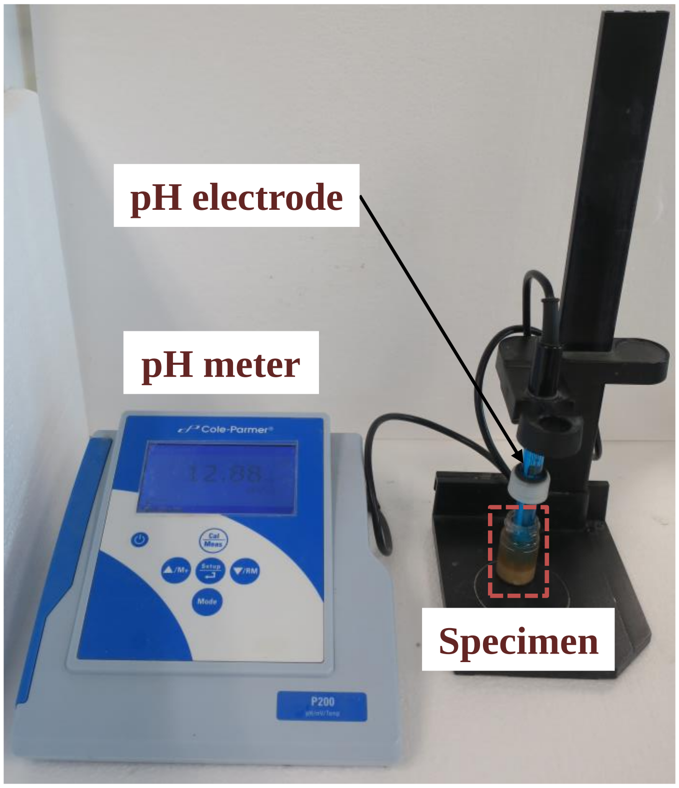


Figure 13. Soil benchtop pH meters.

4.3.5. Durability Test

Most areas in Texas are under humid subtropical climates. Due to such climate, durability tests are necessary to evaluate the effects of exposure to moisture through capillary soaking of sandy soils treated with cement or GP. In this study, the durability tests of chemically-treated soils (i.e., cement-treated, GP-treated, GP-cement-treated specimens) were performed following the recommendations provided by Little *(44)*. In addition, although Little *(44)* recommended the durability tests for expansive soils, the tests were modified by performing capillary soaking of the treated cohesionless soils.

The durability test setup consisted of a plastic container, a plastic wrap, and a porous stone (Figure 14). After treated specimens were cured for a designated period, they were placed on a fully saturated porous stone. For capillary soaking, the specimens were placed for 24 hours and wrapped by an absorbent paper that effectively prevented moisture evaporation from the specimen. In order to sustain net capillary action, the water level was maintained at the mid-height of the porous stone to prevent direct contact with the specimen. A lid with plastic wrap provided a consistent environment during capillary soaking.

The changes in the UCS values of specimen groups for different curing periods could provide an idea about the effect of moisture intrusion on treated soil specimens. The strength retention indicates the changes in UCS values of treated soil specimens before and after capillary soaking and is calculated by the ratio between unsoaked and soaked UCS values.

