Unconfined Compressive Strength of Weakly Cemented Compacted Sand under Different Loads

Messaouda Redjem[1]*, Mustapha Hidjeb[1], Ihcene Lamri[1], and Khaled Boudjellal[1]
[1]*University 20 Aout 1955, Skikda, Faculty of Technology, Department of Civil Engineering, LMGHU Laboratory, Algeria*
**E-mail: redjemsaida22@gmail.com*

ABSTRACT: The exploitation of dune sand for public works, notably in Skikda's northeastern region in Algeria, is a topic of significant interest, given the region's rich sand resources, with the aim of optimizing its effective utilization. This context led to an experimental study focusing on the behavior of cement-stabilized dune sand under static and cyclic loads. The study included various tests: Compaction, California Bearing Ratio (CBR), and Unconfined Compression Strength (UCS). The normal Proctor compaction and CBR tests were carried out on specimens of sand with cement contents of 0, 2, 4, and 6%. The unconfined compression tests were carried out at rates of loading 0.05 mm/min and 0.1 mm/min. Cyclic displacement-controlled unconfined compression tests were performed at a frequency of 0.002 Hz. This tests were conducted on samples cured for 7 and 28 days with a cement content of 0, 2, and 4 %. The research aimed to understand how cement content, loading rate, curing time, frequency, and the number of cycles affect the mechanical properties of the soil. Results under static loading revealed that the low rate of loading, the increase in curing period, and the increase in cement content increased the UCS. This increase was notably evident in a sample with 4% cement content, aged 28 days, and loaded at 0.05 mm/min, showing a UCS approximately 29% higher than a similar sample tested at 0.1 mm/min. It has also been observed that at low loading rate, a denser soil-cement composite is obtained, leading to a more dilatant behavior, resulting in an increase in the modulus of elasticity. Under cyclic loading have shown that with a low frequency and increased cement content, along with an increase in the number of cycles and curing time, both the strength and elastic modulus increase. Conclusively, the results suggest that stabilizing dune sand with cement, considering factors such as low loading rates, curing time, low frequency, and increased cycles, significantly enhances the material's resistance under various loading conditions.

KEYWORDS: Sand, Cement, UCS, Modulus of elasticity, and Different loads.

1. INTRODUCTION

In order to optimize the use of the abundant dune sand deposits, located northeast of Skikda (Algeria), in road construction and soil foundations, compaction, CBR, and UCS tests were performed. These tests are vital for ensuring the stability of roads and railways against various external forces, including traffic and seismic activities. The field of soil mechanics and stabilization has seen significant advancements through recent studies. For instance, Azaiez and Bouassida (2022) introduced a cylindrical penetrometer for assessing the undrained shear resistance of soft soils. Chaiyaput and Ayawanna (2021) explored the effects of furnace slag on lateritic soil, contributing valuable insights into innovative soil stabilization methods. Chompoorat *et al.* (2021) demonstrated that an optimized mix of sediments, cement, and fly ash, stabilized with ordinary Portland cement, can achieve mechanical properties suitable for road construction. They emphasized the importance of curing periods in strength development, shedding light on sustainable methods for road construction using dredged sediments. Earlier, Chompoorat *et al.* (2019) found that adding cement to the sedimentary soils of Lake Phayao significantly enhances compressive strength and durability, offering a feasible solution for road construction

It has been demonstrated that Soil stabilization using different hydraulic binders such as cement and lime, and Soil stabilization reinforced by fiber, has a positive effect on improving soil properties (Al-Zoubi, 2008; Miura, 2008; Ochepo, 2014; Khan *et al.,* 2018 Chompoorat *et al.,* 2023). Sabbaqzade *et al.* (2021) conducted a number of unconfined compression tests (UCS) on the sand with 0%, 4%, 8%, and 12% cement contents at 0, 7, and 28 days of curing. They concluded that the unconfined compression strength increases with the increasing rate of cement content, which agrees with the findings of (Bazazorde, 2018). It has also been shown, by Janalizadeh *et al.* (2017) and Haeri *et al.* (2006), that the elastic modulus and stiffness of sand increase with increasing cement content. The latter also concluded that the cement strengthens the soil and makes it more rigid and brittle. Forcelini *et al.* (2016) found that increasing the cement content increases Young's modulus and decreases the void ratio. Moreover, Vranna *et al.* (2020) concluded that the increase in curing time induces an increase in UCS of cemented sand. For a curing time of 30 days, UCS were 20 % and 60 % higher than those obtained after 7 days, for cement content (C) of 3% and 5% respectively, while for a curing time of 365 days and C = 3%, UCS is 6 fold greater than the UCS obtained after 7 days of cure. Chompoorat *et al.* (2021) noted that the UCS of cement-stabilized sedimentary soils gradually increases with curing time, with a significant increase observable after approximately 28 days. This highlights the importance of this time frame in the development of material strength. The improvement in ground resistance when treated with cement is attributed to a combination of factors including the soil's initial strength without cement, enhancement of basic soil properties due to moisture reduction, cement hydration, and pozzolanic reactions, as suggested by Kitazume and Terashi (2013) and Nakarai *et al.* (2015).

Various factors, such as particle size and shape, porosity, temperature, and cement content, influence the behavior of cemented sands (Consoli *et al.,* 2018b; Biswal *et al.,* 2020; Jiang *et al.,* 2020; Festugato *et al.,* 2020). Sowers *et al.* (1979) found that the microstructure strength of cemented sand with a high void ratio and low density is less stable than sand with a low void ratio and high density.

Lo *et al.* (2003) examined the impact of cement addition on the unconfined compression behavior of quartz sand, focusing on the role of inter-grain bonds in the material's strength and stiffness. They discovered that the progressive failure of these cementing bonds, occurring before overall failure, indicates that the dilatancy of cemented soil close to failure occurs at higher shear levels. This results in more pronounced dilatancy, contributing to the increased shear strength of cemented soil compared to its uncemented counterpart, as also noted by VU Quoc (2008).

Sun *et al.* (2020) explored different ways of understanding the monotonic and cyclic behavior of the soil. Through their research, they determined that the drained and untrained behavior of fine Karlsruhe sand under monotonic and cyclic loadings shifts from contracting behavior when unloading to dilating behavior when reloading, which is consistent with the findings of Philippon *et al.* (2002); Vranna *et al.* (2020) undertook unconfined compressive strength tests, and undrained monotonic and cyclic tests, on clean Sand quartz samples, with Cement content ranging from 1-8%. They found that for samples subjected to monotonic shear with the same density and confining stress, the increase in cement content led to a decrease in sand contractiveness. This shows that as the shear increases, the compacted soil expands, while the loose soil contracts. They also observed that even low cement content (C%=1), improved the behavior of cemented sand over uncemented samples and that samples with low cement content can withstand a significantly higher number of loading cycles compared to the uncemented ones.

