

# Shear Strength Improvement of Silty Soil Via Microbial-Induced Calcite Precipitation for Wind Erosion Mitigation

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## ABSTRACT

The low shear strength of silty soils in arid and semi-arid regions contributes significantly to their vulnerability to wind erosion. This study evaluates the effect of Microbial-Induced Calcite Precipitation (MICP) using *Bacillus thuringiensis* on the shear strength parameters of silty soils from Northwestern Nigeria. Laboratory tests, including direct shear testing, were conducted on untreated and MICP-treated soil samples to assess changes in cohesion and internal friction angle. Results show that bio-treatment significantly alters the shear strength behavior of silty sand. Cohesion decreased from 38.21 kN/m<sup>2</sup> (control) to a minimum of 25.11 kN/m<sup>2</sup>, indicating a transition from clay-like behavior to a more stable granular structure. Conversely, the angle of internal friction increased from 28.2° to a peak of 42.0°, while shear strength improved markedly from 26.3 kN/m<sup>2</sup> to 82.39 kN/m<sup>2</sup> at the optimum treatment condition of  $1.8 \times 10^9$  cells/ml and 0.75 M. The improvements are attributed to calcium carbonate precipitation via microbial-induced calcite precipitation (MICP), which enhances interparticle bonding, increases surface roughness, and reduces pore spaces. Statistical analysis using two-way ANOVA confirmed that both bacterial density and reagent concentration have significant effects ( $p < 0.05$ ) on all measured parameters.

Microstructural analysis (SEM) revealed a transition from a loose, porous structure to a dense, cemented matrix, while XRD analysis confirmed the presence of calcite as the dominant cementing agent. The findings demonstrate the potential of Bt-based MICP as an effective and sustainable technique for improving the mechanical properties and erosion resistance of silty sand.

**Keywords:** Silty sand, *Bacillus Thuringiensis*, Soil crust, Microbial-induced calcite precipitate

## INTRODUCTION

Shear strength is a fundamental engineering property governing soil stability, resistance to particle detachment, and erosion susceptibility. In silty soils, particularly those found in arid and semi-arid environments, low cohesion and limited interparticle bonding often result in weak shear resistance, making such soils highly vulnerable to wind-induced erosion. Enhancing the shear strength of surface soils is therefore a key strategy for mitigating erosion and improving land stability (Sani and Bala, 2021).

Microbial-Induced Calcite Precipitation (MICP) has gained recognition as an effective soil improvement

technique capable of increasing both cohesion and internal friction through microbially mediated mineral precipitation. The precipitation of calcium carbonate within soil pores forms cementitious bonds that improve the mechanical integrity of the soil matrix. *Bacillus thuringiensis*, a urease-producing bacterium, has demonstrated strong potential for inducing calcite precipitation under diverse environmental conditions (Abubakar, 2023; Garba, 2025).

Although the influence of MICP on compressive and tensile strength has been widely reported, fewer studies have systematically evaluated its effect on shear strength parameters cohesion and angle of internal friction under conditions relevant to wind erosion control. This study evaluates the shear strength enhancement of silty soils treated with *Bacillus thuringiensis*-induced MICP, linking mechanical improvements to erosion resistance and providing a geotechnical basis for sustainable wind erosion mitigation in Northwestern Nigeria (Sani and Bala, 2021).

Wind erosion is a major environmental and geomorphological challenge affecting arid and semi-arid regions globally. It contributes to soil degradation, loss of soil productivity, health problems, dust emissions, contamination of air and surface water, reduction in visibility, blockage of roads, drainages and railways etc. (Oyelakin, 2024; Garba, 2025). Agronomic and mechanical techniques, as well as chemical sand-fixing techniques, are the three main ways that wind erosion in silty sand is managed (Plate Ia-c) (Devrani *et al.*, 2021; Kangda *et al.*, 2023). These methods often present limitations including high cost, environmental unfriendliness or poor durability under harsh climatic conditions. As a result, there is increasing interest in sustainable, biologically driven soil stabilization techniques.



a.

b.

c.

Plate I: (a) Chemical sand-fixing techniques (b) Agronomic techniques (c) Mechanical techniques (source: [www.google.com](http://www.google.com))

Microbially Induced Calcite Precipitation (MICP) has emerged as a promising bio-mediated approach for enhancing soil's engineering properties such as strength and resistance to wind-erosive forces. MICP relies on the metabolic activity of ureolytic bacteria to hydrolyze urea, resulting in carbonate ions that react with calcium ions to precipitate calcium carbonate (Whiffin, 2007; DeJong *et al.*, 2010; Abubakar, 2023; Oyelakin, 2025; Garba, 2025). These calcite precipitates bind soil particles together, forming a cemented crust that improves surface integrity and reduces susceptibility to wind erosion.

Crusts on soil faces (see Plate II) are well known for wind erosion mitigation in provinces with either scarce or no vegetative cover (Duniway *et al.*, 2019; Fick *et al.*, 2020) and control of dust secretion from mine tailings and other sources (Gil-Loaiza *et al.*, 2018; Nikseresht *et al.*, 2020).



Plate II: (a) Soil crust (b) Soil crust thickness

Recent studies have demonstrated the potential of MICP to enhance shear strength, surface cohesion and resistance to disintegration in sandy soils (Oyelakin, 2025; Garba, 2025). However, the effectiveness of the process is strongly dependent on bacterial cell density, treatment frequency, and cementation reagent concentration. In particular, the choice of bacterial strain and its suspension density often standardized using McFarland turbidity scales directly influences calcite production and crust formation efficiency.

This study was aimed at evaluation of efficacy in bio-induced soil crust through MICP to mitigate wind-induced erosion by using a ureolytic bacterium known as *Bacillus thuringiensis*. This work contributes to the growing body of research on MICP as a sustainable wind erosion mitigation strategy and provides key insights into parameter optimization for field scale application.