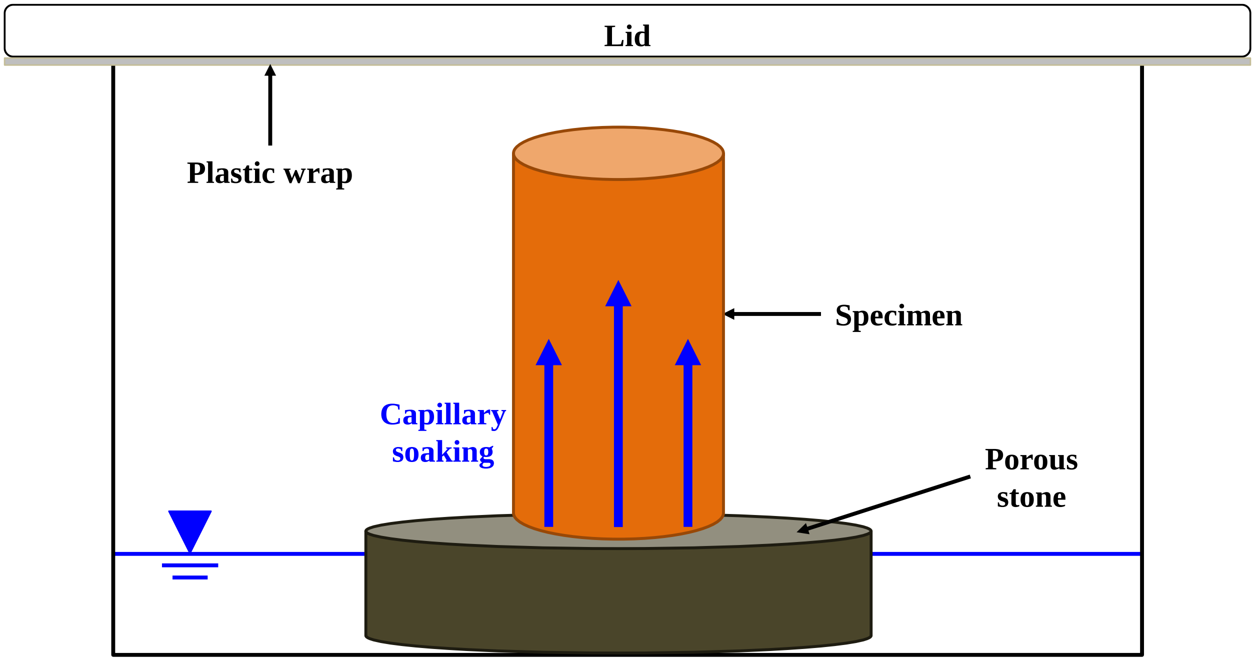


Figure 14. Durability test setup.

4.3.6. SEM-EDS

Characterization techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used to understand the microscopic characteristics of the soil mixtures. SEM-EDS was performed, using the JEOL JSM-7500F (JEOL USA Inc, MA), on each composition to understand the influence of morphology and chemistry.

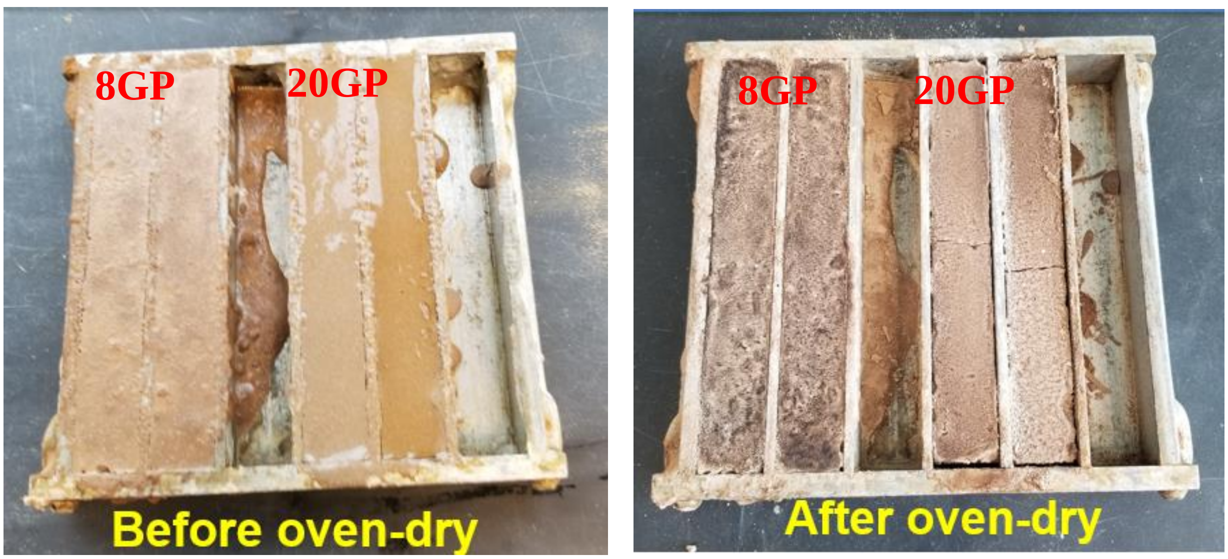
4.3.7. XRD

XRD was also considered for characterizing and understanding the mechanisms in GP-treated specimens. Previous studies have shown that the geopolymerization of MK-based GP can be identified through the shift of an amorphous characteristic hump with a center of $2\theta = 22°$ to $2\theta = 29°$. However, the XRD spectrum of GP-treated sandy soil (results not shown) was essentially identical to that of untreated sandy soil since there is an overlap between the locations of the hump from GP and the primary peak from quartz (SiO_2). XRD results were observed to be not helpful so no further tests were conducted for the remainder of the project.

5. ANALYSIS AND FINDINGS

5.1. Linear Shrinkage Bar Tests

Linear shrinkage bar tests were conducted on the natural sandy soil, cement-treated, GP-treated, and GP-cement-treated soils to study the effect of chemical treatment on the shrinkage behavior of the soil. Typically, linear shrinkage tests are not carried out on sandy cohesionless soil since it does exhibit shrinkage problems. Therefore, the purpose of this test was to evaluate if the swelling of soil particles, that occurs due to chemical treatments, develops any shrinkage potential in the treated soil specimens. The results indicate that the naturally sandy soil does not have any measurable shrinkage strain, and none of the GP treatments affects the shrinkage behavior except for 20% GP, which has a measurable shrinkage of ~2% (Figure 15). In summary, the results of linear shrinkage bar tests confirm that there is no possibility of soil shrinkage due to the use of geopolymers.



(a) (b)

Figure 15. Linear shrinkage bar tests of 8GP and 20GP, (a) before oven-dry and (b) after oven-dry.