These insights build upon previous studies investigating the monotonic and cyclic behavior of sands. For instance, Thay *et al.* (2013) examined Chiang Mai sand in Thailand through monotonic and cyclic direct simple shear tests. Mase *et al.* (2019) conducted cyclic triaxial tests to delve into sand liquefaction resistance behavior. Further, Sukkarak *et al.* (2021) carried out a series of undrained monotonic and cyclic triaxial tests on sand samples from Mae Lao in northern Thailand. Their work highlighted the impact of initial void ratios and confining pressures on the soil's liquefaction potential. The culmination of these studies provides a holistic understanding of the dynamic behavior of various sands under differing loading conditions.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this work are dune sand coming from a deposit located 17 km northeast of Skikda (Algeria), and Portland cement (CPJ CEMII/A 42.5) manufactured in Haddjar Essoud – Algeria. The physical characteristics of these materials are provided in Table 1 and the grain size distribution curve is displayed in figure 1. The mineralogical composition of the sand, as determined by X-ray diffraction (XRD), is presented in Figure 2.

Table 1 Characteristics of the materials used in the study

Materials Properties	Values	
	Soil	Cement
GTR Classification guide	SM	-
D_{10}	0.20	-
D_{30}	0.31	-
D_{60}	0.45	-
Cu	2.25	-
C_C	1.10	-
Maximum Dry Density $\rho_{d\ max}$ (g/cm^3)	1.76	-
Optimum Moisture Content O.M.C.%	11.88	-
Clinker (%)	/	≥74
Gypsum (%)	/	4-6
Limestone (%)	/	0
Fly ash (%)	/	≤20
C3S (%) tricalcium silicate	/	56.60
C2S (%) dicalcium silicate	/	22.98
C3A (%) tricalcium aluminate	/	9.87
C4AF (%)Tetracalcium aluminate ferrite	/	8.25

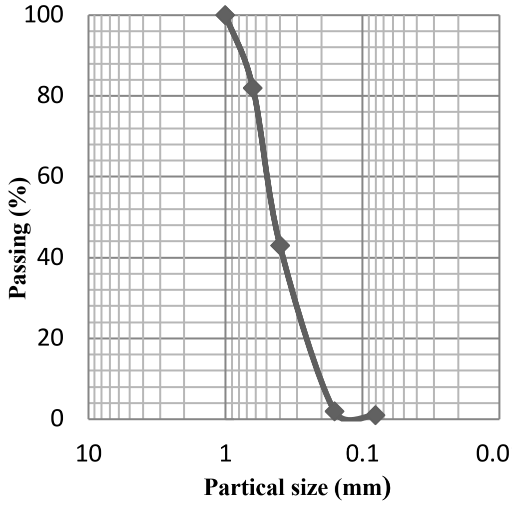


Figure 1 Soil Practical size distribution curve

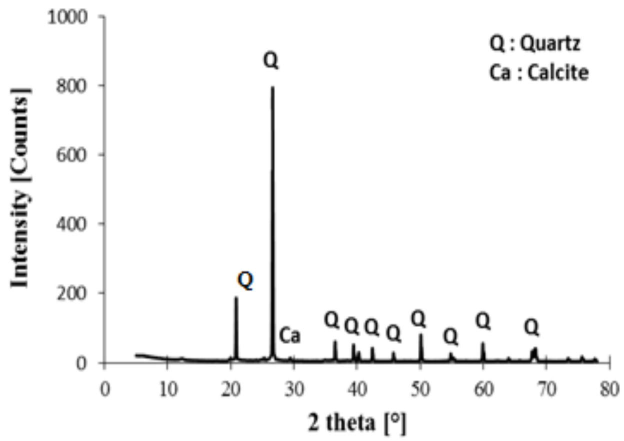


Figure 2 XRD patterns of dune sand

2.2 Methods

Several series were carried out in accordance with French standards (AFNOR). The soil samples were completely dried in a oven at 105 ± 2 °C for 24 h.

The compaction tests, adhering to NF P 94-093 standards, involved compacting the samples in molds measuring 105 mm in diameter and 116 mm in height. For the California Bearing Ratio (CBR) tests, based on NF P 94-077 standards, the samples were compacted in molds with dimensions of 153 mm in both diameter and height. Both normal Proctor compaction tests and CBR tests were performed on sand specimens with varying cement contents of 0%, 2%, 4%, and 6%.

Unconfined compression tests (UCS) and cyclic tests, also following NF P 94-077 guidelines, were conducted on compacted sand specimens prepared in molds of 105 mm diameter and 116 mm height. These specimens were subjected to curing periods of 7 and 28 days, with cement content variations of 0%, 2%, and 4%.

The unconfined compression tests were executed at loading rates of 0.05 mm/min and 0.1 mm/min. Moreover, cyclic displacement-controlled unconfined compression tests were conducted at a frequency of 0.002 Hz. This tests were performed using a Digital Tritest press from ELE International-England, which has a capacity of 50 kN.

Table 2 Summary of tests

Compaction			
Tests	**Mass of the Specimen**	**Cement C (%)**	**Specimen diameter (d) height (h) (mm)**
1	2500	0	d = 105 ; h = 116
2	2500	2	
3	2500	4	
4	2500	6	

CBR			
Tests number	**Mass of the Specimen**	**Cement C (%)**	**Specimen diameter (d) height (h) (mm)**
1	5500	0	d = 153 ; h = 153
2	5500	2	
3	5500	4	
4	5500	6	

Unconfined compression tests

Tests	Cement C (%)	Age (Days)	Rate of loading (mm/min)
1	0	7	0.05
2	2	7	0.05
3	4	7	0.05
4	0	28	0.05
5	2	28	0.05
6	4	28	0.05
7	0	7	0.1
8	2	7	0.1
9	4	7	0.1
10	0	28	0.1
11	2	28	0.1
12	4	28	0.1

Unconfined compression cyclic tests

Test	Cement C(%)	Age (Days)	Displacement (mm)	Frequency (Hz)
1	0	7	0.6	0.002
2	2	7	0.6	0.002
3	4	7	0.6	0.002
4	0	28	0.6	0.002
5	2	28	0.6	0.002
6	4	28	0.6	0.002
7	0	7	1.16	0.002
8	2	7	1.16	0.002
9	4	7	1.16	0.002
10	0	28	1.16	0.002
11	2	28	1.16	0.002
12	4	28	1.16	0.002

3. RESULTS AND DISCUSSIONS

3.1 Normal Proctor Test

Figure 3 shows that an increase in cement content from 0 to 2 to 4 then 6 % leads to an increase in maximum dry density ($\rho_{d\ max}$) from 1.76 g/cm^3 to 1.85 g/cm^3 as well as a decrease in optimum moisture content (O.M.C%) from 11.8 % to 10.33 %.