## MATERIAL AND METHODS

### Materials

#### Soil

The silty sand used in this research was collected from Daura Local Government Area in Katsina state, Nigeria. The soil was collected at a depth of 20 cm. The soil samples were transferred into a clean polythene bag and transported to the Soil Mechanics Research Laboratory of the Ahmadu Bello University, Zaria, Kaduna State, Nigeria.

#### Microorganism

The microbe used in this research is *B. thuringiensis*, which is normally found in soil. This urease positive microbe is rod-shaped, spore-forming and Gram-positive; it was cultured and grown from the soil sample based on microbiological procedures, 2010.

#### Cementation reagent

The cementation reagent ( $C_r$ ) was composed of an equi-molar of calcium chloride and urea as well as other nutrients such as sodium bicarbonate, ammonium chloride, and nutrient broth. The molar concentrations were varied to produce four different  $C_r$  (i.e., 0.25, 0.5, 0.75, and 1 M). The mass concentrations of the various components that make up the  $C_r$  are presented in Table 1.

**Table 1: Mass per litre of cementation reagents.**

Concentrations (M)	0.25	0.5	0.75	1.0
Calcium chloride ( $CaCl_2$ ) (g/L)	27.75	55.49	83.24	110.98

Nutrient broth (g/L)	3	3	3	3
Sodium bicarbonate (NaHCO <sub>3</sub> ) (g/L)	2.12	2.12	2.12	2.12
Ammonium chloride (NH <sub>4</sub> Cl) (g/L)	10	10	10	10
Urea (CO(NH <sub>2</sub> ) <sub>2</sub> ) (g/L)	15.05	30.03	45.05	60.06

**Methods**

**Shear strength testing (Direct Shear test)**

The shear strength characteristics of the natural and bio-treated silty sand specimens were determined using the direct shear test in accordance with BS 1377 (1990) and BS 1924 (1990) (Plate IIIc, d).

Square specimens measuring approximately 60 mm × 60 mm in plan and 20 mm in height were prepared at the required moisture content and compaction conditions. For treated samples, the soil was first mixed with the specified *Bacillus thuringiensis* (Bt) suspension and cementation reagent (Cr) at predetermined concentrations, followed by curing for the required period before testing.

Each specimen was carefully placed inside the shear box, which consists of two horizontally split halves. Porous stones and loading plates were positioned at the top and bottom of the specimen to ensure uniform load distribution and proper drainage.

A predetermined normal stress was applied vertically to the specimen and maintained constant throughout the test. After allowing sufficient time for consolidation under the applied normal load, horizontal shear force was applied at a constant rate of displacement.

The rate of shearing was selected to ensure drained conditions and was maintained at approximately 0.5 - 1.0 mm/min, in line with standard practice. During the test, horizontal displacement and corresponding shear force were measured using a proving ring and dial gauge system. Vertical displacement was also recorded to monitor volume change behavior during shearing.

Readings of shear force and displacement were taken at regular intervals throughout the test. The test was continued until failure occurred, defined as the point at which the shear stress reached a peak value or remained approximately constant with increasing displacement.

The maximum shear stress at failure was determined for each applied normal stress. The shear strength parameters cohesion (c) and angle of internal friction (φ) were obtained by plotting the Mohr–Coulomb failure envelope from the relationship between normal stress and corresponding shear stress at failure.



a.



b.

Plate III: (a) crust strength measurement using pocket penetrometer (b) measurement of bio-crust formed using Vanier caliper (c) shear box test set up (d) typical sheared sample

## Microanalysis of soil

The microscopic particle interaction after bio-treatment was assessed using the Phenom-world analyzer tool for the evaluation of particle morphology at the micro level (i.e., scanning electron microscopy, SEM). X-ray diffraction (XRD) test was also carried out to confirm that the soil mineralogical composition indeed contained calcite after bio-treatment.