5.2. UCS Tests

The UCS results of all the compositions for the three different curing periods are presented in Figure 16. Natural sandy soil exhibited a UCS value of 13 kPa. The 4% cement-treated soil samples cured for 14 days reached a UCS strength of ~900 kPa. It is also interesting to note that cement treatment can result in immediate strength gain (~100 kPa) after just 6 hours of curing. However, GP treatment does not offer any immediate strength gain at 6 hours, and 8% GP was not able to improve the strength significantly. The 20% GP-treated soils cured for 6 hours did not improve the soil significantly; however, after 3 days of curing, it reached 1,500 kPa. In summary, the UCS results from this study show a similar trend to that of the previously published studies. Cement treatment is effective at a low dosage, while the improvement due to GP treatment is gradual until an optimum point and scales exponentially with higher dosages.

This study also assessed the effect of using a combination of cement and GP as co-additives on UCS for cohesionless sandy soils. The 8% GP-2% cement-treated specimen demonstrated a mechanical behavior similar to that of the 4% cement-treated specimen. This highlights the synergy between GP and OPC towards improving the soil strength. This synergy effect can be attributed to the availability of sufficient moisture to form a geopolymer network and carry out pozzolanic reactions of the cement during the curing period. Another advantage of this synergistic effect is to reduce the carbon footprint of the transportation projects as it decreases the dosage of OPC required to improve the soil characteristics.

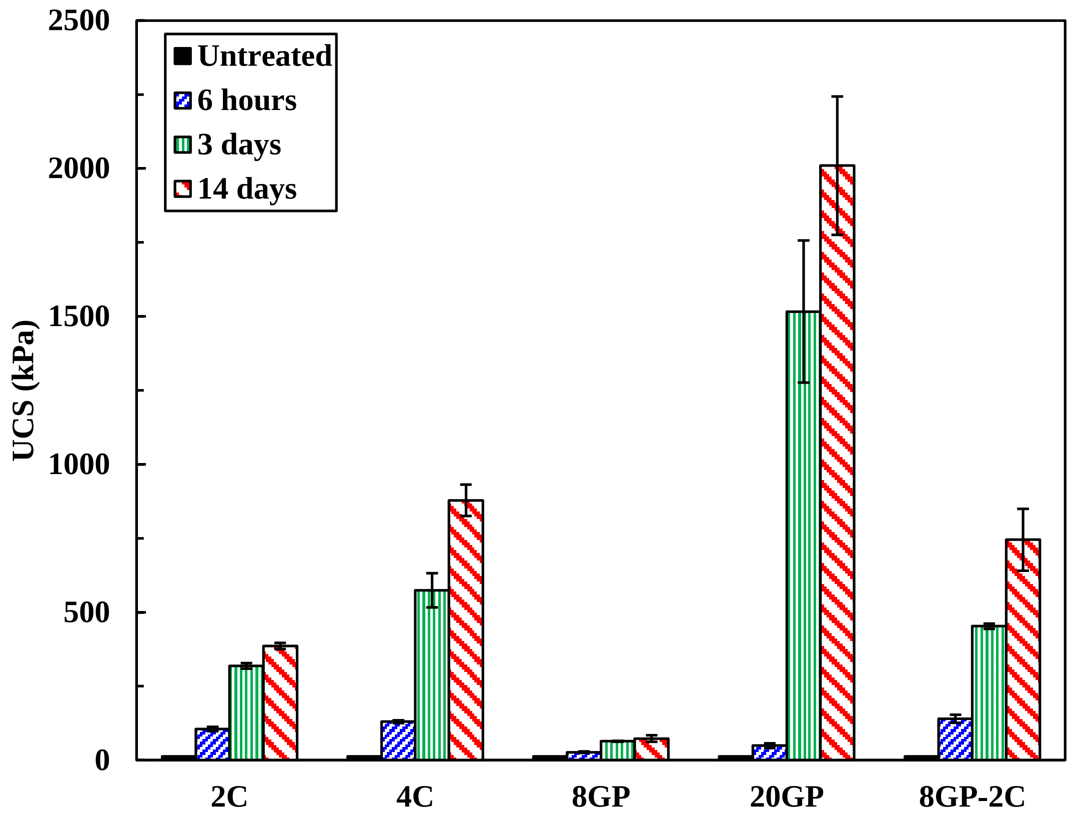


Figure 16. Summary of UCS tests for different stabilized silty sand mixes cured for different periods.

5.3. Repeated load triaxial tests (RLTT)

The RLTT was conducted on cemented-treated, GP-treated, GP-cement-treated soil specimens. The RLTT could not be conducted on the untreated soil and 8% GP soil cured for 6 hours as they failed during tests. RLTT was performed at two cement dosages (2% and 4%), two GP dosages (8% and 20%), and 8% GP-2% cement dosage with three different curing periods of 0 (6 hours), 3, and 14 days. Figure 17 shows the resilient modulus values of each test.