This trend is further supported by the relative positioning of the compaction curves for the cement-treated samples compared to the Proctor curve of the untreated soil. Notably, the compaction curves for the cement-treated specimens are observed to be positioned above and to the right of the Proctor curve of the untreated soil.

This shift implies that the addition of cement to sandy soil reduces the water requirement to achieve maximum dry density. The likely causes for this behavior include:

Water-induced soil viscosity: This factor contributes to the tightening of soil particles, thereby enhancing compactness and density. Such an effect aligns with findings reported by Nwaiwu *et al.* (2022). Changes in particle size due to the chemical interaction between soil, cement, and water: This reaction facilitates the densification process, further contributing to the observed increase in soil compactness.

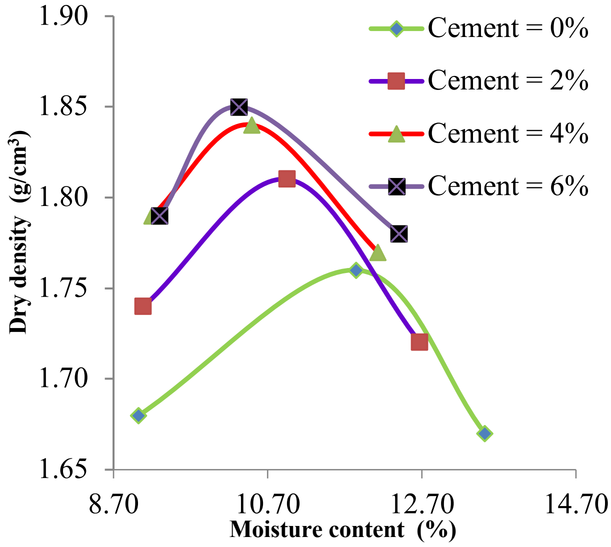


Figure 3 Compaction test curves for different cement contents

3.2 California Bearing Ratio (CBR) Test

To assess the bearing capacity of the soil, for use in the construction of earthworks or pavement foundations, CBR tests were carried out to determine the immediate CBR index.

The CBR tests were carried out on sand samples with 0, 2, 4, and 6 % cement content.

It can be seen in Figure 4 that increasing the cement content from 0, 2, 4, and 6 % induced a significant increase in the immediate CBR indexes (at 2.5 mm penetration) of 3.6, 6.7, 12.5, and 16.9 % While, the increase in the cement content from 0, 2, 4, and 6 % induced an increase in the immediate CBR indexes (at 5 mm penetration) of 7.4, 13.2, 18.5, and 19.9 %. These results indicate that increasing the cement rate improves soil performance.These results are consistent with those obtained in previous works (Okonkwo, 2009; Bello, 2011; Mujedu *et al.,* 2016).

The improvement in soil bearing capacity is primarily attributed to immediate chemical reactions, particularly the hydration of cement. This process leads to a reorganization and improved distribution of the soil particles, contributing to the enhanced bearing capacity of the soil.

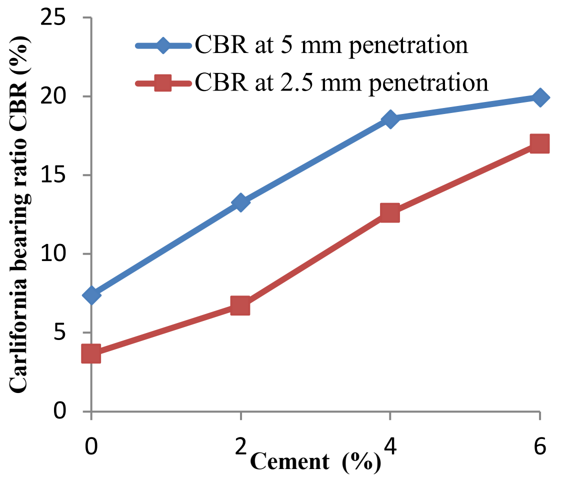


Figure 4 CBR index versus of cement content

3.3 Unconfined Compression Test (UCS)

3.3.1 Effect of Cement on UCS

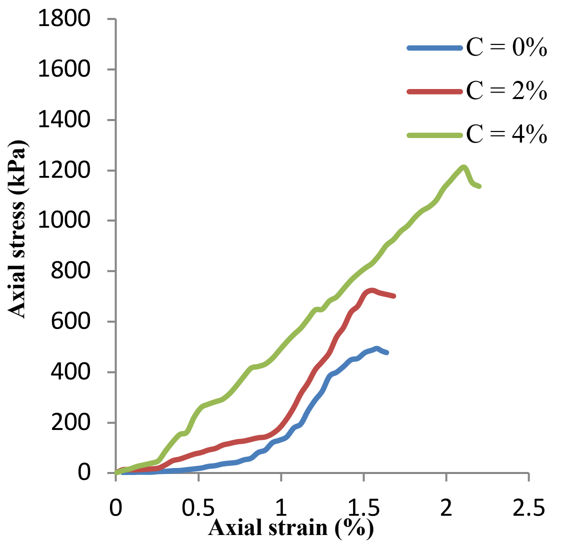
The optimum rate of cement of 4%, obtained by compaction, corresponds to an optimum moisture content of 10.5% and a maximum density of 1.84 g/cm^3. For economic reasons and a better understanding of the pozzolanic reaction on the strength of the composite, the author carried out a comparative study of loading tests on samples with cement contents of 0, 2, and 4%.

For specimens of 7 days of cure, loaded at a rate of 0.05 mm/min Figure 5(a), an increase in cement content from 0 to 2 % and 0 to 4% induced a rise in UCS from 46.7% to 145.4%.