## RESULTS AND DISCUSSION

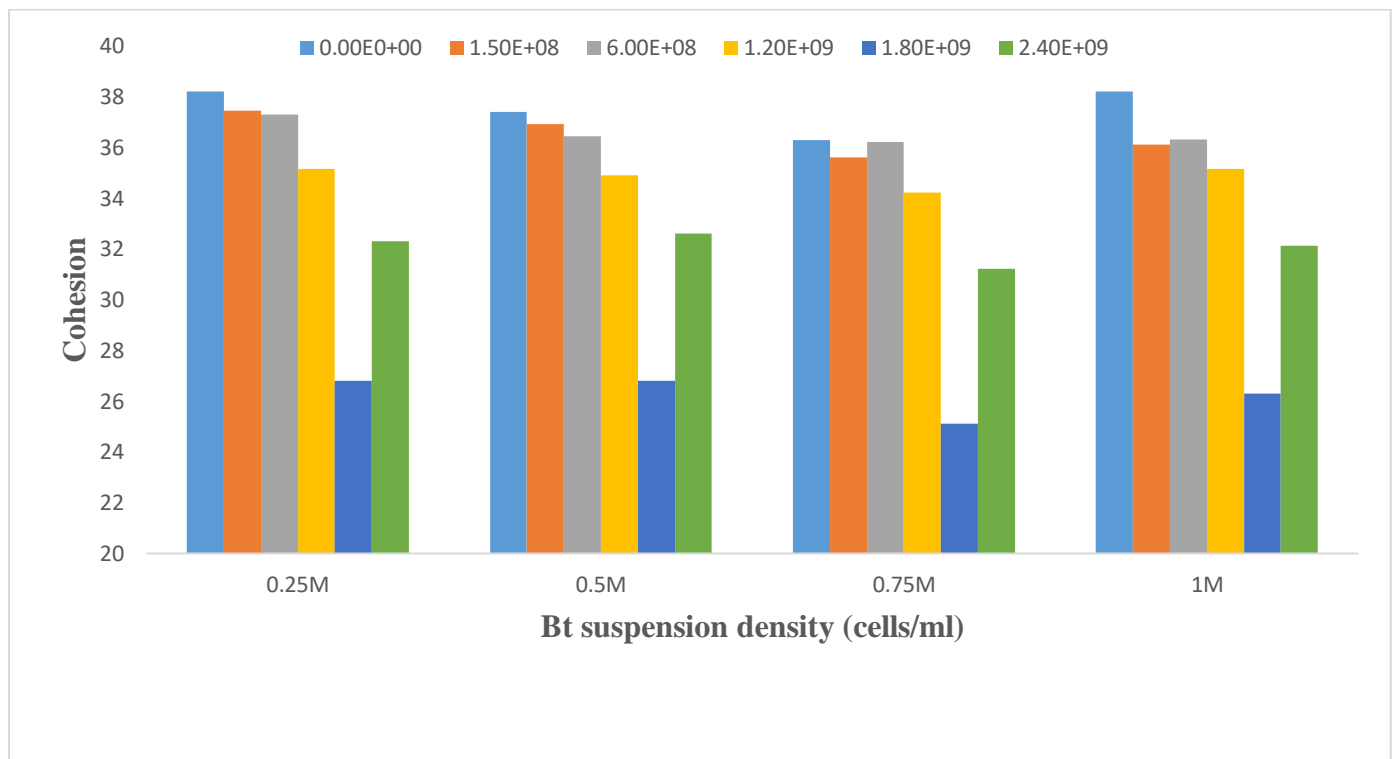
### Shear strength parameters

#### Cohesion

The variation of cohesion of the natural Silty sand - Bt mixtures compacted with Cr is shown in Figure 1.

The variation of cohesion for silty sand treated with *Bacillus thuringiensis* (Bt) and cementation reagent (Cr) is presented in Figure 1. The natural and control samples recorded cohesion values of 39.23 kN/m<sup>2</sup> and 38.21 kN/m<sup>2</sup>, respectively. Following bio-treatment, cohesion decreased progressively with increasing Bt nucleation site and Cr concentration, reaching a minimum value of 25.11 kN/m<sup>2</sup> at  $18 \times 10^8$  cells/mL and 0.75 M, after which a slight increase was observed.

The initial cohesion in the untreated silty sand is largely apparent cohesion, arising from electrochemical forces and the presence of fines. Such cohesion is typically weak and highly sensitive to environmental conditions such as moisture variations.



**Figure 1: Variation of cohesion of silty sand – cementation reagent mixtures with Bt nucleation site**

The MICP process alters this behavior by inducing calcium carbonate precipitation, which modifies the soil fabric. The formation of calcite bridges reduces reliance on weak physicochemical bonding and instead promotes mechanical interlocking between particles, thereby shifting the soil response from a partially cohesive system toward a more stable friction-dominated granular structure. This interpretation is consistent with studies by Sani and Bala (2021), Garba (2025), and Oyelakin (2025), who reported similar reductions in apparent cohesion accompanied by improvements in overall soil stability.

Importantly, similar trends have been observed in MICP-treated soils in the literature, where reductions in cohesion are often accompanied by significant increases in friction angle and shear strength (Harkes *et al.*, 2010; Mujah *et al.*, 2019). Therefore, the decrease in cohesion should not be interpreted in isolation but rather in conjunction with other shear strength parameters. From an engineering perspective, the reduction in cohesion may even be advantageous, as it reduces susceptibility to moisture-induced softening and enhances long-term durability.

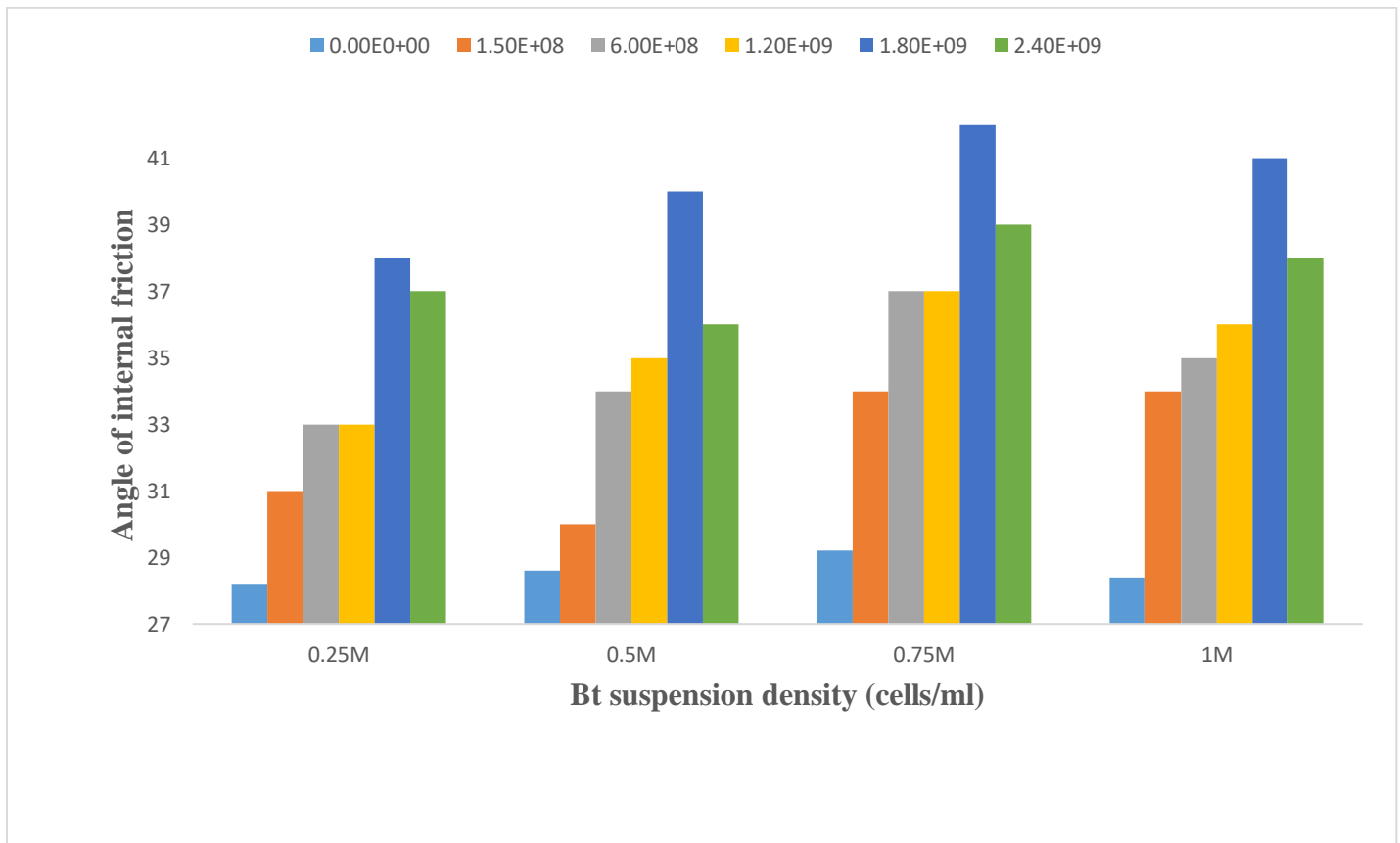
The two-way analysis of variance (ANOVA) test (see Table 2) for crust thickness results showed that the effect of the Bt nucleation site and Cr on silty sand was statistically significant ( $F_{CAL} = 502.3791 > F_{CRIT} = 2.901295$  and  $F_{CAL} = 15.44001 > F_{CRIT} = 3.287382$ ).