The resilient moduli of soil specimens treated with cement, GP, or GP-cement mixture increased with an increase in curing periods. After 6 hours of curing, resilient moduli of cement-treated soil specimens were observed to be higher than that of GP-treated soil specimens. It can be attributed to a rapid pozzolanic reaction of cement. Also, this is consistent with the UCS results. Similar to UCS results, the resilient moduli of 8% GP-2% cement mixture specimens are higher than 20%

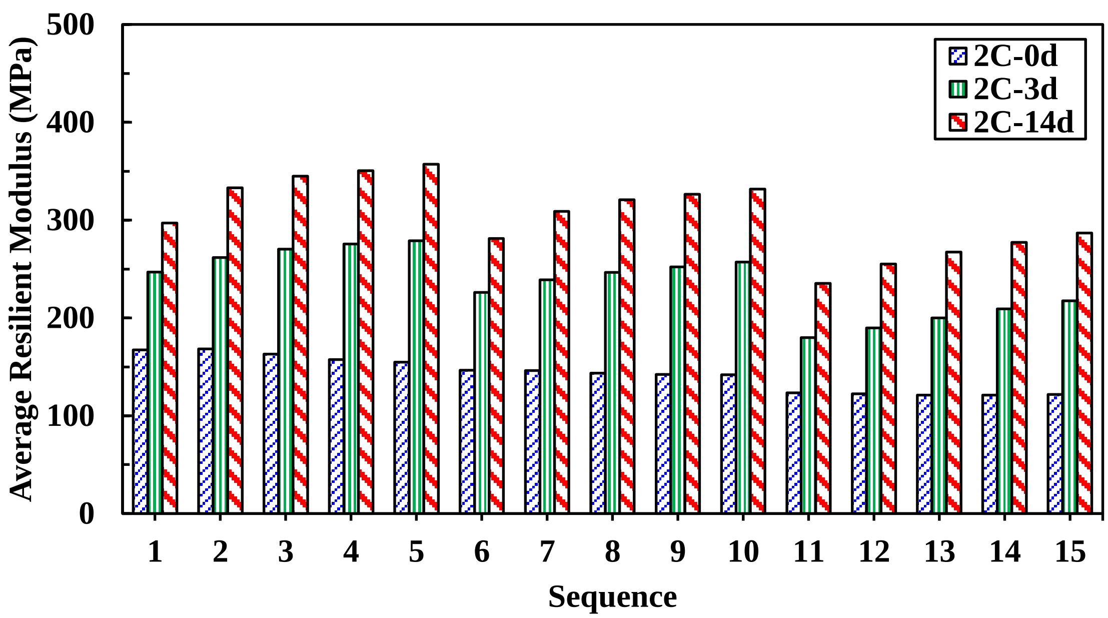
GP soil specimen. However, the resilient moduli of GP-cement mixture specimens were much lower than 4% cement-treated specimens.

After 3 days of curing, the resilient moduli of 20% GP-treated soil specimens were observed to be higher than cement-treated soil specimens. A similar trend was also observed in the UCS test results. Based on these results, it can be inferred that the curing period required to complete the geopolymerization in GP-treated soil specimens is not very long (e.g., approximately within 3 days).

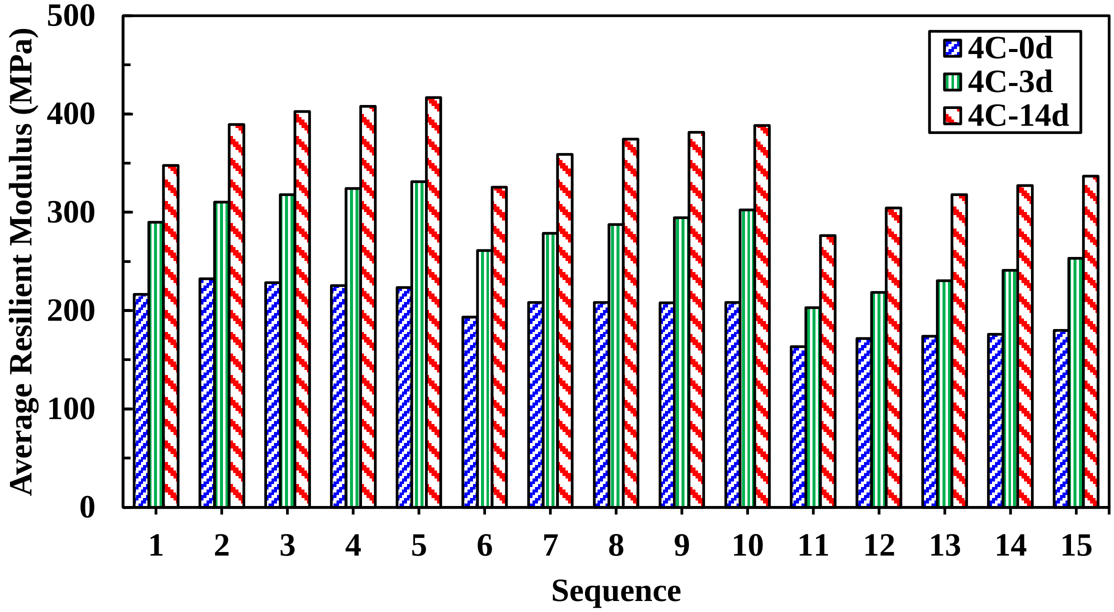
The resilient moduli of cement-treated soil specimens that were cured for 14 days are higher than those that were cured for 3 days. This can be explained by the formation of cementitious materials due to long-term pozzolanic reactions in the cement-treated soil specimens. The cementitious binder hardens the mix and contributes towards improving the engineering performance of the cement-treated soil specimens.

