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EFFECT OF BIO-CEMENTATION ON THE UNCONFINED COMPRESSIVE STRENGTH OF COMPACTED LATERITIC SOIL BIO - TREATED AND UNTREATED CONDITIONS

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Abstract

Obviously, not all available soils found on earth satisfied the requirement for engineering projects. Therefore, enhancement of soil engineering properties is one of the key concerns of a geotechnical engineers. This paper evaluates the unconfined compressive strength characteristics of compacted natural and bio-treated problematic lateritic soil classified as A-2- 6 [2] using the American Association of State Highway and Transportation Officials (AASHTO) classification system and SC using the Unified Soil Classification system (USCS) after upgraded, using microbial induced calcite precipitation (MICP) technique for 7days, 14 days and 28 days curing period respectively. The soil was bio-treated with 0, 1.50 x 10^8, 6.0 x 10^8, 12 x 10^8, 18 x 10^8, 240 x 10^8 cells/ml of Bacillus pumilus (B. pumilus) suspension densities, a non- infective microorganism extracted from the natural lateritic soil, and cultured. The bio-treated soil was compacted using the British Standard Light (BSL), West African Standard (WAS) and British Standard High (BSH) compactive efforts at the moulding water content range of -2 to +4% optimum moisture content (OMC). The trampled soil samples were then infused with a cementitious reagent containing 10 g of NH_4Cl, 20 g of Urea, 2.8 g of $CaCl_2$, 3 g of Nutrient broth and 2.12 g of $NaHCO_3$ per litre of de ionized water that trigger the MICP process in three circles with 2/3rd pore volume. The Atterberg limits results and linear shrinkage showed a better enhancement in the bio-treated than the natural soil. Peak unconfined compressive strength (UCS) values of 2,414 N/m², 3,072 N/m² and 3,143 N/m² were achieved for specimen's bio-treated with 25 % B_p – 75 % C_r,

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50 % B_p – 50 % C_r and 75 % B_p – 25 % C_r mix ratios respectively using 12 x 10^8 cells/ml, when compacted with BSH energy and cured for the three curing periods, respectively. Similarly, a considerable increase in strength was observed when the specimens were bio- treated with 75 % B_p – 25 % C_r mix ratio and cured for 28 days recorded UCS values of 2,897 N/m^2, 3,572 N/m^2 and 3,710 N/m^2 for specimens compacted with BSH energy. The calcite formed binds the soil grains together and then improved the stiffness as well as reduce the soil compressibility.

Introduction

Over decades, several researchers have utilized many soil improvement techniques such as application of cement, glass, lime, bitumen, sand columns, chemical grouting, and sodium silicate grouting etc. to enhance engineering properties of deficient soils for different engineering projects (Ola, 1978; Huat *et al*., 2005; Osinubi, 2019). Nevertheless, most of these soil improvement techniques were found to satisfy their engineering requirements, but have also been reported to be ecologically unfriendly (i.e., noxious and hazardous) to ecosystem (Karol 2003; DeJong *et al*., 2010). This necessitate and compelled Geotechnical engineers in collaboration with microbiologist to introduce a multidiscipline approach using microorganisms known as Microbially - Induced Calcite Precipitate (MICP). This finding has made researchers to viewed soil as an ecosystem in addition to being an engineering material (Choi *et al*., 2020; Wani and Mir, 2020; Mujah *et al*., 2021; Cui *et al*., 2021).

Several researchers such as Gadzama *et al*. (2022; 2024), Osinubi *et al.* (2021; 2024), Eberemu (2021), Cui *et al.* (2021), Yohanna *et al*. (2021) and Gowthaman *et al*. (2021) have conducted numerous experiments using Genus Bacillus microorganism's species suspension densities family (such as Bacillus *Megaterium*, Sporosarcina *pasteurii*, Bacillus *pumilus* etc.) that are isolated from soil to be suitable materials in MICP processes to improve the engineering characteristics of lateritic soil.

The essence of application of microbial – induced calcite precipitate to a soil is for precipitation of calcite to soil matrix which subsequently binds the particles together, and thus enhances the stiffness, shear strength and reduces the permeability of the soils (DeJong *et al*., 2010; Lee *et al*., 2012; Tianzheng *et al*., 2023).

The aim of this work is to assess the unconfined compressive strength of lateritic soil bio- treated with *B. pumilus* in MICP process on the soil to be used for Civil engineering structure.

Lateritic soil

Problematic lateritic soil was collected from a location near Abagana, Njikuka Local Government in Anambra state of Nigeria at a depth not below 3m from the soil surface to avoid organic matter.