Table 2: Two-way analysis of variance for crust thickness results of bio-treated silty sand and control specimens

Property	Source of Variation	Degree of Freedom	$F_{CAL}$	P-Value	$F_{CRIT}$	Remark
cohesion	Bt Nucleation site	5	502.3791	3.86E-16	2.901295	$F_{CAL} > F_{CRIT}$ , Significant Effect
	Cementation Reagent	3	15.44001	7.44E-05	3.287382	$F_{CAL} > F_{CRIT}$ , Significant Effect

### Angle of internal friction

The variation of the angle of internal friction ( $\phi$ ) with Bt nucleation site and cementation reagent concentration is shown in Figure 2. The natural and control samples recorded values of  $28.11^\circ$  and  $28.2^\circ$ , respectively, while a peak value of  $42.0^\circ$  was obtained at  $18 \times 10^8$  cells/mL and 0.75 M. Beyond this optimum condition, a slight decline in  $\phi$  was observed.



**Figure 2: Variation of angle of internal friction of Silty sand– cementation reagent mixtures with Bt nucleation site.**

The increase in  $\phi$  represents the primary contributor to the observed improvement in shear strength and reflects enhanced resistance to particle rearrangement and detachment. Unlike cohesion, which is sensitive to physicochemical interactions, the angle of internal friction is governed by particle interlocking, surface roughness, and contact mechanics, all of which are directly influenced by calcite precipitation.

The MICP process facilitates urea hydrolysis, generating carbonate ions that react with calcium ions to form calcium carbonate. These precipitates accumulate at particle contacts, forming cementitious bridges and increasing surface stiffness. As a result, the bio-treated soil exhibits greater interparticle friction and improved resistance to shear deformation. This mechanism has been widely reported in previous studies (Harkes *et al.*, 2010; Mujah *et al.*, 2019; Osinubi *et al.*, 2019d), where increases in  $\phi$  were identified as the dominant factor governing strength enhancement in MICP-treated soils.

The slight reduction in  $\phi$  beyond the optimum treatment level suggests that excessive bacterial concentration may lead to inefficient utilization of cementation reagents, resulting in non-uniform calcite distribution or localized clogging. Similar observations have been reported in recent studies (Garba, 2025), where an imbalance between microbial activity and reagent availability reduced bio-treatment efficiency.

From an application perspective, the significant increase in  $\phi$  is particularly relevant for erosion control and slope stability. Higher friction angles enhance resistance to particle detachment under wind or hydraulic forces and improve the durability of surface crusts, making MICP-treated soils more resilient in harsh environmental conditions.

The two-way analysis of variance (ANOVA) test (see Table 3) for crust thickness results showed that the effect of the Bt nucleation site and Cr on silty sand was statistically significant ( $F_{CAL} = 90.69939 > F_{CRIT} = 2.901295$  and  $F_{CAL} = 15.50307 > F_{CRIT} = 3.287382$ ).