Unlike cement-treated soil specimens, the improvement in modulus of GP-treated specimens strongly depends on the geopolymer dosage for the geopolymerization. Especially, the resilient moduli of 20% GP-treated soil specimens cured for 14 days are quite similar to that of the specimens cured for 3 days. Therefore, it can be inferred that the geopolymerization lacked moisture after a curing period of 3 days.

8% GP-treated soil specimens could not be tested due to insufficient strength; however, adding cement has provided strength to conduct the resilient modulus test after 6 hours of curing period. Although 8% GP-2% cement treatment did not show as much increase in modulus increase as the UCS values, it supported the case for using reduced cement content.

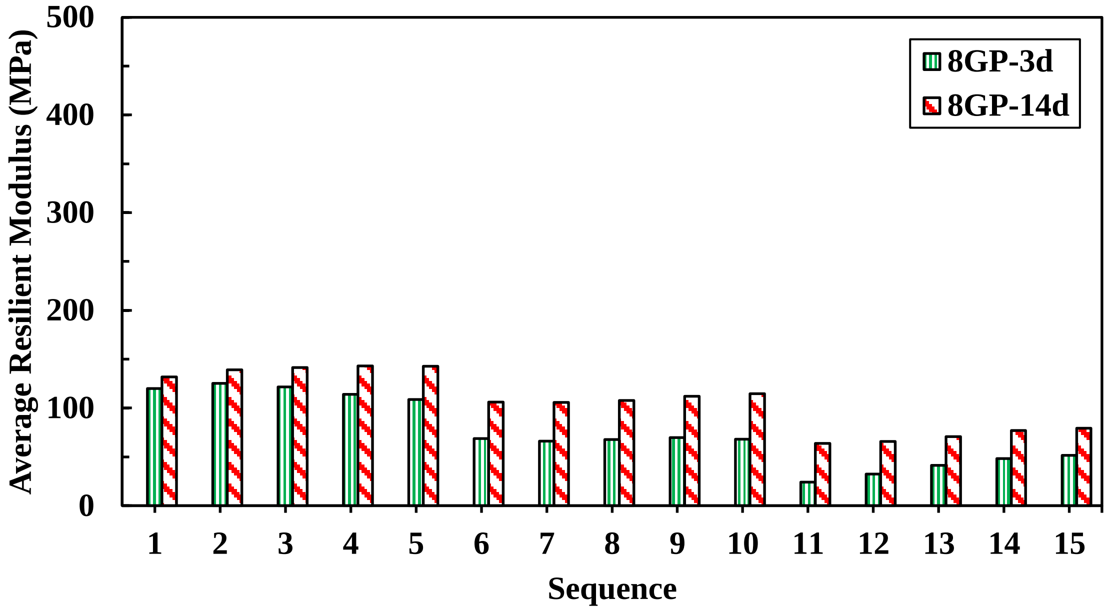


(a)



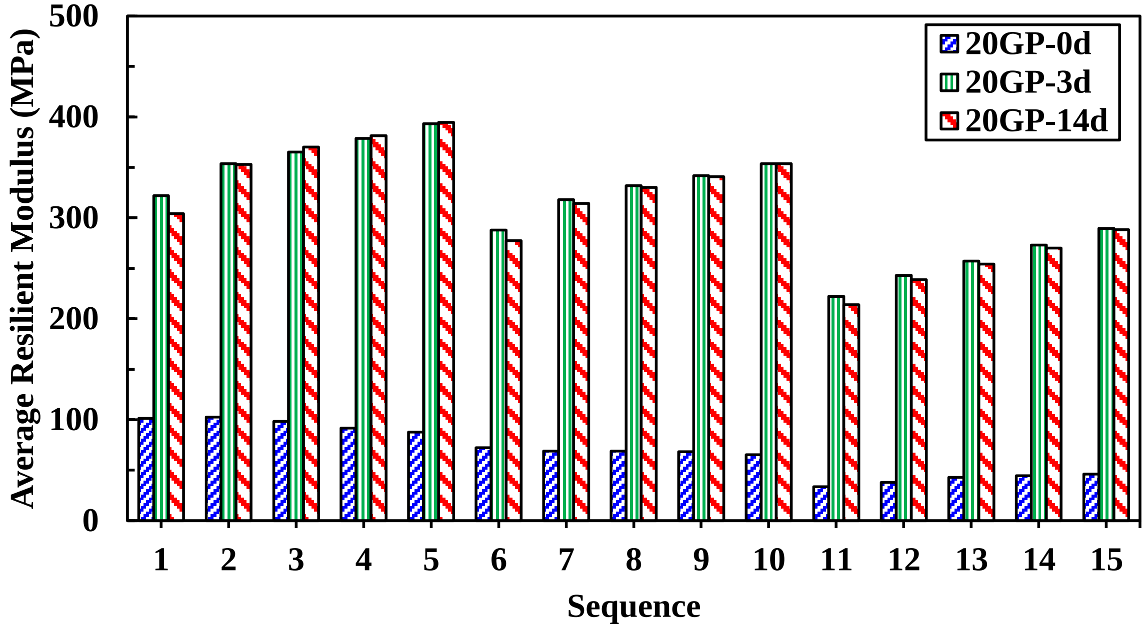
Average Resilient Modulus (MPa)
4C-0d
4C-3d
4C-14d
0
100
200
300
400
500
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Sequence

