Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Evaluation of Strength Properties of Bio-remediated Crude Oil Contaminated Soil using Bacillus pumilus for Use as Liner and Cover Material in Municipal Solid Waste Containment Applications

Hinafulo Simon Joel
Ahmadu Bello University
Thomas Stephen Ijimdiya
Ahmadu Bello University
Kolawole Juwonlo Osinubi
kjosinubi@abu.edu.ng

Ahmadu Bello University

Research Article

Keywords:

Posted Date: March 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8755825/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Evaluation of Strength Properties of Bio-remediated Crude Oil Contaminated Soil using *Bacillus pumilus* for Use as Liner and Cover Material in Municipal Solid Waste Containment Applications

Hinafulo Simon Joel[1], Thomas Stephen Ijimdiya[2] and Kolawole Juwonlo Osinubi[2]

[1,2]Department of Civil Engineering, Ahmadu Bello University, Zaria, Kaduna State.

Abstract

This study evaluates the effectiveness of Bacillus *pumilus*-induced calcite precipitate to enhance the engineering performance of bio-remediated crude oil-contaminated soils for waste containment applications. Remediated soil samples were bio-treated with Bacillus *pumilus* (B) – cementation reagent (C) mixtures. Trial mix ratios of 75 % B – 25 % C, 50 % B – 50 % C, and 25 % B – 75 % C with B. *pumilus* suspension densities in the range 1.5×10^8 - 2.4×10^9 cells/ml and a fixed cementation reagent concentration. The 50 % B – 50 % C ratio yielded optimum improvement and was adopted in this study. The cementation reagent was prepared and applied to soil samples compacted using three energy levels namely, British Standard light (BSL), West African Standard (WAS), and British Standard heavy (BSH). The bio-cementation with *B. pumilus* (1.5×10^8 to 2.4×10^9 cells/ml) cementation solutions under gravity infiltration on the post-remediated soil specimens showed slight improvements with liquid limit reducing from 43.8 % to 41.1 %, plastic limit increased from 36.3 % to 37.5 %, and the plasticity index increased from 7.3 % to 7.4 %. UCS values reached 225.4, 264.4, and 385.1 kN/m² for BSL, WAS, and BSH compaction, respectively, recorded exceeded the minimum requirement of 200 kN/m². The findings confirm that bio-cementation using B. *pumilus* can effectively enhance the strength and plasticity characteristics of bioremediated oil-contaminated soils, supporting their suitability as liner and cover materials in waste containment systems.

Introduction

The relative abundance of microorganism in the soil made available by nature is of great importance in engineering application such as soil improvement. In recent times, soil improvement has been done with cement, lime, waste materials, fibres and geosynthetic materials

(Horpibulsuk *et al.,* 2017; Dhami *et al*., 2018 El-Shanshoury *et al*., 2025). These techniques though efficient, are not eco-friendly and some of them are toxic, expensive and often taint the groundwater (Alazigha *et al.,* 2016; Dora, 2019, Olorunfemi *et al.,2024*). In pursuit of green techniques for soil improvement, geotechnical engineers are striving for viable and affordable techniques for bio-cementation using microbes which are eco-friendly (Osinubi *et al.,* 2017; Dhami *et al*., 2018; Eberemu *et al.,* 2021).

The microbes found in the soils were used in the biological process. This process results in the formation of mineral precipitates in the pores of the soil matrix which changes the soil properties by cementation process called bio-cementation (Krzmarzick *et al*., 2018; Kour *et al*., 2021). Bio-cementation processes can be used in place of energy demanding, costly and environmentally unfriendly techniques, at a significantly lower cost (Dhami *et al*., 2018; Ijimdiya *et al*., 2022). The mechanical properties of the in-situ soil can be improved via bio-cementation processes.

Bio-cementation can be defined as the method of increasing the strength properties of engineering soils by enhancing the fastening of soil particle through the activities of microbial organisms. This is mostly employed in geotechnical engineering application as a green technology to strengthen the engineering properties of soils (Gomez *et al*., 2017; Dhami *et al.,* 2018 Spencer *et al*.,2023). This study, therefore, focused on evaluation of the potential of bio-cementation of a post-remediated soil using *B. pumilus* and the bio-cemented material was evaluated for use as a viable cover and liner material in waste containment applications.

Microbially Induced Calcite Precipitation (MICP) has emerged as a promising biotechnology with two principal applications in geotechnical engineering: bio-cementation and bio-clogging. Bio-cementation enhances the mechanical behaviour of soil specifically, their stiffness and strength—through biologically mediated precipitation of calcite, which binds soil particles and improves structural integrity. In contrast, bio-clogging involves the microbial production of metabolic by-products that accumulate within soil pore spaces, leading to a significant reduction in hydraulic conductivity and porosity. These processes are increasingly being explored for sustainable soil improvement and subsurface engineering applications (Delgado-Baquerizo *et al*., 2018; Osinubi *et al*., 2020a, b, c).

2.0 Microbial Induced Calcite Precipitation

In 1992 the thought of employing microbes in bio-geotechnical engineering was first considered and communicated (Ferris and Stehmeier, 1992). Subsequently, several research have been carried out to ascertain the possibility, prospect and the pros and cons of using microbial organisms in the geotechnical profession as a welcomed eco-friendly technique. The underlying concept in this method is that sediments produced by microorganisms catalysed chemical reactions ably bind or and pelage soil particles.