Bacteria

The Bacillus *pumilus* (B. *pumilus*), which is classified according to the American Type Culture Collection as ATCC 27142 was used as the bacteria in this research adopted from Osinubi *et al*. (2017); it was also isolated and cultured from the soil specimen.

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Cementation reagent

The liquid media comprises of 20 g of Urea, 3 g of Nutrient Broth, 10 g of Sodium Chloride (NH_4Cl), 2.12 g of Bicarbonate ($NaHCO_3$) for every litre of distilled water (glass) and pH measuring 9.7 which served as a medium to culture the bacteria. Liquid media was sterilised for 20 min by means of autoclaving at a temperature not greater than 125° C. The different molar concentrations of cementation reagents used in this study are 0.25, 0.5, 0.75 and 1.0 M.

Compaction

The soil specimen was compacted using British standard light (BSL), West African Standard (WAS) and British standard height (BSH) in line with British Standard 1377 (1990), Nigerian General Specification (1999) and British Standard 1924 (1990) guide for both the natural and bio-treated soils, respectively.

Culture and growth of Bacillus *pumilus*

The identification of the bacteria described by Cheesbrough (2006) using the conventional procedure was adopted. Bacillus *pumilus* when separated from soil was cultured in a media of Ammonium-Yeast Extract and injected into a media comprising of: 20 g of yeast extract, 10 g NH_4Cl_2, 2 g urea 0.1 g nickel per litre of distilled water and Sodium Hydroxide which regulates pH of the media to 9.0.

Unconfined Compressive Strength of Bio-treated Lateritic Soil

The variation of unconfined compressive strength (UCS) of lateritic soil – cementation reagent mixtures with Bacillus *pumilus* suspension density for different curing periods is shown in Figures 1, 2 and 3. Peak UCS values of 2,454 N/m², 3,112 N/m² and 3,183 N/m² were achieved for specimen's bio-treated with various mix ratios (i.e., 25 % B_p – 75 % C_r, 50 % B_p – 50 % C_r and 75 % B_p – 25 % C_r respectively), using 12 x 10^8 cells/ml, when compacted with BSH energy and cured for 7, 14, and 28 days, respectively.

The general trend of the UCS values indicate increase with increase in B. *pumilus* suspension density, compactive effort, and curing period with the BSH energy producing the highest UCS

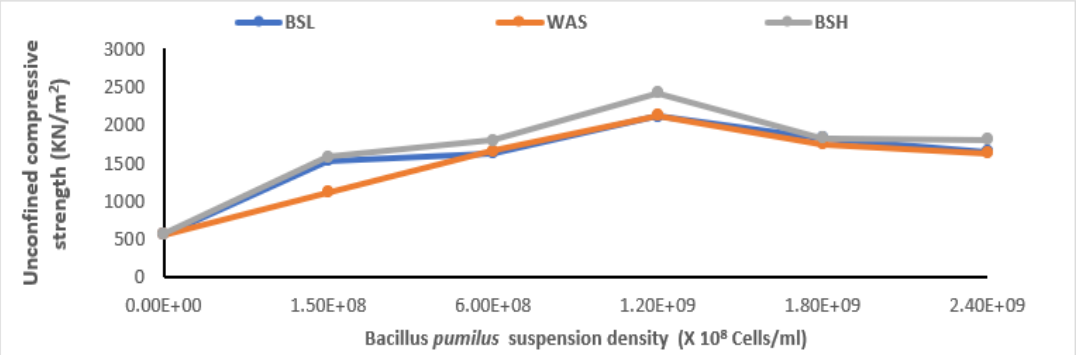

Figure 1: Variation of unconfined compressive strength of lateritic soil – cementation using different mix ratio with Bacillus *pumilus* suspension density for 7 days curing period

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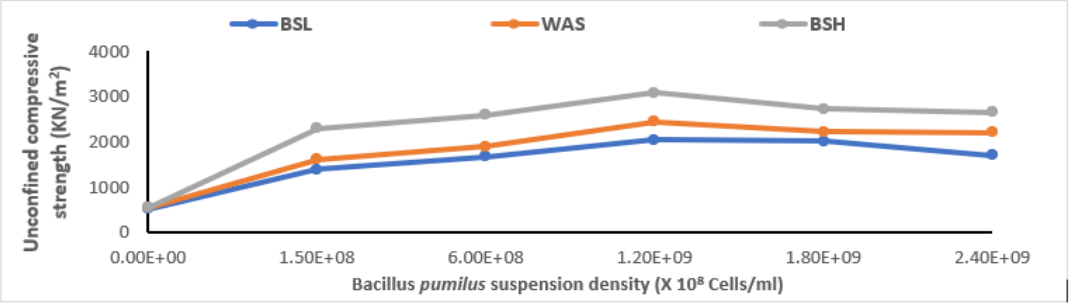