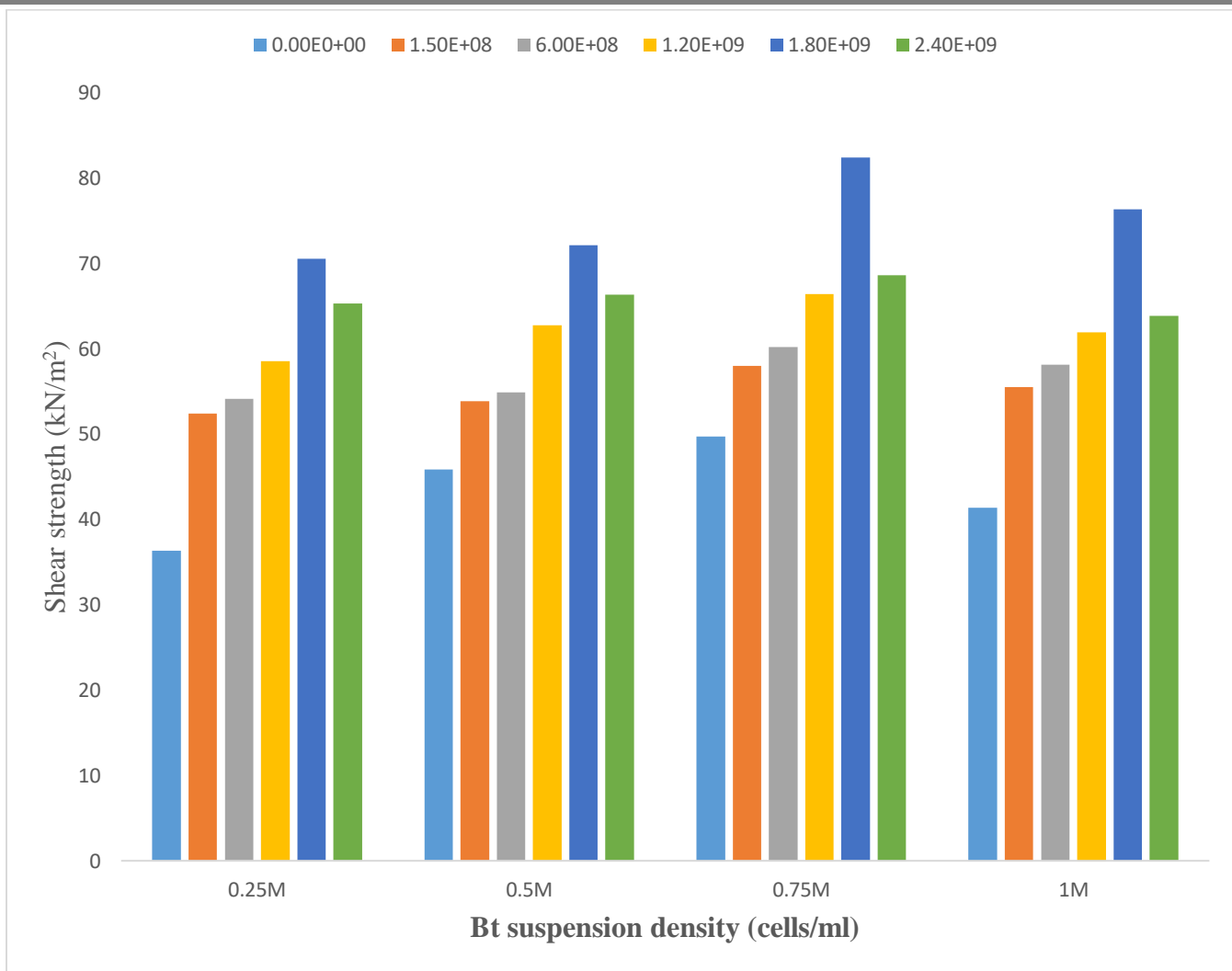
Table 3: Two-way analysis of variance for crust thickness results of bio-treated silty sand and control specimens

Property	Source of Variation	Degree of Freedom	$F_{CAL}$	P-Value	$F_{CRIT}$	Remark
Cohesion	Bt Nucleation site	5	90.69939	1.15E-10	2.901295	$F_{CAL} > F_{CRIT}$ , Significant Effect
	Cementation Reagent	3	15.50307	7.27E-05	3.287382	$F_{CAL} > F_{CRIT}$ , Significant Effect

**Shear strength**

The variation of shear strength of silty sand treated with *Bacillus thuringiensis* (Bt) and cementation reagent (Cr) is presented in Figure 3. The results show a noticeable increase in shear strength with increasing Bt nucleation site and Cr concentration up to an optimum level, beyond which a slight reduction was observed.

The natural and control samples recorded shear strength values of 26.1 kN/m<sup>2</sup> and 26.3 kN/m<sup>2</sup>, respectively, whereas a peak value of 82.39 kN/m<sup>2</sup> was achieved at  $1.8 \times 10^9$  cells/mL and 0.75 M. This represents a substantial enhancement in shear resistance compared to untreated conditions.



**Figure 3: Variation of shear strength aeolian soil – cementation reagent mixtures with *B. brevis* nucleation site**

Unlike cohesion, which showed a decreasing trend, the increase in shear strength is primarily governed by the significant improvement in the angle of internal friction, indicating that frictional resistance rather than cohesive bonding dominates the strength gain in the treated soil. This distinction is important, as it highlights that the effectiveness of MICP treatment should be evaluated based on the combined evolution of shear strength parameters rather than individual components.

The observed improvement in shear strength is attributed to calcium carbonate precipitation during the MICP process. The hydrolysis of urea by urease-producing bacteria generates carbonate ions, which react with calcium ions to form calcite. These calcite crystals precipitate at particle contacts, forming cementitious bridges that enhance interparticle bonding, reduce pore space, and improve load transfer within the soil matrix. As a result, the bio-treated soil exhibits increased resistance to shear deformation. Similar strength enhancement mechanisms have been widely reported in previous studies (Zamani and Montoya, 2015; Ali and Karkush, 2021; Jia *et al.*, 2022; Garba, 2025).

In addition to bonding, calcite precipitation modifies the soil fabric by increasing surface roughness and promoting particle interlocking, which further contributes to the increase in shear strength. This mechanism is particularly relevant for erosion resistance, as improved interlocking reduces particle detachment under wind or mechanical disturbance (Ankur *et al.*, 2019; Gang *et al.*, 2023; Jia *et al.*, 2022).

The slight reduction in shear strength observed beyond the optimum treatment condition suggests that the efficiency of calcite precipitation is sensitive to the balance between bacterial population and cementation

reagent availability. At higher bacterial densities, the available calcium ions may become insufficient to sustain effective precipitation, resulting in incomplete or non-uniform calcite formation. This imbalance can lead to reduced bonding efficiency and localized clogging, which ultimately limits further strength gain. Similar trends have been reported by Ankur *et al.* (2019), Abubakar (2023), Gang *et al.* (2023), and Garba (2025), who emphasized the importance of optimizing bacterial concentration and reagent supply in MICP applications.