Microbial Induced Calcite Precipitation (MICP) is a term for a group of microbiological soil improvement technique that has been and is still being developed through interdisciplinary research; it's an outcome of collaboration and concerted contributions of researchers in the specialties of microbiology, geochemistry, geotechnical engineering and their allied professions. MICP has several established applications, including enhancement of soil strength, reduction of hydraulic conductivity, surface erosion control, and seismic ground improvement (Kim and Youn, 2016; Varjani and Upasani, 2017; Siles and Margesin, 2018, Wilcox *et al.,2024*).

Bacillus species are rod shape normally 4-10 µm large (0.5-1.2 µm width by 1.0-4.0 µm length) and are usually Gram-positive and stringently aerobic or facultative anaerobic capsulized bacilli. They possess vital features in production of spores that are extraordinary in opposing an unpleasant situation. *Bacillus species* type is classified into categories of *B. polymyxa, B. subtilis* (which includes *B. cereus* and *B. licheniformis*), *B. brevis* and *B. anthracis* (Bartram, 2003, Ijimdiya *et al*., 2022).

Bio-cementation using MICP technique uses certain bacteria (microbes or micro-organism) which by some biochemical activities hydrolyses urea (an organic chemical compound) thereby generating carbonate ions (less stable sub-molecular chemical species) (Ijimdiya and Musa, 2017; Wu, *et al.,* 2019; Ma *et al.,* 2020,). These anions on reaction with calcium chloride give calcite that performs the function of soil particles fastening, hence increasing soil strength and solidity/firmness (Choi *et al.,* 2016; Chi *et al.,* 2017; Osinubi *et al*., 2017, Xiao *et al*.,2025).

The role played by the microbes (i.e., *Bacillus pumilus*) is the release of the active urease enzyme which is commonly used for urea hydrolysis. The metabolic action of these bacteria ingests the urea (NH_2CONH_2) and split into ammonia (NH_3) and carbonate (NH_2COOH) via chemical reaction (as shown (1)). These chemical compounds disperse from the cell wall of microbe into the neighbouring media. In closeness with water ammonia change into ammonium, NH_4^+ (as shown in (4)) and carbonate alter into carbonate, bicarbonate ions and carbonic acid. When ammonia reacts with water it forms hydroxyl ions (OH^-) which increases the pH of the media and facilitate precipitation of available Ca^{2+} into calcium carbonate ($CaCO_3$) as shown in eq. (5):

$$NH_2CONH_2 + H_2O \rightarrow NH_3 + NH_2COOH \quad (1)$$

$$NH_2CONH_2 + H_2O \leftrightarrow H_2CO_3 + NH_3 \quad (2)$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (3)$$

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \quad (4)$$

$$Ca^{2+} + HCO_3 + OH^- \leftrightarrow CaCO_3 (\downarrow) + H_2O \quad (5)$$

The urea hydrolysis depicted in equations (1) – (5) has been employed by interstudy for MICP processes in the treatment and modification of the properties of engineering soils in the last few years (Osinubi *et al.*, 2017 Caldoso *et al*., 2018; Yu *et al.,* 2020). In the present-day environmentally conscious society, one very prominent and pertinent movement is that of a concerted call and commitment to and towards devising and accepting only technologies that are to some reasonable extent "green" and sustainable. The green and sustainable technologies ideology has some queries for all chemical grouts apart from sodium silicate because of their toxicity and harmful properties (DeJong *et al.,* 2010; Eberemu *et al.,* 2021).

3.0 Materials and Methods

3.1 Materials

3.1.1 Soil

The soil sample employed in this study was collected from the vicinity of the Kaduna Refinery, located in Chikun Local Government Area of Kaduna State, Nigeria, along the Abuja–Keffi Road (Latitude 10°27′16.85″ N, Longitude 7°24′46.58″ E). Sampling was conducted at a depth of 0.5 m below the ground surface using a disturbed sampling technique.

3.1.2 Micro-organism

The Gram-positive, rod-shaped, spore-forming bacteria residing in the soil sample that is crude oil contaminated soil (COCS) used in this research study was B. *pumilus* which was classified based on (ATCC) as ATCC 27142.

3.1.3 Cementation reagent

The cementation reagent utilised in this research work is composed of 20 g urea ($CO(NH_2)_2$), 2.8 g calcium chloride ($CaCl_2$), 3 g nutrient broth, 10 g ammonium chloride (NH_4Cl), and 2.12 g sodium bicarbonate ($NaHCO_3$) per litre of deionised solvent (Stocks-Fischer *et al.,* 1999; Al Qabany *et al.,* 2011; Osinubi *et al.,* 2018c; Osinubi *et al.,* 2019a, b, Xiao *et al*.,2025).

3.2 Methods

3.2.1 Sample inoculums

Equal drops of each diluted of soil suspension was turned and spread over the agar nutrient plates via sterile L rod. The bacteria colonies were formed on the plates, after incubation for 24 hours at 37^o C (Cappuccino and Sherman, 2002; Begum *et al.,* 2017, Wilcox *et al.,2024*).

3.2.2 Sample preparation for bio-cementation

Three trial mix ratios (i.e., 75 % B – 25 % C,50 % B – 50 % C, and 25 % B – 75 % C) were used to determine the optimum quantity of B. *pumilus* concentration that gave the required improvement when the bio-remediated crude oil contaminated soil was subjected to bio-cementation using B. *pumilus* suspension densities 1.5 x 10^8, 6.0 x 10^8, 1.2 x 10^9, 1.8 x 10^9, and 2.4 x 10^9 cells/ml and cementation reagent only. The optimum quantity that gave the best result was at 50 % B – 50 % C which was then used in the study.