(b)



Average Resilient Modulus (MPa)
8GP-3d
8GP-14d
0
100
200
300
400
500
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Sequence

(c)



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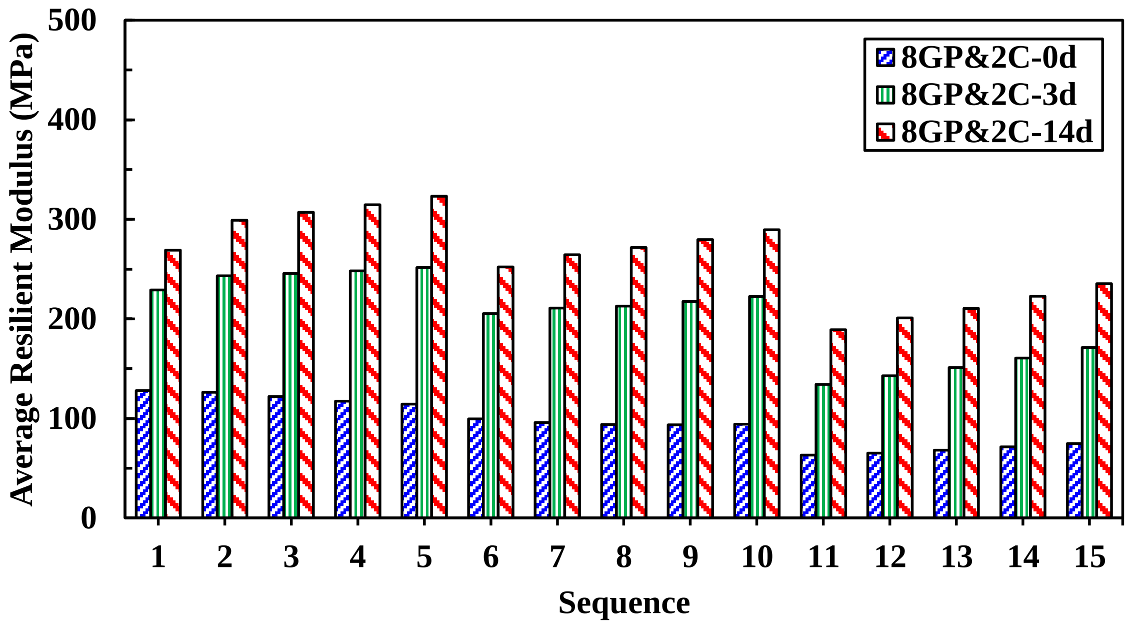


(e)

Figure 17. Resilient modulus (M_R) values of treated soil specimens: (a) 2% cement, (b) 4% cement, (c) 8% GP, (d) 20% GP, and (e) 8% GP-2% cement.

5.4. pH Test

The soil pH values were measured for treated soil specimens with different dosages after three curing periods 0 (6 hours), 3, and 14 days and summarized in Table 8. The pH value of untreated sandy soil was measured to be 7.28. The pH values of soils treated with GP or cement or GP-cement combination range between 12 and 13.

The pH values slightly increased from 6 hours to 3 days curing and decreased slightly at the end of the 14-day curing period for all treated cases except for 8% GP-2% cement-treated specimens. Besides, the pH values of the GP-treated soils are observed to be slightly higher than the cement-treated soils. The pH values of soils treated with GP and cement are observed to be higher than 12 after a curing period of 14 days. This confirms the presence of strong alkaline conditions that are conducive towards pozzolanic reactions and hydroxyl-promoted dissolution in cement- and geopolymer-treated soils, respectively.

Table 8. pH test summary.

Soil Specimen Group	6 hours	3 days	14 days
Untreated Soil	7.28	-	-
2C	12.23 ± 0.04	12.37 ± 0.02	12.15 ± 0.06
4C	12.26 ± 0.01	12.31 ± 0.03	12.28 ± 0.04
8GP	12.57 ± 0.03	12.61 ± 0.04	12.49 ± 0.03
20GP	12.90 ± 0.03	12.92 ± 0.02	12.85 ± 0.01
8GP-2C	12.58 ± 0.06	12.56 ± 0.06	12.56 ± 0.09

5.5. Durability Tests

Durability test results for 4% cement-treated, 20% GP-treated, and 8% GP-2% cement-treated specimens cured for 3 and 14 days are presented in
Table 9. Treated specimens with lower dosages of cement and GP and a short curing period of 6 hours were not performed as they did not have sufficient dosages and time for chemical reactions.