From an engineering view, the substantial increase in shear strength combined with the observed increase in the angle of internal friction indicates that MICP treatment significantly enhances the mechanical stability of silty sand. This improvement is particularly beneficial for applications such as wind erosion control, slope stabilization, and surface crust formation, where resistance to shear deformation and particle detachment is critical

The two-way analysis of variance (ANOVA) test (see Table 4) for shear strength results showed that the effect of the Bt nucleation site on shear strength of silty sand was statistically significant ( $F_{CAL} = 97.63346 > F_{CRIT} = 2.901295$ ,  $F_{CAL} = 13.57817 > F_{CRIT} = 3.287382$ ).

Table 4: Two-way analysis of variance for shear strength tests results of treated aeolian soil specimens

Property	Source of Variation	Degree of Freedom	$F_{CAL}$	P-Value	$F_{CRIT}$	Remark
Shear strength	Bt Nucleation site	5	97.63346	6.75E-11	2.901295	$F_{CAL} > F_{CRIT}$ , Significant Effect
	Cementation Reagent	3	13.57817	0.00015	3.287382	$F_{CAL} > F_{CRIT}$ , Significant Effect

### Micro-analysis

The scanning electronic microscopy (SEM) micrographs of specimens are shown in Plates IV. The particles of the natural silty sand (plate IVa) are shown to be individually separated from each other where the aggregates of the soil revealed its cohesionless nature and depict rough honeycombed-like structure with voids thus, indicates its susceptibility to wind effects due to its low resistance to wind erosion while the micrograph of specimen biotreated with optimal Bt nucleation site ( $18 \times 10^8$  cells/ml) – Cr concentration (0.75 M) (Plate IVB) reveals a smooth morphology that indicates an agglomerated and compacted soil mass as a result of the enrichment and stimulation of the existing or native microbes in the natural soil specimen (Devrani *et al.*, 2024; Garba, 2025; Oyelakin, 2025).

The formation of this cementitious product may have influenced the improved in crust strength developed for the specimen. Additionally, the aggregation may have been due to cation exchange and clusteration-agglomeration that occurred within the bio-treated soil’s matrix during the curing period (Bassey, 2021; Abubakar, 2023). The micrograph depicts the development of cementitious products from the precipitated calcite that increased the bonding between the soil particles (Ng *et al.*, 2012; Bassey, 2021). The improved flocculation of the soil particles could also be attributed to the electrostatic attractive forces between negative particle surfaces and positive particle edges, causing the agglomeration of the particles (Anbu *et al.*, 2016; Bassey, 2021; Abubakar, 2023; Garba, 2025; Oyelakin, 2025). The increase in the attractive forces prevailing over the repulsive forces with curing period according to Mitchell (1956), is an indication of the soil's sample flocculent nature.

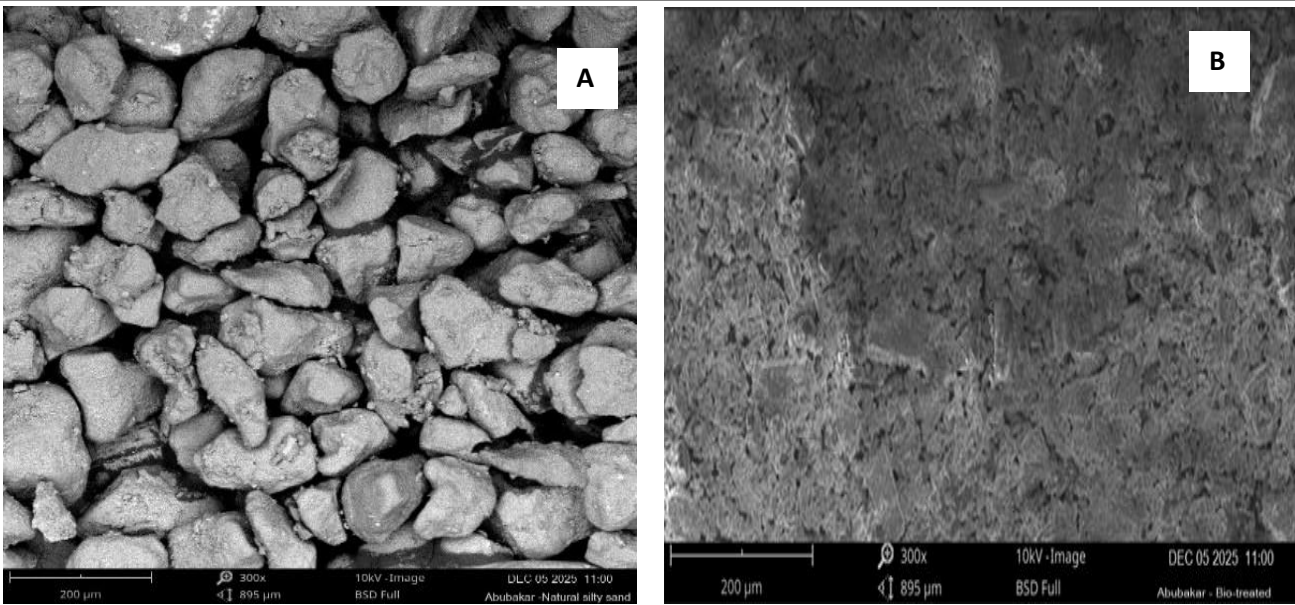


Plate IV: Micrographs of specimens: (a) Natural soil (b) Specimen bio-treated with  $18 \times 10^8$  cells/ml – 0.75 M

### X-ray Diffraction

The X-ray diffraction (XRD) analysis produced the diffractogram shown on Plate V that indicate the major component of the silty sand as quartz while  $\text{CaCO}_3$  was found as the mineral constituent. This shows that silty sand contains more of quartz minerals, which exhibit solubility and swelling in water (Gowthaman *et al.*, 2021; Liang *et al.*, 2022), causing soil to loss, soften and disintegrate its bonding easily under wind pressure been it cohesionless.