Initially the tests were done to determine the natural strength qualities of the soil. For the treated specimen, a volume of cementation reagent and a volume of each bacterial suspension were used, with the bacterial suspension partially replacing an amount of the total volume of cementation reagent. The volumes of cementation reagent and bacterial suspension required for treatment were calculated using equations (6) and (7), respectively:

$$Volume\ of\ Bacteria = \frac{50}{100} \times Total\ Volume \quad (6)$$

$$Volume\ of\ Cementation\ Reagent = \frac{50}{100} \times Total\ Volume \quad (7)$$

The cementation reagent was prepared and applied to soil samples compacted using three energy levels namely, British Standard light (BSL), West African Standard (WAS), and British Standard heavy (BSH). The treated samples were sealed in plastic containers and cured for 24 hours to allow adequate hydration. Compaction was subsequently carried out in accordance with BS 1924 (1990) and BS 1377: Part 7 (1990).

3.2.3 Bio-treatment of post-remediated soil

Soil samples were mixed thoroughly with B. *pumilus* in stepped suspension density of 1.5 x 10^8 /ml, 6.0 x 10^8 /ml, 1.2 x 10^8 /ml, 1.8 x 10^8 /ml, and 2.4 x 10^9 /ml and was kept in closed plastic containers at room temperature for 24 hours to allow for the even distribution of bacteria to get distributed into the soil grains. The soil samples were compacted at OMC in accordance with BS 1377: 1990 in 1000 cm^3 moulds using the three compactive efforts. The compacted samples were saturated with cementation reagent in four circles for 24 hours as described by Yasuhara (2016). The cementation reagent utilised in the treatment of the soil samples was allowed to flow by gravity method using top and bottom approach to allow microbial induced calcite precipitation to take place (Chi *et al.,* 2017; Ijimdiya and Musa, 2017, Spencer *et al*.,2023).

3.2.4 Index properties

The index tests were carried out accordance with BS 1377: 1990.

Atterberg limits

The Atterberg limits tests consists of liquid limit, plastic limit and plasticity index. Soil samples passing through BS sieve No. 40 (425 μm aperture size) was used in accordance with BS 1377 (1990).

Liquid Limit

The liquid limit test was conducted in accordance to BS 1377-2:1990. Treated soil samples were mixed with water to form a uniform paste, placed in the Casagrande apparatus, and grooved at the center. The crank was turned at two revolutions per second until the groove

closed over 13 mm. The number of blows was recorded, and a sample was taken for moisture content analysis. This process was repeated across a range of blows, and the liquid limit was determined from the moisture content corresponding to 25 blows on a semi-log plot.

Plastic Limit

The plastic limit test was conducted in accordance to BS 1377-2:1990, involved using 20 g of the paste from the liquid limit test. The soil was partially dried until plastic, then rolled by hand into 3 mm threads until it crumbled. The crumbled sample was collected for moisture content determination to establish the plastic limit.

Plasticity Index

The plasticity index (PI) of both the natural and bio-remediated soil samples were determined using the expression:

$$PI = LL - PL \tag{8}$$

3.2.5 Unconfined compressive strength

The Unconfined Compressive Strength (UCS) test was conducted on the bioremediated and bio-cemented soil samples in accordance with BS 1377-2:1990 and BS 1924:1990. Soil specimens, compacted and treated with *Bacillus pumilus*, were initially cured for 24 hours and extruded from cylindrical moulds measuring 38.1 mm in diameter and 76.2 mm in height. The extruded samples were air-dried at 25 ± 2 °C for 24 hours, then sealed in plastic containers and cured for 7, 14, and 28 days. UCS tests were performed using a compression testing machine, applying axial load at a strain rate of 0.01 mm/min. Axial load and deformation were recorded continuously until failure. The UCS was determined from the peak point on the stress–strain curve, using Equation (9).

$$\text{Unconfined compressive strength} = \frac{failure\ load}{Surface\ Area\ of\ specimen} \quad (kN/m^2) \tag{9}$$

4.0 Results and Discussion

4.1 Soil Index Properties

The geotechnical properties of the crude oil-contaminated soil are presented in Table 1. Based on AASHTO (1986) and the Unified Soil Classification System (ASTM, 1992), the soil is classified as A-2-5(0) and SM, respectively. The particle size distribution curve of the bioremediated soil is shown in Figure 1. Preliminary tests revealed a natural moisture content of 8.5 %, and the percentage passing the No. 200 sieve is 32.6 % for the bioremediated soil sample.

Table 1: Properties of the crude oil contaminated soil

Property	**Quantity**
Percentage passing No. 200 sieve	29.1
Optimum Moisture Content, %	
British Standard light	12.6
West African Standard	11.1
British Standard heavy	9.4
Maximum Dry Density, Mg/m3	
British Standard light	1.62
West African Standard	1.70
British Standard heavy	1.75
Unconfined Compressive Strength, kN/m^2	
7 Days	
British Standard light	169.1
West African Standard	211.1
British Standard heavy	327.2
14 Days	
British Standard light	190.1
West African Standard	253.7
British Standard heavy	370.3
28 Days	
British Standard light	211.5
West African Standard	295.3
British Standard heavy	391.5
Permeability (Hydraulic Conductivity), m/s	
British Standard light	8.46×10^{-9}
West African Standard	7.71×10^{-9}
British Standard heavy	5.21×10^{-9}
Colour	Dark