Figure 2: Variation of unconfined compressive strength of lateritic soil – cementation using different mix ratios with Bacillus *pumilus* suspension density for 14 days curing period

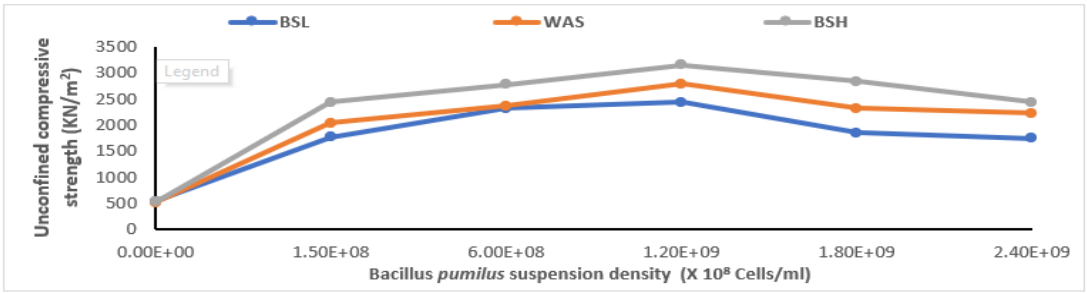

Figure 3: Variation of unconfined compressive strength of lateritic soil – cementation using different mix ratios with Bacillus *pumilus* suspension density for 28 days curing period

values of 2,454 N/m², 3,112 N/m² and 3,183 N/m² for all treatments considered. This outcome is consistent with the findings reported by Cheng and Cord-Ruwisch (2012), Etim *et al*. (2025a, b), Yohanna *et al*. (2022) as well as Fu *et al*. 2023).

Effect of B. *pumilus*

The variation of unconfined compressive strength (UCS) of lateritic soil with B. *pumilus* suspension density when compacted with BSL, WAS and BSH energy and cured for 7, 14, and 28 days is shown in Figure 4, 5 and 6. Peak UCS value of 3,143 N/m² was obtained at B. *pumilus* suspension density of 12 x 10^8 cells/m – 0.75 M cementation reagent concentration for samples compacted with BSH energy and cured for 28 days (Figure 3.2C).

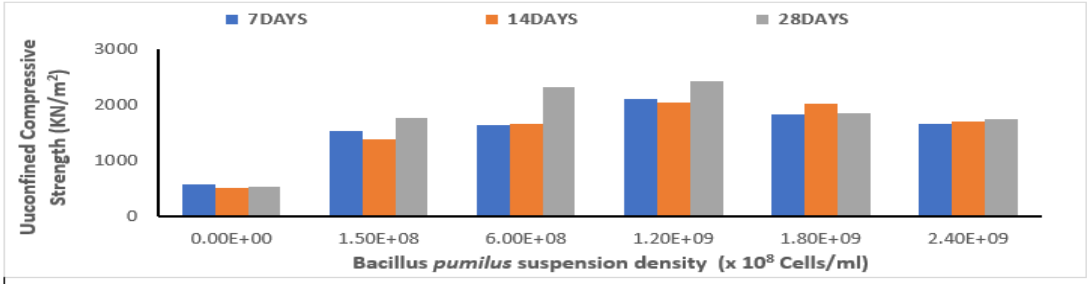

Figure 4: Variation of unconfined compressive strength of lateritic soil with Bacillus *pumilus* suspension density for BSL compactive effort

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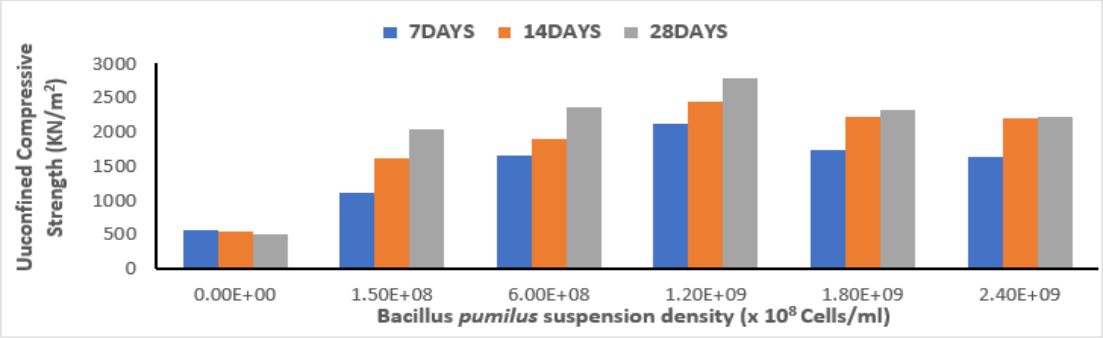