The UCS values obtained after 24 hours of capillary soaking of 4% cement-treated soil specimens cured for 3 and 14 days were smaller than that of cement-treated soil specimens without capillary soaking. This is because the strength retention values are lower than 100%, which means that the soaked UCS values are less than the unsoaked UCS values. Moreover, this can also be attributed to the carbonation process during cement treatment. Carbonation occurs due to the chemical reaction between carbon dioxide in air and calcium reaction compounds to convert the calcium material into calcium carbonate ($CaCO_3$) *(46)*.

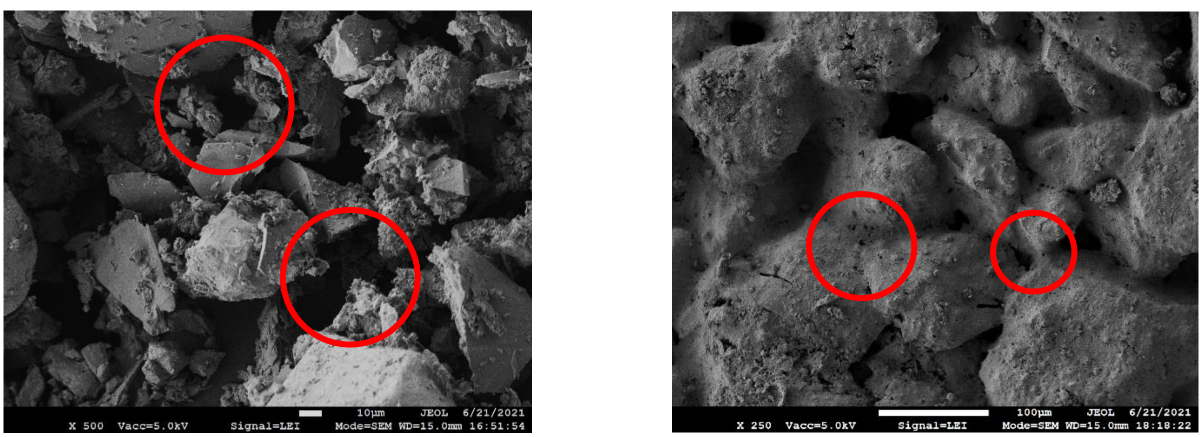
Unlike the cement-treated soil specimens, the UCS values of 20% GP-treated, 8% GP-2% cement-treated soil specimens cured for 3 and 14 days decreased after 24 hours of capillary soaking. This capillary soaking could be attributed to the acceleration of geopolymerization, with the addition of moisture, in the GP-treated soil specimen. As the geopolymerization is required to supply moisture, adding excess water to the initial water content could accelerate the rate of geopolymerization, resulting in the formation of more GP gels in the GP-treated soil specimen.

Table 9. Strength retention values of 4% cement-treated, 20% GP-treated, and 8% GP-2% cement-treated specimens cured with three different curing periods.

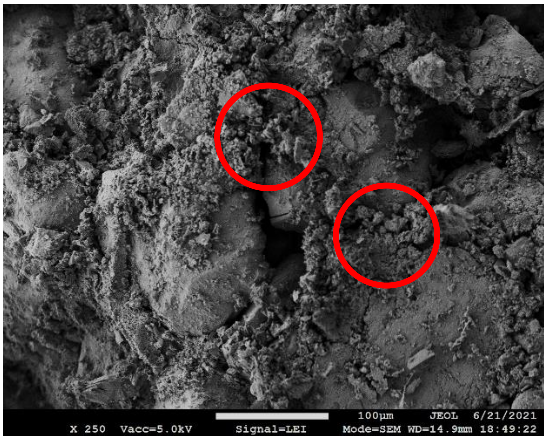
Soil specimen group	Curing period (days)	Unsoaked UCS (kPa) (1)	Soaked UCS (kPa) (2)	Strength retention = (2)/(1) (%)
4C	3	574.5 ± 70.9	550.5 ± 46.2	95.8
4C	14	878.4 ± 64.9	680.5 ± 109.0	77.5
20GP	3	1516.3 ± 294.2	1813.9 ± 403.5	119.6
20GP	14	2009.5 ± 286.8	2146.3 ± 531.7	106.8
8GP-2C	3	452.8 ± 10.8	529.3 ± 37.9	116.9
8GP-2C	14	745.1 ± 128.2	818.5 ± 51.8	109.9