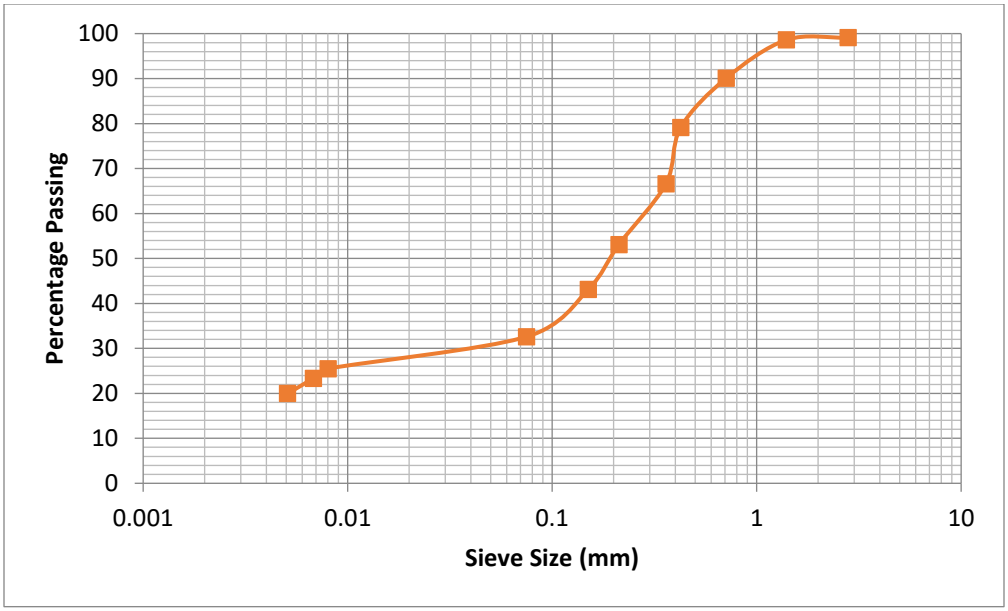


Figure 1: Particle size distribution curves for the bio-remediated soil.

4.2 Effect of *Bacillus pumilus* on Bio-remediated Soil

4.2.1 Atterberg Limits

The variation of Atterberg limits with Bacillus pumilus suspension density is shown in Fig. 2.

4.2.2 Liquid limit

The liquid limit (LL) of the bioremediated crude oil-contaminated soil initially decreased from 43.8 % to 41.1 % at *B. pumilus* suspension density of 1.5×10^8 cells/ml due to low microbial activity. It then increased to 46.0 % at 2.4×10^9 cells/ml, possibly due to calcite formation from microbial reaction with the cementation reagent. The calcite may have coated soil particles, enhancing surface charge and water absorption. This result agrees with the findings reported by Habib-ur-Rahman (2007) as well as Musa and Ijimdiya (2017) that as the specific surface increases, more water molecule are attracted thus, liquid limit increased (Osinubi *et al.,* 2019, Mohammad *et al.,2025*).

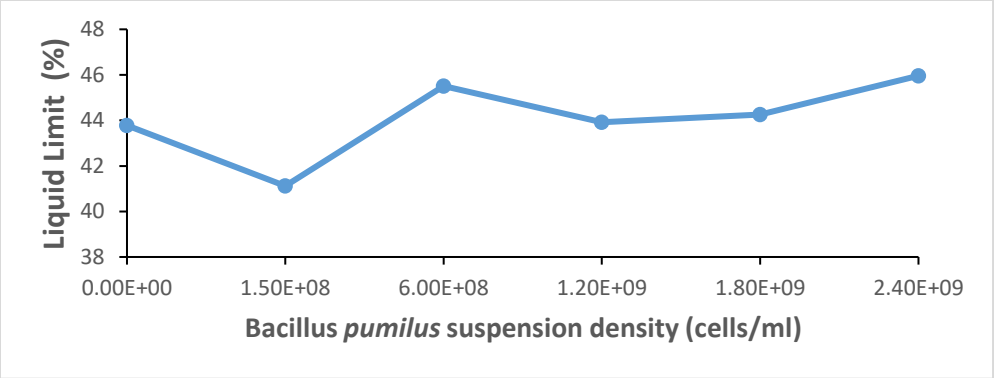


Figure 2: Variation of Atterberg limits of bio-remediated crude oil contaminated soil with B. *pumilus* suspension density

4.2.3 Plastic limit

It was observed that the plastic limit initially decreased from 35.7 to 32.7 % at B. *pumilus* suspension density of 1.5 x 10^8 cells/ml. At 1.8 x 10^9 cells/ml, the PL value increased to the peak value of 37.5 %. The reason for the initial decrease in PL value may be due to the presence of deposited calcite within the soil pores and the observed increase may be due to the microbial urease hydrolysis of the urea that formed dissolved ammonium, inorganic carbon dioxide which led to accumulation of calcium trioxocarbonate (IV). The results are similar to the findings reported by (Ijimdiya and Musa, 2017; Osinubi *et al.,* 2019, Mohammad *et al.,2025*).