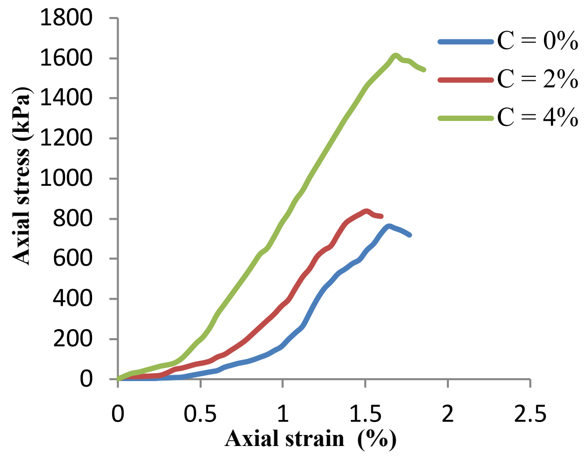
Additionally, 28 day - old specimens, loaded at a rate of 0.05 mm/min Figure 5(b), increasing cement content by 0 - 2% and 0 - 4%, UCS increased by 9.97% and 111.8%.

For Specimens of 7 days of cure, loaded at a rate of 0.1mm/min Figure 6(a), an increase in cement content from 0 to 2% and 0 to 4% induced a rise in UCS of 46.4% and 153.6%. Moreover, for specimens of 28 days of age, loaded at a rate of 0.1 mm/min Figure 6(b) .The increase in cement content from 0 to 2% and 0 to 4%, the UCS increased from 48.10% to 143.5%.

Lo *et al.* (2003) and Festugato *et al.* (2020) suggested that due to cementation the increase in soil strength may be due to the dilatancy of the sand.

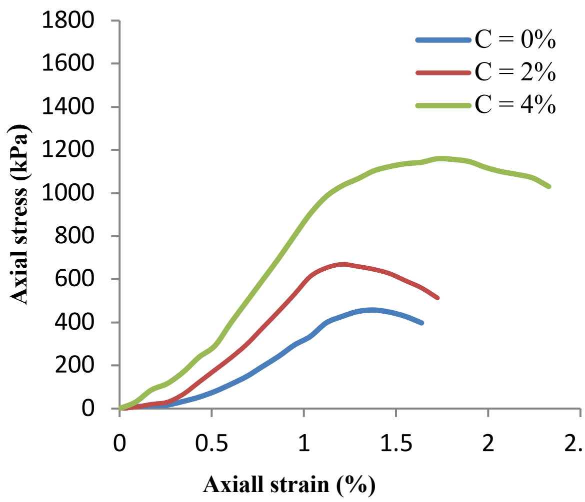


(a)

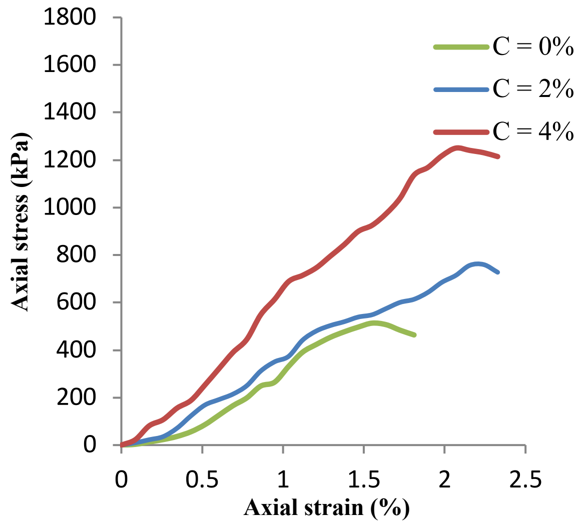


(b)

Figure 5 Unconfined compressive strength versus axial strain for different cement content values (C%) : (a) rate of loading = 0.05 mm/min 7 days; (b) rate of loading = 0.05 mm/min 28 days



(a)



(b)

Figure 6 Unconfined compressive strength versus axial strain for different cement content values (C%) : (a) rate of loading = 0. 1 mm/min 7 days; (b) rate of loading = 0.1mm/min 28 days

3.3.2 Effect of Cement Content on the Modulus of Elasticity (E)

It can be seen in Figure 7 that specimens of 7 days of cure loaded at a rate of 0.05 mm/min and increases in cement content from 0 to 2% and 0 to 4%, induced increases in E of 43.2% and 77.4% respectively whereas, for specimens of 28 days of age, the increases in cement content from 0 to 2% and 0 to 4% induced increases in E of 25.1% and 104.6% respectively. For the specimens of 7 days of cure loaded at a rate of 0.1mm/min, the increase in cement content from 0 to 2% and 0 to 4% induced a rise in E of 22.7% and 83.3% respectively.Moreover, for the specimens of 28 days of age, an increase in cement content from 0 to 2% and 0 to 4%, E increased from 21.9% to 103.6 %.

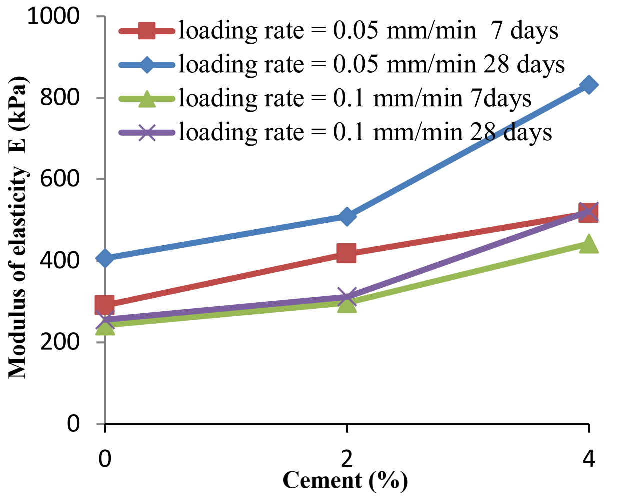


Figure 7 Modulus of elasticity versus cement content

The increase in UCS and the modulus of elasticity induced by the increase in cement content would probably be due to chemical reactions between the cement, water, and soil.

Indeed, the cement-water mixture leads to cement hydration, which forms a porous cement paste with a poorly crystallized gel-like structure around the particles of the soil grains. This phenomenon increases the granular bonds and reduces the porosity.

The main components of this paste are hydrated calcium silicates (C-S-H) and calcium hydroxide (CH). The (C-S-H) make up most of the volume of the hydrated cement paste.

The combined reaction of (C-S-H) and (CH) with water results in a crystallized gel, which would fill the voids and increases the volume of the cement paste. This volume change would induce an increase in the density and the UCS.

Therefore, it can be inferred that the mechanical properties of the sand, such as UCS and Young's modulus, are predominantly influenced by the presence and behavior of C-S-H, as supported by studies from Kitazume and Terashi (2013) and Helson (2017).

3.3.3 Effect of Curing Time on UCS

For the sample aged 28 days with a cement content of 4%, loaded at a rate of 0.05 mm/min, the UCS is about 33% higher than a similar sample tested after 7 days Figure 8(a). For samples prepared under the same conditions as the previous ones but with a rate of loading of 0.1 mm/min, UCS was about 8% higher than a similar sample tested after 7 days Figure 8(b).