5.6. SEM-EDS

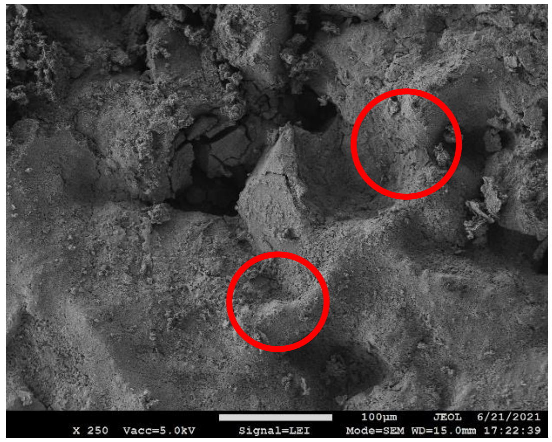
The effectiveness of a stabilizer can be understood by evaluating the bonding created between the particles. With SEM, the micro-morphologies of each sample can be observed, as shown in Figure 18. To our expectation, the untreated SM has little to no cohesion between the particles as it is mostly made up of sand (SiO_2) and not pozzolanic compounds. SEM studies were conducted on SM stabilized with 4% C to establish a benchmark as per the current stabilization techniques. The SEM micrograph showed a thin layer of coating covering almost all the particles and providing cohesion between the particles. As for GP-stabilized soil specimens, both UCS and RLTT results have shown the ineffectiveness of stabilizing with 8% GP. However, 20% GP seems to be an effective dosage with a better performance compared to the 4C treatment. The observations from SEM are consistent with the results from UCS and RLTT. 8% GP does not have a coating like 4% C; instead, 8% GP has its voids and pores filled up by smaller particles. On the other hand, 20% GP with a coating that covers most of the particles has a morphology similar to 4% C.



(a) **(b)**



(c)



(d)

Figure 18. SEM micrographs of (a) untreated, (b) 4C, (c) 8GP, and (d) 20GP.

Table 10 shows the results of the average atomic % detected for different elements through EDS. These values were obtained by taking the average of three distinctive area scans within the SEM micrograph. As expected, the untreated SM is mostly composed of Si. When OPC is added, a large amount of carbon was observed, and the amount of Si decreased significantly. On the other hand, 20% GP has a very similar chemistry to untreated SM, and the only major difference is that 20% GP has a significant increase in potassium (K).

Table 10. Average atomic % of untreated, 4C, and 20GP from EDS.

Element	Untreated	4C	20GP
C	0	23.6	5.8
O	70.3	58.1	69.0
Na	1.0	0	0
Mg	1.5	0.3	0.3
Al	4.8	1.0	4.3
Si	18.8	9.5	17.1
K	1.2	0.2	2.6
Ca	1.0	1.3	0.5
Ti	0.1	5.7	0.1
Fe	1.3	0.3	0.3

6. CONCLUSIONS

This research study was aimed to evaluate the feasibility of using metakaolin-based geopolymer to treat coastal sandy soils. Extensive characterization and engineering tests were performed to evaluate the behavior of sandy soils treated with different combinations of Portland cement and geopolymer. The following conclusions can be drawn based on the findings of this research study:

1) Metakaolin-based geopolymer treatment was effective in stabilizing cohesionless soil. However, it requires high dosages for the treatment to be effective (~20%), unlike OPC which can perform adequately at low dosages between 2-4%. However, it is important to note that the durability and environmental benefits of geopolymer-treated soils could outweigh the fact that it needs a higher dosage to be effective.
2) The linear shrinkage bar test results showed that all treatments except for 20% GP do not induce any shrinkage behavior in the GP treated sandy soil. Besides, 20% GP induced only around 2% shrinkage after 14 days.
3) The UCS results showed that the 20% GP has about double the strength of 4% OPC stabilized soil after 14-days of curing. Further studies are recommended to find lower dosages of GP that are equivalent to 4% OPC. This would then provide a better comparison for life cycle analysis.
4) The resilient modulus values indicated that the 20% GP treatment yielded resilient modulus values similar to that of 4% OPC treatment. After a curing period of 3 days, the stiffness of soil treated with GP was better than soil treated with OPC. In summary, GP treatment can be effective when quick stabilization practices are needed to restore the connectivity of pavement networks constructed over sandy soils located in coastal areas.
5) GP- and cement-based treatments were observed to transform the pH of soil from neutral to alkaline. Moreover, the pH values of the GP- and cement-treated soils cured for 14 days were measured to be higher than 12, indicating the presence of strong alkaline environments. These environments are conducive towards the geopolymerization process in GP-treated soils and pozzolanic reactions in cement-treated soils.
6) Durability results showed that the strength of GP-treated specimens increased after soaking unlike OPC-treated specimens. This indicates the suitability of GP to stabilize coastal soils, which often experience extreme weather events. It is also important to note that further studies are recommended to understand the influence of the number of durability cycles (wet/dry) on the mechanical behavior of GP-treated specimens.
7) The SEM-EDS results agree well with the findings from other tests. The 4% OPC and 20% GP performed well since the treatments formed a coating over the soil particles. On the other hand, 8% GP showed minimal improvement in its engineering properties due to the absence of a proper coating on the particles. These findings indicate that SEM could be used as a quick method to find the minimum dosage needed to stabilize coastal soils without the need for making multiple samples and laborious testing.

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