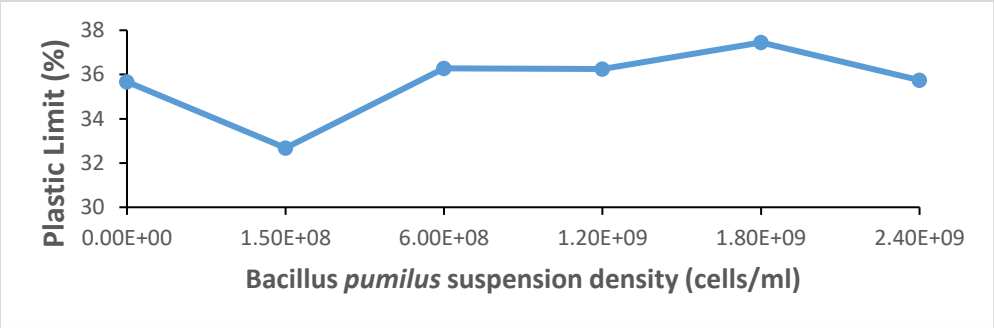


Figure 3: Variation of plastic limit of bio-remediated crude oil contaminated soil with Bacillus *pumilus* suspension density

4.2.4 Plasticity index

The PI value initially decreased to a minimum value of 7.1 % at 1.5 x 10^8 cells/ml before increasing to 7.4 % at 1.8 x 10^9 cells/ml and thereafter decreased to 7.2 % at B. *pumilus* suspension

density of 2.4 x 10^9 cells/ml. The reason for the increase is probably due to the agglomeration of the soil particle by the calcite formed, while the decrease could have been due to unavailable nutrient for the microbial flora as reported by Yengejeh *et al*. (2014), Ijimdiya and Musa (2017), and Eberemu *et al*. (2021).

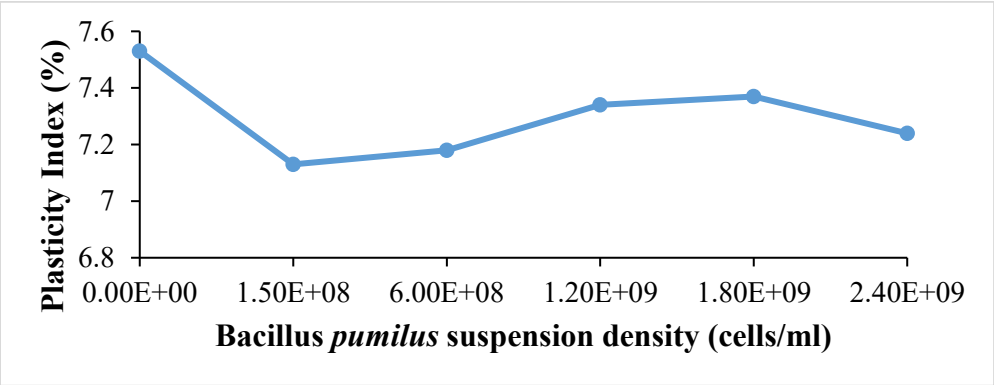


Figure 4.: Variation of plasticity index of bio-remediated crude oil contaminated soil with Bacillus *pumilus* suspension density

4.3 Unconfined Compressive Strength

The variation of UCS with *B. pumilus* concentration for bioremediated soil (50 % B – 50 %C mix ratio) compacted with BSL, WAS, and BSH energies is shown in Figure 3. UCS increased from 169.1, 211.1, and 327.24 kN/m² to peak values of 225.4, 264.4, and 385.1 kN/m² at *B. pumilus* densities of 2.4 × 10^9, 1.8 × 10^9, and 6.0 × 10^8 cells/ml, respectively. The increase is attributed to calcite deposition from microbial activity, while subsequent decreases may result from nutrient limitations at higher bacterial concentrations as reported by DeJong *et al*. (2010), Ijimdiya and Musa (2017) and Osinubi *et al.* (2019a).

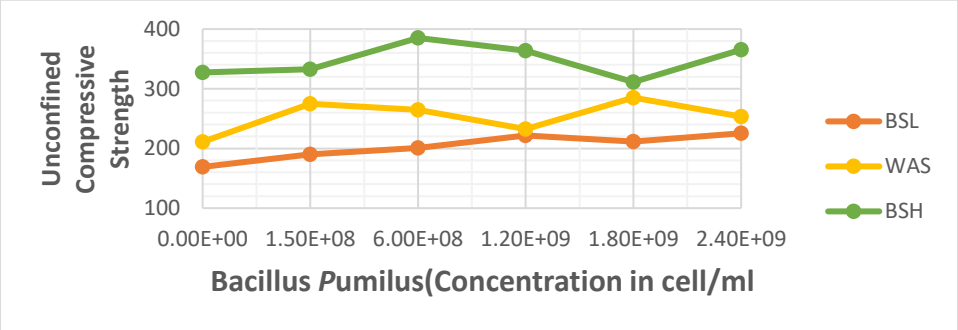


Fig. 3: Variation of unconfined compressive strength of bio-remediated crude oil contaminated soil with B. *pumilus* suspension density

4.4 Micro-analysis

The micrographs of untreated crude oil-contaminated soil and bio-cemented sample treated with *Bacillus pumilus* at 2.4 × 10^9 cells/ml using a 50 % B – 50 % C mix ratio compacted using BSL energy are depicted on Plate I. The untreated soil (Plate Ia) exhibits a relatively smooth surface with fissures and irregular crystal formations, indicating weak particle bonding. In contrast, the bio-cemented sample (Plate Ib) reveals a rougher texture with visible bonding within the soil matrix and the presence of whitish calcite patches, indicative of successful microbial-induced calcite precipitation (MICP). The calcite crystals are observed at grain contacts and along particle surfaces, bridging pore spaces and enhancing soil structure, consistent with findings by Kanyi (2017) and Osinubi *et al*. (2019).