Several researchers have posited that the UCS value at 28 days is typically about twice that at 7 days. This estimation is supported by findings from Topolnicki (2004), Ganne *et al.* (2010), and Szymkiewicz (2011). This trend underscores the significant impact of extended curing time on the strength development in cement-treated samples.

The enhancement in Unconfined Compressive Strength (UCS) of the composite material over time is likely attributable to several phenomena, as suggested by the research of Jacobson *et al.* (2003), Nakarai *et al.* (2015), Helson (2017), Nie *et al.* (2017), and Chompoorat *et al.* (2019). These phenomena include:

1. Hydration: This process contributes to the reduction in the volume of pores within the composite material.
2. Filling of Voids: This is a result of pozzolanic reactions which are initiated after a period that can range from a few days to weeks, or even longer.

These mechanisms collectively contribute to the increased strength and density of the composite material as it ages, demonstrating the significant impact of both hydration and pozzolanic reactions on the material's structural properties

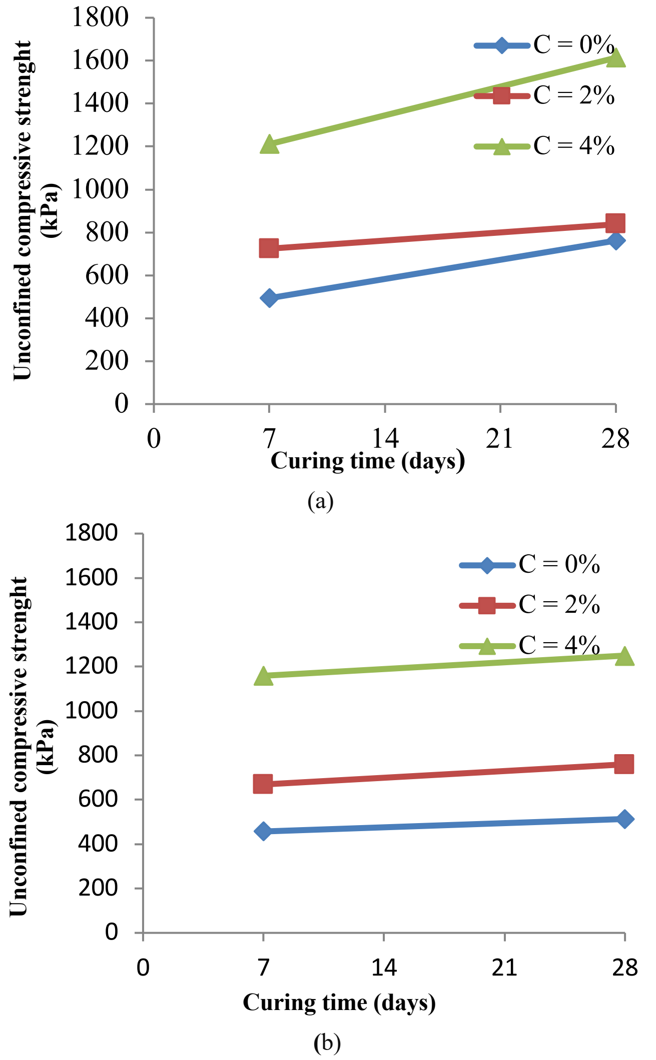


Figure 8 Effect of curing time on UCS : (a) rate of loading = 0. 05 mm/min (b) rate of loading = 0.1mm/min

3.3.4 Effect of Loading Rate on UCS and E

It can be seen in Figure 9 that the UCS at a rate of loading 0.05 mm/min is higher than that obtained at a rate of 0.1 mm/min. This may be due to the slow loading rate inducing an increase in the density of he cement-sand composite and consequently exhibiting a more dilating behavior that tends to increase its volume during shear.

The underlying reason for this phenomenon is closely linked to the microstructure of the sand, particularly its particle size distribution. Sand's microstructure is marked by the absence of an adsorbed water layer, which significantly diminishes the bonding between particles. Therefore, when the sand is subjected to slow loading, the grains have more time to rearrange themselves in a denser configuration.

This rearrangement leads to a reconfiguration of the particle structure, which in turn results in a notable increase in both strength and elasticity modulus, as depicted in Figure 7. In essence, the slower loading speed facilitates a more compact and efficient reorganization of the sand grains, thereby enhancing the mechanical properties of the composite material.

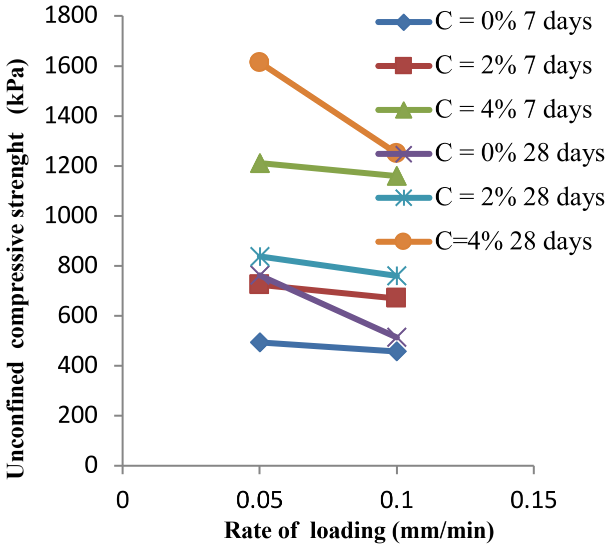


Figure 9 UCS versus rate of loading

4. CYCLIC LOADING TESTS

4.1 Effect of Cement on Unconfined Strength under Cyclic Loading after 7 and 28 Days.

The optimum rate of cement content of 4%, obtained by compaction, corresponds to an OMC = 10.5%. and ρd_{max} = 1.84 g/cm3. To highlight the role of the pozzolanic reaction, the author carried out a series of cyclic loading tests on samples with C% = 0.2.4.

Figure 10 suggests that the increase in cement rate induces no substantial increase in the unconfined peak strength under displacement-controlled = 0.6mm repeated cyclic loading after 28 days compared to after 7 days. Likewise, the latter remark may be made for the tests under displacement-controlled repeated cyclic loading 1.16 mm. For specimens cured for 7 days, with a displacement of 1.16 mm, an increase in cement content from 0% to 2% and from 0% to 4% induced an increase in Unconfined Compressive Strength (UCS) of 75% and 186.5%, respectively. Moreover, for specimens aged 28 days, the increase in cement content from 0% to 2% and from 0% to 4% resulted in a UCS increase of 57.49% and 150%.While specimens cured for 7 days, with a displacement of 0.6 mm, an increase in cement content from 0% to 2% and from 0% to 4% induced an increase in UCS of 267.36% and 438.80%, respectively. Moreover, for specimens aged 28 days, the increase in cement content from 0% to 2% and from 0% to 4% resulted in a UCS increase of 261.54% and 426.94%.