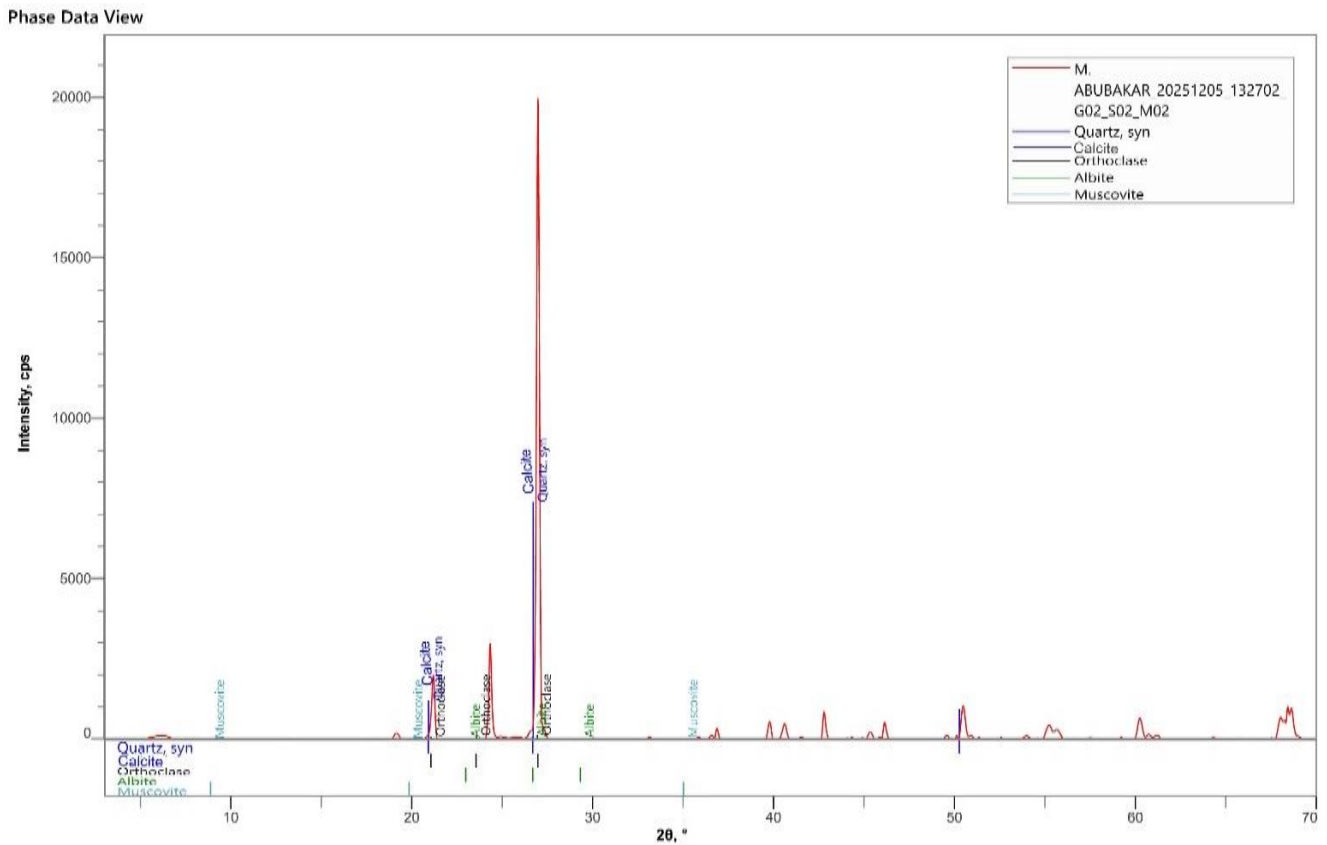


Plate V: Diffractogram of silty sand used in the study for bio-treated sample.

## CONCLUSION AND RECOMMENDATION

### Conclusion

Based on the results recorded the following conclusion can be deduced:

1. The cohesion of the soil shows a decrease in values with an increase *Bt* nucleation site and cementation reagent with a minimum value of 25.11 kN/m<sup>2</sup> recorded at  $18.0 \times 10^8$  cells/ml - 0.75 M. The result indicates there is a great improvement in the silty, on the other hand, the angle of internal friction and shear strength increases at higher *Bt* nucleation site and cementation reagent concentrations with maximum value of 42.0° and 82.39 kN/m<sup>2</sup> recorded at  $18.0 \times 10^8$  cells/ml - 0.75 M respectively.
2. The micrographs of the natural silty sand depicted its cohesionless, a roughly honeycombed-like structure with voids, indicating its susceptibility to wind effects due to its low resistance to wind erosion, and smooth morphology, agglomerated and compacted soil mass by the bio-treated silty sand thus, indicating its higher resistance to wind erosion.

### RECOMMENDATION

A bacterial nucleation site – cementation reagent concentration of  $18.0 \times 10^8$  cells/ml - 0.75 M be considered for bio-treatment of the silty sand in order to obtain better strength properties against wind detachment.