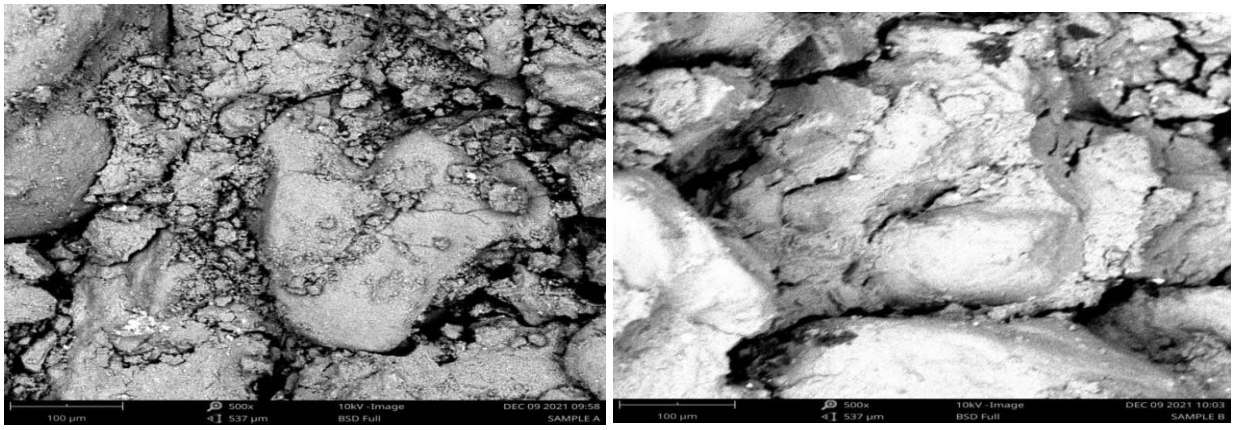


Plate I: Micrograph of the crude oil ontaminated soil at x1500 magnification: (a) 0 cells/ml (b) Treatment with B. *pumilus* concentration of 2.4 x 10^9 cells/ml

5.0 CONCLUSION

The bio-remediated soil was classified as A-2-5(0) according to AASHTO (1986) and as SM under the Unified Soil Classification System (ASTM, 1992). Specimens were prepared at optimum moisture content using *Bacillus pumilus* at stepped suspension density of 0, 1.5 × 10^8, 6.0 × 10^8, 1.2 × 10^9, 1.8 × 10^9, and 2.4 × 10^9 cells/ml were compacted using British Standard light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) energies. The bio-cementation using *B. pumilus* (1.5 × 10^8 to 2.4 × 10^9 cells/ml) with cementation solutions under gravity infiltration on the post-remediate soils showed slight improvements as the liquid limit reduced from 43.8 % to 41.1 %, plastic limit increased from 36.3 % to 37.5 %, and the

plasticity index increased from 7.3 % to 7.4 %. The unconfined compressive strength (UCS) improved with increasing *B. pumilus* concentration. Soil samples treated with 2.4×10^9 cells/ml recorded UCS values that exceeded the minimum UCS design requirement of 200 kN/m², supporting their suitability for use as cover and liner materials in waste containment applications.

1. Data Availability statement

The datasets generated during and/or analysed during the current study are not publicly available due [REASON(S) WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.].

2. We kindly request you to address the following sections has "Not Applicable"

a.) Ethics Not Applicable

b.) Consent to Participate Not Applicable

c.) Consent to publish Not Applicable

REFERENCES

AASHTO (1986). *Standard Specifications for Transport Materials and Methods of Sampling and Testing.* 14th Edition, American Association of State Highway and Transport Officials (AASHTO), Washington, D.C.

Alazigha, D., Indraratna, B., Vinod, J. S. and Ezeajugh, L. (2016). "The swelling behaviour of lignosulfonate-treated expansive soil." *Proceedings of the Institution of Civil Engineers* - Ground Improvement; Volume 169(3): pp.182-193.

Al-Qabany. A., Mortensen, B., Martinez, B., Soga, K., and DeJong, J. T. (2011). Carbonate Precipitation Correlation of S-Wave Velocity with Calcite Precipitation. *Pro. Geo-Frontiers 2011*: *Advances in Geotechnical Engineering, Dallas Texas, ASCE Geotechnical Special Publication* 211, 3993-400.

ASTM (1992). *Annual Book of Standards* Volume. 04.08, American Society for Testing and Materials, Philadelphia.

Bartram, J. (2003) *Heterotrophic plate counts and drinking-water safety: the significance of HPCs for water quality and human health*. WHO Emerging Issues in Water and Infectious Disease Series. London, IWA Publishing.

Begum, K, Mannan, J. S., Rahman, M. M., Rezwan, R., Rahaman, Md. M., Rahaman, Md. S. and Nur-E-Kamal, A. (2017). "Isolation and Characterization of Bacteria with Biochemical and Pharmacological Importance from Soil Samples of Dhaka City, Dhaka University." *Journal. Pharmacy. Science*. 16(1): 129-136.

BS 1377 (1990). *Method of Testing for Soils for Civil Engineering Purposes.* British Standard Institution, BSI, London.

BS 1924 (1990). *Method of Test for Stabilized Soils*. British Standard Institution, BSI, London.

Cappuccino, J. G. and Sherman, N. (2002). *Microbiology. A laboratory Manual*. 6th edition. Pearson education inc. San Francisco, California.215-224.

Caldose, R. Pines, I., Duarte, S. D. and Monteiro, G.A (2018). "Effects of clays chemical interactions on biocementation." *Applied Clay Science*, 156: 8-103.