The significant difference in peak unconfined strength under repeated displacement-controlled cyclic loading can be attributed to the progressive failure of the cementitious bonds in the cemented sand. When subjected to cyclic loading, the cemented sand experiences higher shear levels before reaching complete failure compared to non-cemented sand as reported by (Lo *et al.* 2003 ;VU Quoc, 2008). This results in an increased dilatancy of the cemented sand, leading to more than a twofold increase in strength after 28 days, with a displacement of 1.16 mm, than obtained with a similar samples tested at a displacement of 0.6 mm.

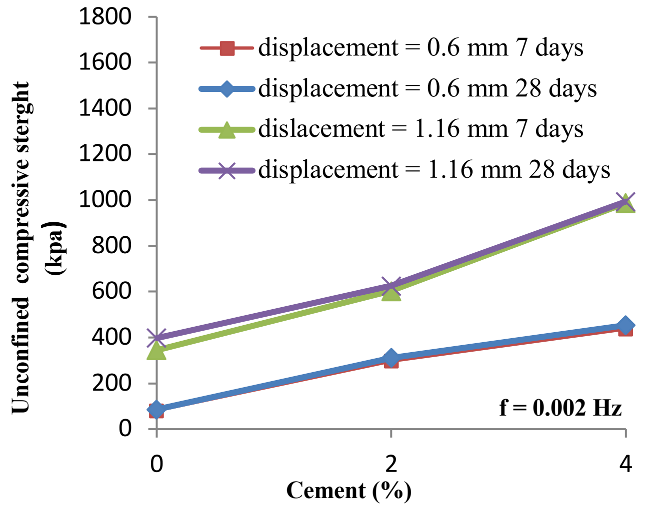


Figure 10 Effect of cement content on unconfined strength under cyclic loading

4.2 Effect of Cement Content on the Number of Cycles to Failure

Figure 11 shows that the number of cycles to failure in the composite material increases with the cement content. This trend is likely a consequence of additional bonds formed between the cement and sand due to pozzolanic reactions. These reactions lead to the creation of calcium silicate hydrate (C-S-H) and portlandite (CH), which contribute to the enhanced durability of the composite. Consequently, this results in an increased number of cycles the material can withstand before failure. Additionally, as noted by Sun *et al.* (2020), loading the sand increases its dilatancy, which further contributes to the material's ability to endure more cycles before failure. This process indicates a relationship between the mechanical loading and the microstructural changes in the sand-cement composite, enhancing its overall resilience and longevity under cyclic loading.

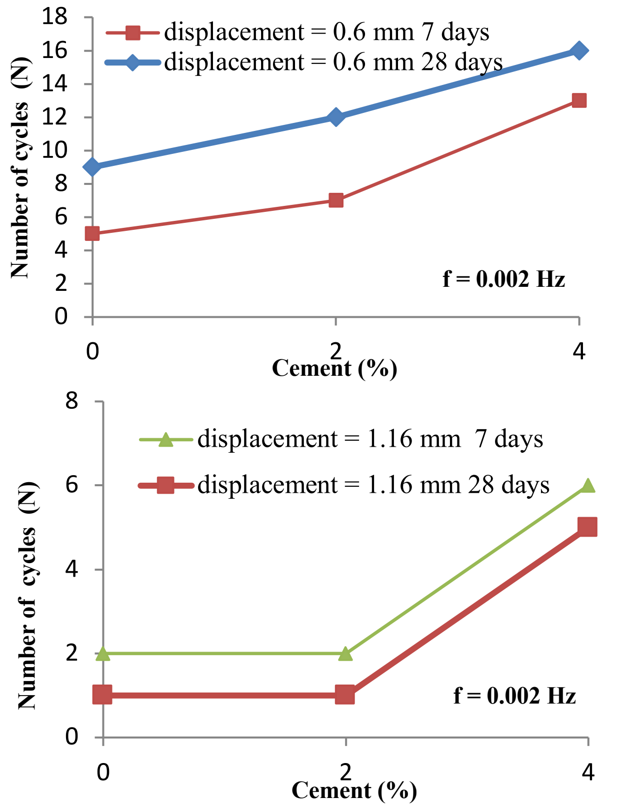


Figure 11 Effect of cement rate on the number of cycles to failure

4.3 Effect of Cement Content on the Modulus of Elasticity

Figure 11 reveals that the modulus of elasticity (E) increases with the cement content in the specimens.

For 7-day-old specimens subjected to a displacement amplitude of 0.6 mm, an increase in cement content from 0% to 2% and from 0% to 4% led to an increase in E of 267.3% and 438.8% respectively. In 28-day-old specimens, an increase in cement content from 0% to 2% and from 0% to 4% resulted in an increase in E of 261.54% and 426.9%, respectively. Furthermore, for 7-day-old specimens with a displacement of 1.16 mm, an increase in cement content from 0% to 2% and from 0% to 4% led to increases in E of 75% and 186.5%, respectively. In 28-day-old specimens, an increase in cement content from 0% to 2% and from 0% to 4% resulted in an increase in Unconfined Compressive Strength (UCS) of 57.4% and 150%, respectively.

These significant increases in the modulus of elasticity are likely due to the non-elastic behavior of the composites under large deformations, which are associated with major changes in the microstructure. The substantial modifications in the microstructure of the composites reflect a plastic behavior that eventually leads to failure. This behavior results in a notable increase in strength before failure, particularly observed in samples with 4% cement content and a displacement of 1.16 mm. This indicates a progressive deterioration of the cementitious bonds before failure, contrasting with the behavior of non-cemented samples, and leads to a to a subsequent increase in elasticity.