Figure 5: Variation of unconfined compressive strength of lateritic soil with Bacillus *pumilus* suspension density for WAS compactive effort

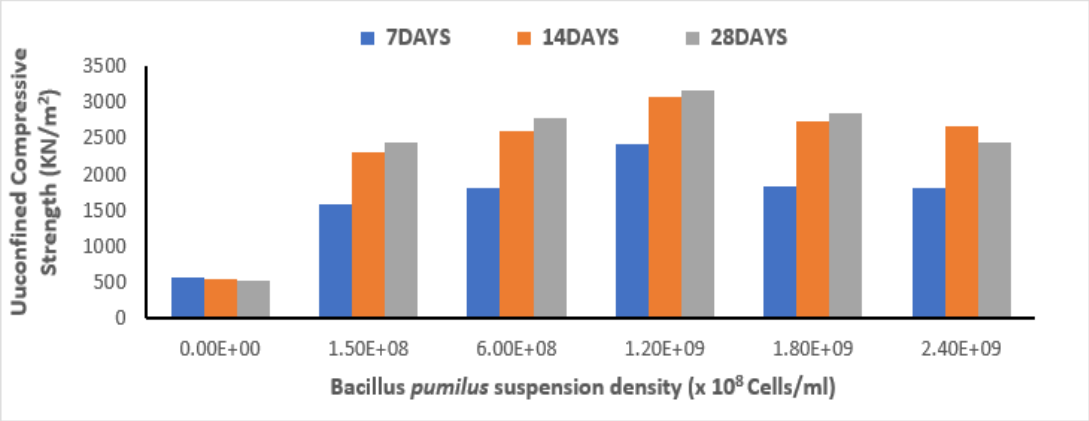

Figure 6: Variation of unconfined compressive strength of lateritic soil with Bacillus *pumilus* suspension density for BSH compactive effort

The observed trend was as a result of soil voids that was clogged with calcite which eventually increased the specimens' UCS values and ultimately increase resistance to erosion.
This outcome concurs with the research findings reported by Cheng and Cord-Ruwisch (2012), Sani *et al* (2020).

Effect of curing period

The variation of unconfined compressive strength (UCS) of lateritic soil prepared with different mix ratios with curing period is shown in Figure 7, 8 and 9. A considerable increase in strength was observed when the specimens were bio- treated with 75 % B_p – 25 % C_r mix ratio and cured for 28 days. Peak UCS values of 2,897 N/m², 3,572 N/m² and 3,730 N/m² were recorded for specimens compacted with BSH energy. The observed trend may have been caused by the calcite formed which was responsible for bridging the soil particles and clogging the voids in

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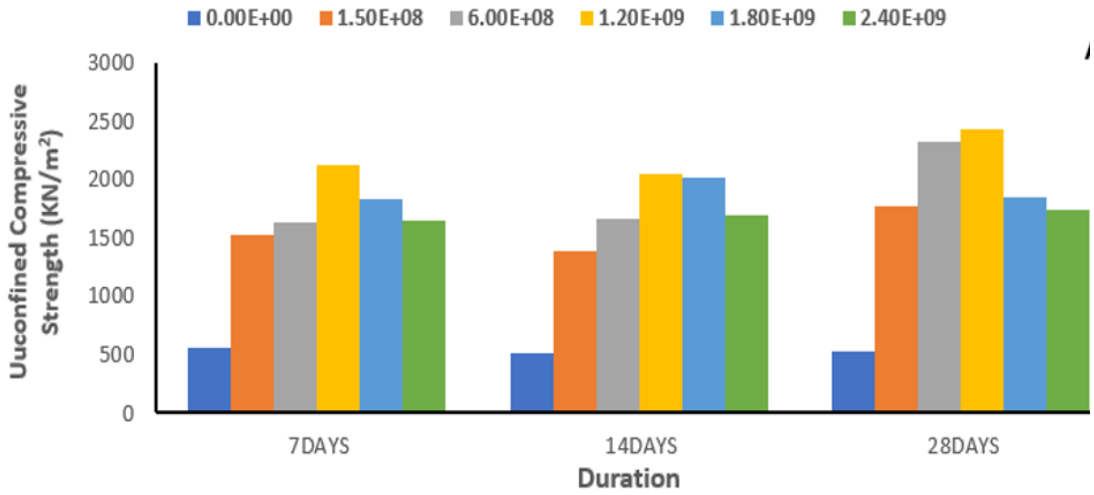