Chi L, De Y, Shihui, L., Tuanjie, Z., Siriguleng, B, Yu, G., and Lin, L. (2017). « Improvement of geomechanical properties of bio-remediated Aeolian sand." *Geomicrobiology Journal,* DOI: 10.1080/01490451.2017.1338798.

Choi, S. G., Wang, K., Chu, J. (2016). "Properties of biocemented, fiber reinforced sand." *Journal of Construction and Building Materials* 120:623–629.

DeJong, J. T., Mortensen, B. M., Martinez, B. C., and Nelson, D.C. (2010). "Bio-mediated soil improvement." *Ecological Engineering,* 36(2):197 – 210.

Delgado-Baquerizo M., Oliverio A. M., Brewer T. E., González A. B., Eldridge D. J., Bardgett R. D., Maestre F. T., Singh B. K., and Noah F. (2018). "A global atlas of the dominant bacteria found in soil." *Science.* 359 :320–325. DOI: 10.1126/science. aap9516.

Dhami., N. K., Mukherjee., A. and Watkin., E. L. J. (2018). "Microbial diversity and mineralogical-mechanical properties of calcitic cave speleothems in natural and in vitro biomineralization conditions." *Frontiers in Microbiology*, 9(40):1-22 doi: 10.3389/fmicb.2018.00040.

Dora, N. (2019). "The role of soil pH in plant nutrition and soil remediation." *Applied and Environmental Soil Science*, Volume. 2019 Article ID 5794869,9 pages. https.//doi.org/10.1155/2019/5794869.

Eberemu, A. O., Bassey, A. B., and Osinubi, K. J. (2021). "Evaluation of the free swell and physio-chemical properties of black cotton soil treated with Bacillus *coagulans" IOP Conference Series: Materials Science and Engineering,* Vol. 1036, *2nd International Conference on Sustainable Infrastructural Development* (ICSID 2020) 27th - 28th July 2020, Ota, Nigeria.

El-Shanshoury, A. E. R., Metwally, M. A. E., Allam, N. G., Hemdan, H. E., & Mohammed, Y. M. (2025). Nano-bioremediation of metal-polluted industrial wastewater using myco-synthesized iron oxide nanoparticles derived from Aspergillus niger *AUMC 16028. Scientific Reports, 15*, 35008.

Ferris, F. G. and Stehmeier, L. G. (1992). "Bacteriogenic mineral plugging." *Journal of Canadian Petroleum Technology,* 36(9); Doi: 10.2118/97-09-07.

Gomez, M. G., Anderson, C. M., and Graddy, C. M. (2017). "Large-scale comparison of bioaugmentation and biostimulation approaches for biocementation of sands." *Journal Geotechnical Geoenvironment Engineering,* 143(5):04016124.

Habib-ur-Rehman, Sahel, N. A. and Akram, T. (2007). "Geotechnical behavior of oil-contaminated fine-grained soils." *Journals of Geotechnical Engineering,* (7) B

Horpibulsuk, S., Hoy, M., Witchayaphong, P., Rachan, R., and Aruliajah, A.(2017). "Recycled asphalt pavement – fly ash geopolymer as a sustainable stabilized pavement material." *INCITE Conference in Material Science and Engineering,* 273: 1-11.

Ijimdiya, T. S. and Musa, A. K. (2017). "Hydraulic conductivity behaviuor of crude oil contaminated soil bioremediated using chicken droppings for use in waste containment systems." *Journal of the Nigerian Society of engineers, Technical Transactions*. April June, 51(2): 19-30.

Ijimdiya, T. S., Alhassan, M. K., and Singh, R. M. (2022). "Hydraulic conductivity behaviour of compacted crude oil contaminated soil treated with Bacillus licheniformis for use as liner material in waste containment system." *Taraba Journal Of Engineering And*

Technology (TAJET), Faculty of Engineering, Taraba State University, Jalingo. Volume 2 issue 2.

Kanyi, M. I. (2017). *Cement Stabilization of Lateritic Soil Using Iron Ore Tailing as Admixture*. A Thesis Submitted to the Postgraduate School, Ahmadu Bello University, Zaria.

Kim, G. and Youn, H. (2016). "Microbially induced calcite precipitation employing environmental isolates." *Materials*, 9(6):.468; Doi:10.3390/ma9060468.

Kour, D., Kaur, T., Devi, R., Yadav, A., Singh, M., and Joshi, D. (2021). "Beneficial microbiomes for bioremediation of diverse contaminated environments for environmental sustainability: Present status and future challenge." *Environment, Science and Pollution Research,* 28,24917–24939.

Krzmarzick, M. J., Taylor, D. K., Fu, X. and McCutchan, A. L. (2018). "Diversity and niche of archaea in bioremediation." *Archaea2018*, 2018,3194108.

Ma L, Pang A, Luo Y, Lu X. and Lin F. (2020). "Beneficial factors for biomineralization by ureolytic bacterium Sporosarcina pasteurii". *Microbial Cell Factories,* 19 (1): 1-12

Mohammad, S. J., Ling, Y. E., Halim, K. A., and others. (2025). Heavy metal pollution and transformation in soil: A comprehensive review of natural bioremediation strategies. *Journal of Umm Al-Qura University for Applied Sciences, 11*, 528–544.

Olorunfemi O. Babalola, O. O., Adetunji, C. O., Aruwa, C. E., Manjia, J. N., & Muftaudeen, T. K. (2024). A review on bioremediation by microbial immobilization — an effective alternative for wastewater treatment. *AIMS Environmental Science, 11*(6), 918-939.