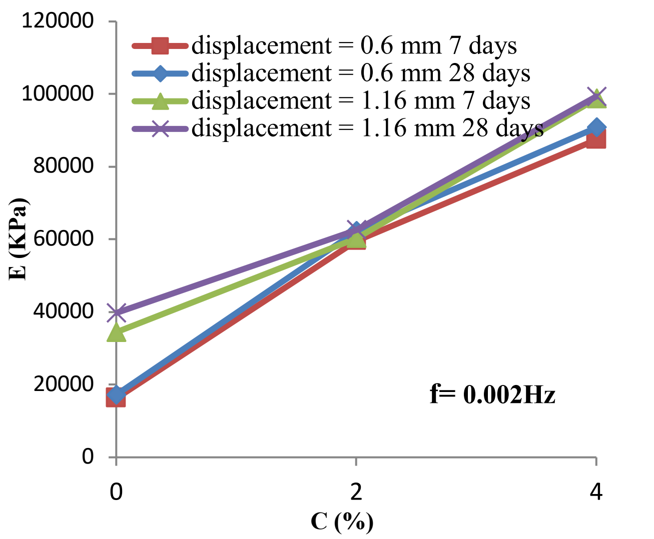


Figure 11 Modulus of elasticity versus of cement content

5. CONCLUSIONS

This experimental study on the mechanical behavior of cement-stabilized dune sand under various loading rates, curing times, frequencies, and cycle numbers has successfully demonstrated the enhanced strength characteristics of the composite sand under different loading conditions. The key findings can be summarized as follows:

5.1 Results of the Static Tests

Two sets of unconfined compression tests were performed at loading rates of 0.05 mm/min and 0.1 mm/min on sand samples aged 7 and 28 days with cement contents of 0%, 2%, and 4%.

1. Effect of Curing Time: For samples with 4% cement content and a 28-day curing period, loaded at 0.05 mm/min, the UCS was approximately 33% higher than similar samples tested after 7 days. Samples loaded at 0.1 mm/min showed an 8% higher UCS than those tested after 7 days.
2. Modulus of Elasticity: An increase in cement content from 0% to 2% and then to 4% led to an increase in the modulus of elasticity at both loading rates. The highest values were noted in 28-day-old samples with 4% cement content.
3. Rate of Loading: A slower loading rate resulted in the soil-cement composite becoming more compact, delaying the onset of cracking due to increased dilatancy, which in turn increased the modulus of elasticity.

5.2 Results of the Cyclic Tests

Two series of cyclic displacement-controlled unconfined compression tests were conducted on sand samples aged 7 and 28 days with cement contents of 0%, 2%, and 4%, at a frequency of 0.002 Hz.

1. UCS under Cyclic Loading: UCS increased with the rise in cement content.
2. Number of Cycles to Failure: The increase in the number of cycles to failure with higher cement content at low frequency is likely due to the slower degradation of the increasing number of cement-sand bonds from the pozzolanic reaction and the increased dilatancy induced by cyclic loading.
3. Evolution of E: The progressive failure of cementitious bonds in cemented sand at higher shear levels before complete failure leads to increased dilatancy compared to non-cemented sand, resulting in an increase in E.

The outcomes of this study hold significant economic and ecological potential for the construction industry, advocating for the use of dune sand as a primary material in road construction and suitable foundations for various structures. Continued research is recommended for a deeper understanding and optimization of the mechanical behavior of cement-treated soils.

Further exploration into reinforcing dune sand, such as integrating fibers or marble fragments, can address environmental and economic challenges. Conducting a mineralogical study to understand sand behavior in aggressive environments and employing numerical modeling to gain better insights into its mechanical performance under varying loads are vital. Overall, these efforts aim to optimize the use of dune sand in construction, striking a balance between innovation, environmental stewardship, and economic viability.

6. REFERENCES

Al-Zoubi, M. S. (2008). “Undrained Shear Strength and Swelling Characteristics of Cement Treated Soil.” *Jordan Journal of Civil Engineering,* 2(1), 53-62.

AFNOR NF P 94-093. (1999). “Soils: Reconnaissance and Tests Determination of the Compaction References of a Material – Normal Proctor test – Modified Proctor Test.”

AFNOR NF P 94-078. (1997). “Soils: Reconnaissance and Tests - CBR Index after Immersion - Immediate CBR Index - Immediate Bearing Index - Measurement on Sample Compacted in the CBR Mould.”

AFNOR NF P 94-077. (1997). “Soils: Reconnaissance and Tests – Uniaxiale Compression Tests.”

Azaiez, D., & Bouassida, M. (2022). “An Efficient Tool to Determine Undrained Shear Strength of Soft Soils Geotechnical Engineering .” (00465828), 53(4).

Bazazorde, S. (2018). “UCS and CBR Behaviour of Perth Sandy Soil Reinforced with Waste Tyrefibres and Cement."

Bello, A. A. (2011). “Influence of Compaction Delay on CBR and UCS of Cement-Stabilized Lateritic Soil.” *The Pacific Journal of Science and Technology,* 12 (2), 87-98.

Biswal, D. R., Sahoo, U. C., & Dash, S. R. (2020). “Fatigue Characteristics of Cement-Stabilized Granular Lateritic Soils.” *Journal of Transportation Engineering,* Part B: Pavements, 146(1), 04019038.

Chaiyaput, S., & Ayawanna, J. (2021). “Lateritic Soil Stabilization by Addition of Steel Slags.” *Geotechnical Engineering,* (00465828), 52(3).

Chompoorat, T., Likitlersuang, S., Thepumong, T., Tanapalungkorn, W., Jamsawang, P., & Jongpradist, P. (2021). "Solidification of Sediments Deposited in Reservoirs with Cement and Fly Ash for Road Construction." *International Journal of Geosynthetics and Ground Engineering,* 7(4), 85.

Chompoorat, T., Likitlersuang, S., Buathong, P., Jongpradist, P., & Jamsawang, P. (2023). "Flexural Performance and Microstructural Characterization of Cement-Treated Sand Reinforced with Palm Fiber." *Journal of Materials Research and Technology.*

Chompoorat, T., Maikhun, T., & Likitlersuang, S. (2019). "Cement-Improved Lake Bed Sedimentary Soil for Road Construction." *Proceedings of the Institution of Civil Engineers-Ground Improvement,* 172(3), 192-20 1 doi: 10.1680/jgrim.18. 00076.

Chompoorat, T., Thanawong, K., & Likitlersuang, S. (2021). "Swell-Shrink Behaviour of Cement with Fly Ash-Stabilised Lakebed Sediment." *Bulletin of Engineering Geology and the Environment,* 80, 2617-2628.

Consoli, N. C., Winter, D., Leon, H. B., & Scheuermann Filho, H. C. (2018). "Durability, Strength, and Stiffness of Green Stabilized Sand." *Journal of Geotechnical and Geoenvironmental Engineering,* 144(9), 04018057.

Festugato, L., Venson, G. I., & Consoli, N. C. (2021). "Parameters Controlling Cyclic Behaviour of Cement-Treated Sand." *Transportation Geotechnics,* 27, 100488. https://doi.org/10.1016/ j.trgeo.2020.100488.