### REFERENCES

1. Abubakar, M. (2023). Evaluation of bio-cementation of lateritic soil with *brevibacillus brevis* using different modes of application for road construction. A Thesis Submitted to the Postgraduate School, Ahmadu Bello University, Zaria.
2. Ali N, Karkush M. (2021). "Improvement of Unconfined Compressive Strength of Soft Clay using Microbial Calcite Precipitates." *Journal Engineering*; 27(3):67–75.
3. Ankur N., Noosrat R., Ashikuzzaman M., Syed A. M. (2019). "Department Comparative Study of Consistency Behavior and Shear Strength of Clayey Soils of Rajshahi District, Bangladesh." *Journal of Civil, Construction and Environmental Engineering*; 4(1): 28-34 doi: 10.11648/j.jccee.20190401.13
4. Basseyy, A. B. (2021). "Microbial-Induced Calcite Precipitate Improvement Potential of Black Cotton Soil with *Bacillus Coagulans*." A dissertation submitted to the Postgraduate School, Ahmadu Bello University, Zaria.
5. BS 1377 (1990). Method of Testing Soils for Civil Engineering Purposes. British Standard Institute, BSI, London.
6. BS 1924 (1990). Method of Test for Stabilized Soils. British Standard Institute BSI London
7. DeJong, J. T., Mortensen B. M., Martinez B. C., and Nelson D. C. (2010). "Bio-mediated soil improvement." *Ecological Engineering*, 36(2):197 - 210.
8. Devrani, R., A. A. Dubey, K. Ravi, and Sahoo, L. (2021). "Applications of bio-cementation and bio-polymerization for aeolian erosion control." *J. Arid. Environ.* 187 (Aug): 104433. <https://doi.org/10.1016/j.jaridenv.2020.104433>.
9. Duniway, M. C., Pfennigwerth, A. A., Fick, S. E., Nauman, T. W., Belnap, J., & Barger, N. N. (2019). Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. *Ecosphere*, 10(3), e02650. <https://doi.org/10.1002/ecs2.2650>.
10. Fick, S.E., Barger, N., Tatarko, J., Duniway, M.C. (2020). Induced biological soil crust controls on wind erodibility and dust (PM10) emissions. *Earth Surf. Process. Landforms* 45 (1), 224–236. <https://doi.org/10.1002/esp.4731>.
11. Gang, Li, Jia, L., Jinli, Z. and Shufeng, C. (2023). "Shear Strength Behaviors of Aeolian Sand Solidified by Microbially Induced Calcite Precipitation and Basalt Fiber Reinforcement." *Materials*; 16(17): 5857. doi: 10.3390/ma16175857
12. Garba A. M. (2025). Evaluation of *bacillus brevis* - induced calcite precipitate for mitigation of aeolian soil erosion. . A Thesis Submitted to the Postgraduate School, Ahmadu Bello University, Zaria

13. Gowthaman, S., Nakashima, K., Kawasaki, S. (2020). "Freeze-thaw durability and shear responses of cemented slope soil treated by microbial induced carbonate precipitation, *Soils Found.*" 60 (2020) 840–855, <https://doi.org/10.1016/j.sandf.2020.05.012>
14. Gil-Loaiza, J., Field, J.P., White, S.A., Csavina, J., Felix, O., Betterton, E.A., S´aez, A.E., Maier, R. M. (2018). Phytoremediation reduces dust emissions from metal (loid)- contaminated mine tailings. *Environ. Sci. Technol.* 52 (10), 5851–5858.
15. Harkes, M. P., Van Paassen, L. A., Booster, J. L., Whiffin, V. S., and Van Loosdrecht, M. C. M. (2010). "Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement." *Ecological Engineering*, 36(2) :112-117.
16. Jia, L., Gang, L., and Xi'an, L. (2022). "Geotechnical Engineering Properties of Soils Solidified by Microbially Induced CaCO<sub>3</sub> Precipitation (MICP)." *Hindawi Advances in Civil Engineering*;12:1, Article ID 6683930 <https://doi.org/10.1155/2021/6683930>
17. Liang, S., Xiao, X., Fang, C., Feng, D., Wang, Y. (2022). "Experimental Study on the Mechanical Properties and Disintegration Resistance of Microbially Solidified Granite Residual Soil." *Crystals* **2022**, 12:132. <https://doi.org/10.3390/cryst12020132>
18. Microbiology Procedures/Guidelines (2010). "College of Physicians and Surgeons of Saskatchewan." Laboratory Quality Assurance Program.
19. Ng, W., Lee, M. and Hii, S. (2012). "An Overview of the Factors Affecting Microbial-Induced Calcite Precipitation and its Potential Application in Soil Improvement." *World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering* (6)2:188-193.
20. Nikseresht, F., Landi, A., Sayyad, G., Ghezelbash, G., Schulin, R. (2020). Sugarcane molasse and vinasse added as microbial growth substrates increase calcium carbonate content, surface stability and resistance against wind erosion of desert soils. *J. Environ. Manag.* 268, 110639. O'Brien, P., Neuman, C.M., 2012. A wind tunnel
21. Osinubi, K. J., Sani, J. E., Eberemu, A. O., Ijimdiya, T. S. and Yakubu, S. E.(2019d). 'Unconfined compressive strength of *Bacillus pumilus* treated lateritic soil.' *Proceedings of the 8th International Congress on Environmental Geotechnics (ICEG 2018)*, "Towards a Sustainable Geoenvironment" Edited by Liangtong Zhan, Yunmin Chen and Abdelmalek Bouazza, 28th October – 1<sup>st</sup> November, Hangzhou, China,c Springer Nature Singapore Pte Ltd., 3 : 410–418, Online: [https://doi.org/10.1007/978-981-13-2227-3\\_51](https://doi.org/10.1007/978-981-13-2227-3_51)
22. Oyelakin, A. M. (2025). "Mitigation of wind erosion of semi-arid zone soil using *Bacillus megaterium* in microbial - induced calcite precipitation." A Thesis Submitted to the Postgraduate School, Ahmadu Bello University, Zaria.
23. Sani, J. E. and Bala, K. B. (2021). "Microbial Induced Modification of Silty Soil Using *Bacillus Coagulans* for Building Foundation." *journal of science technology and education* 9(3), september, 2021. ISSN: 2277-0011; 1(1) 12 – 24
24. Zamani, A., and Montoya, B. M. (2015). "Undrained Behavior of Silty Soil Improved with Microbial Induced Cementation." 6<sup>th</sup> International Conference on Earthquake Geotechnical Engineering 1-4 November 2015, Christchurch, New Zealand