Osinubi, K. J., Eberemu, A. O., Ijimdiya, S. T., Yakubu, S. E. and Sani, J. E. (2017). "Potential use of B. *pumilus* in microbial induced calcite precipitation improvement of lateritic soil." *Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2*), Leeds, United Kingdom, 6th – 8th September. Session: Clean-ups, Paper 64, 1 – 6.

Osinubi, K. J., Sani, J. E., Eberemu, A. O., Ijimdiya, T. S., Yakubu, S. E., (2018c). "Unconfined compressive strength of Bacillus pumilus treated lateritic soil." *Proceedings of the 8thInternational Congress on Environmental Geotechnics*, 3:410 – 418.

Osinubi, K. J., Gadzama, E. W., Eberemu, A. O., Ijimdiya, T. S. and Yakubu, S. E.(2019a).''Evaluation of the strength of compacted lateritic soil treated with Sporosarcina pasteurii.'' *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 – 1st November, Hangzhou, China, © *Springer* Nature Singapore Pte Ltd., Volume. 3, pp. 419–428, On-line: https://doi.org/10.1007/978-981-13-2227-3_52.

Osinubi, K. J., Sani, J. E., Eberemu, A. O., Ijimdiya, T. S. and Yakubu, S. E. (2019b). ''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 – 1st November, Hangzhou, China, © *Springer Nature* Singapore Pte Ltd., Volume. 3, pp. 410–418, On-line:https://doi.org/10.1007/978-981-13-2227-3_51

Osinubi, K. J., Eberemu, A. O., Ijimdiya, T. S., Yakubu, S. E., Gadzama, E. W., Sani, J. E. and Yohanna, P. (2020a). "Review of the use of microorganisms in geotechnical engineering applications." *SN Applied Sciences*, *Springer. Published online* https://doi.org/10.1007/s42452-020-1974-2.

Osinubi, K. J., Gadzama, E. W., Eberemu, A. O. and Ijimdiya, T. S. (2020b). "Comparative evaluation of strength of compacted lateritic soil improved with microbial-induced calcite precipitate." *Geo-Congress 2020 – Geo-Systems, Sustanability, Geoenvironmental Engineering, and Unsaturated Soil Mechanics*, U. S. A. Edited by James P. Hambleton, Roman Makhnenko and Aaron S. Budge, American Society of Civil Engineers *Geotechnical Special Publication,* GSP No 319, pp. 240 – 248.

Osinubi, K. J., Eberemu, A. O., Ijimdiya, T. S. and Yohanna, P. (2020c). ''Interaction of Landfill Leachate with Compacted Lateritic Soil treated with Bacillus Coagulans using Microbial Induced Calcite Precipitation Approach.'' *Journal of Hazardous, Toxic,*

and Radioactive Waste. ASCE. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000465.

Siles, J. A. and Margesin, R. (2018). « Insights into microbial communities mediating the bioremediation of hydrocarbon-contaminated soil from an Alpine former military site." *Application of Microbiology and Biotechno*logy,102:4409–4421.

Spencer, C. A., Sass, H., and van Paassen, L. (2023). Increased microbially induced calcium carbonate precipitation (MICP) efficiency in multiple treatment sand biocementation processes by augmentation of cementation medium with ammonium chloride. *Geotechnics, 3*(4), 1047-1068.

Stocks-Fischer, S., Galinat, J. K., and Bang, S. S. (1999). "Microbiological precipitation of $CaCO_3$." *Soil Biology and Biochemistry,* 31 (11): 1563–1571.

Varjani, S. J. and Upasani, V. N. (2017). "A new look on factors affecting microbial degradation of petroleum hydrocarbon pollutants." *International Biodeterioration and Biodegradation*, 120: 71–83.

Wilcox, S. M., Mulligan, C. N., and Neculita, C. M. (2024). Microbially induced calcium carbonate precipitation as a bioremediation technique for mining waste. *Toxics, 12*(2), 107.

Wu, M., Hu, X, Zhang, Q., Xue, D., and Zhao, Y. (2019). "Growth environment optimization for inducing bacterial mineralization and its application in concrete healing". *Construction and Building Materials*, 209: 631-643.

Xiao, R., Jiang, G., Chai, W., Jin, Z., Du, R., Khan, M., Liu, Z., Yin, H., and Xu, L. (2025). Microbially induced calcium carbonate precipitation (MICP): Bibliometric analysis, *research hotspot evolution, and mechanistic insights (2005–2024). Water, 17*(23), 3332.

Yasuhara, H. Putra, H. and Kinoshita, N. (2016). "Enzyme-mediated carbonate precipitation (EMCP) for soil improvement the effect of magnesium: substitution." *Advances in Civil Environmental and Material Research* (ACEM16).

Yengejeh, J. R., Sehkatvatjou, M. S., Maktabi, P., Arbab, S. N. and Khadivi, S. (2014). "The Biodegradation of Crude Oil by *Bacillus subtilis* Isolated from Contaminated Soil in Hot Weather Areas." *International Journal of Environmental Resources*, 8(2):509-514

Yu, T., Souli, H,, Péchaud, Y., and Fleureau, J. M. (2020). **"**Optimizing protocols for microbial induced calcite precipitation (MICP) for soil improvement - A review." *European JournalofEnvironmentalandCivilEngineering.*Pp.116doi.org/10.1080/19648189.2020.1755370

1. Kolawole Juwonlo Osinubi
2. Nigeria
3. No funding
4. Fully address in the system
5. Ethics, Consent to participate, and consent to publish declaration: not applicable
6. kosinubi@yahoo.com
7. Nigeria