Forcelini, M., Garbin, G. R., Faro, V. P., & Consoli, N. C. (2016). "Mechanical Behavior of Soil Cement Blends with Osorio Sand." *Procedia Engineering,* 143, 75-81, doi: 10.1016/j.proeng.2016. 06.010.

Ganne, P., Huybrechts, N., De Cock, F., Lameire, B., & Maertens, J. (2010). "Soil Mix Walls as Retaining Structures–Critical Analysis of the Material Design Parameters." *In International Conference on Geotechnical Challenges in Megacities,* June 07-10, 2010, Moscow, Russia, 991-998.

Haeri, S. M., Hamidi, A., Hosseini, S. M., Asghari, E., & Toll, D. G. (2006). "Effect of Cement Type on the Mechanical Behavior of a Gravely Sand." *Geotechnical & Geological Engineering*, 24(2), 335-360.

Helson, O. (2017). "Comportement Thermo-Hydro-Mécanique et Durabilité des Bétons de Sol: Influence des Paramètres de Formulation et Conditions D'exposition." *(Doctoral dissertation, Université de Cergy Pontoise).*

Jacobson, J. R., Filz, G. M., & Mitchell, J. K. (2003). "Factors Affecting Strength Gain in Lime-Cement Columns and Development of a Laboratory Testing Procedure." *Virginia Center for Transportation Innovation and Research.*

Jiang, Y., Yuan, K., Deng, C., &Tian, T. (2020). "Fatigue Performance of Cement-Stabilized Crushed Gravel Produced using Vertical Vibration Compaction Method." *Journal of Materials in Civil Engineering,* 32(11), 04020318.

Janalizadeh Choobbasti, A., & Soleimani Kutanaei, S. (2017). "Effect of Fiber Reinforcement on Deformability Properties of Cemented Sand." *Journal of Adhesion Science and Technology,* 31(14), 1576-1590.

Khan, A., Adil, M., Ahmad, A., Hussain, R., and Zaman, H. (2018). "Stabilization of Soil using Cement and Bale Straw." *J. Development,* 5 (9), 44-49.

Kitazume, M., & Terashi, M. (2013). "The Deep Mixing Method (Vol. 21)." *London: CRC press.*

Lo, S. C. R., Lade, P. V., &Wardani, S. P. R. (2003). "An Experimental Study of the Mechanics of Two Weakly Cemented Soils." *Geotechnical Testing Journal,* 26(3), 328-341.

Mase, L. Z., Likitlersuang, S., & Tobita, T. (2019). "Cyclic Behaviour and Liquefaction Resistance of Izumio Sands in Osaka, Japan." *Marine Georesources & Geotechnology,* 37(7), 765-774. doi:10.1080/1064119X.2018.1485793.

Miura, N., Horpibulsuk, S., and Nagaraj, T. S. (2001). "Engineering Behavior of Cement-Stabilized Clay at High Water Content." *J. Soils and Foundations,* 41(5), 33-45.

Mujedu, K. A., Adebara, S. A., and Lamidi I. O. (2016). "Influence of Compaction Delay on Cement-Stabilized Lateritic Soil". *International Journal of Science,* Engineering and Environmental Technology, 1 (5), 29-38.

Nakarai, K., & Yoshida, T. (2015). "Effect of Carbonation on Strength Development of Cement-Treated Toyoura Silica Sand." *Soils and Foundations,* 55(4),857-865.

Nie, S., Hu, S., Wang, F., Hu, C., Li, X., & Zhu, Y. (2017). "Pozzolanic Reaction of Lightweight Fine Aggregate and Its Influence on the Hydration of Cement." *Construction and Building Materials,* 153, 165-173. https://doi.org/10.1016/j.conbu ildmat.2017.07.111.

Nwaiwu, C. M., Ubani, O. U., & Mahawayi, C. (2022). "Influence of Compaction Delay on the CBR and Compaction Behaviour of Cement Treated Lateritic Gravels." *Jordan Journal of Civil Engineering*, 16(1).

Ochepo, J., & Joseph, V. (2014). « Effet de la Contamination par l'huile Sur un Sol Stabilisé à la Chaux." *Journal jordanien de génie civil,* 8 (1), 88-96.

Okonkwo, U.N. (2009). "Effect of Compaction Delay on the Properties of Cement-Bound Lateritic Soils." *Nigerian Journal of Technology,* 28 (2), 5-12.

Philipponnat,G.,& Hubert, B. (2002). "Fondations et Ouvrages en terre, Troisième Tirage."

Sabbaqzade, F., Keramati, M., MoradiMoghaddam, H., &Hamidian, P. (2021). "Evaluation of the Mechanical Behaviour of Cement-Stabilised Collapsible Soils Treated with Natural Fibres." *Geomechanics and Geoengineering,* 1-16.

Sowers, G. B., and G. F. Sowers. (1979). "Introductory Soil Mechanics and Foundations." *3rd ed. New York: McMillan.*

Sun, Y., Wichtmann, T., Sumelka, W., & Kan, M. E. (2020). "Karlsruhe Fine Sand under Monotonic and Cyclic Loads: Modelling and Validation." *Soil Dynamics and Earthquake Engineering,* 133, 106119. https://doi.org/10.1016/j.soildyn.2020. 106119.

Sukkarak, R., Tanapalungkorn, W., Likitlersuang, S., & Ueda, K. (2021). "Liquefaction Analysis of Sandy Soil During Strong Earthquake in Northern Thailand." *Soils and Foundations,* 61(5),1302-1318, doi:10.1016/j.sandf.2021.07.003.

Szymkiewicz, F. (2011). "Evaluation of the Mechanical Properties of a Soil Treated with Cement." *(Doctoral dissertation, Université Paris-Est).*

Thay, S., Likitlersuang, S., & Pipatpongsa, T. (2013). "Monotonic and Cyclic Behavior of Chiang Mai Sand under Simple Shear Mode." *Geotechnical and Geological Engineering*, 31, 67-82. doi:10.1007/s10706-012-9563-9.

Topolnicki, M. (2004). "In Situ Soil Mixing." *Ground Improvement,* Edited by.

Vranna, A., & Tika, T. (2020). "Undrained Monotonic and Cyclic Response of Weakly Cemented Sand." *Journal of Geotechnical and Geoenvironmental Engineering,* 146(5), 04020018 doi: 10.1061/(ASCE)GT.1943-5606.0002246.

Vu, Q. H. (2008). "Modélisation Micromécanique du Comportement d'un sol Injecté." *(Doctoral dissertation, Université Pierre et Marie Curie-Paris VI).*