Figure 7: Variation of unconfined compressive strength of lateritic soil – B. *pumilus* mixtures prepared using different mix ratios with curing period for BSL compaction energy

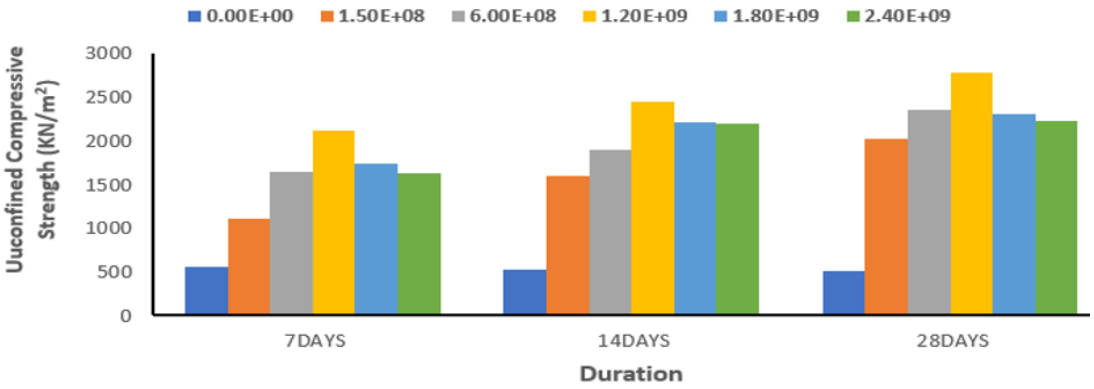

Figure 8: Variation of unconfined compressive strength of lateritic soil – B. *pumilus* mixtures prepared using different mix ratios with curing period for WAS compaction energy

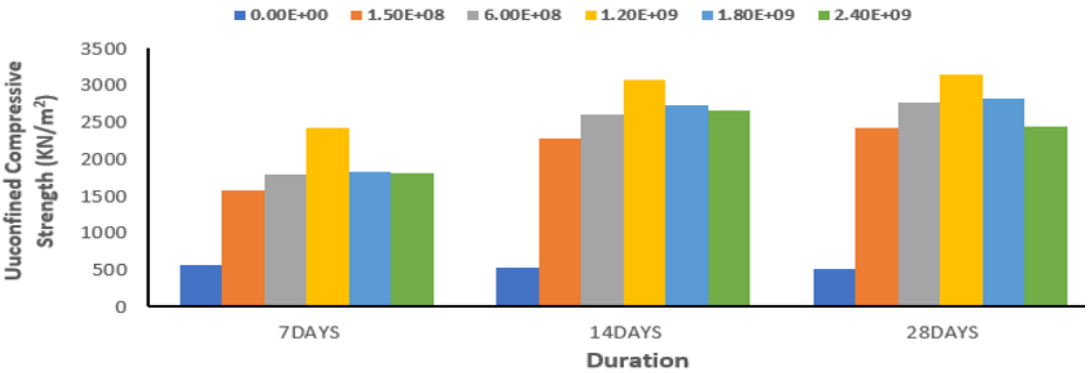

Figure 9: Variation of unconfined compressive strength of lateritic soil- B. *pumilus* mixtures prepared using different mix ratios with curing period for BSH compaction energy the specimen.

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These results are consistent with the findings published by Cheng *et al*. (2013), Sani *et al*. (2020), Ying *et al*. (2021) and Wang *et al*. (2024).

Effect of compactive effort

The variation of unconfined compressive strength (UCS) of lateritic soil prepared different mix ratios (i.e., 25 % B_p – 75 % C_r, 50 % B_p – 50 % C_r and 75 % B_p – 25 % C_r) results for 7, 14 and 28 days respectively, is shown in Figure 3.4A - C. Peak UCS values of 2,471 N/m^2, 2,816 N/m^2 and 3,183 N/m^2 were obtained for specimens compacted with BSH energy at 12 x 10^8 cells/ml – 0.75 M.

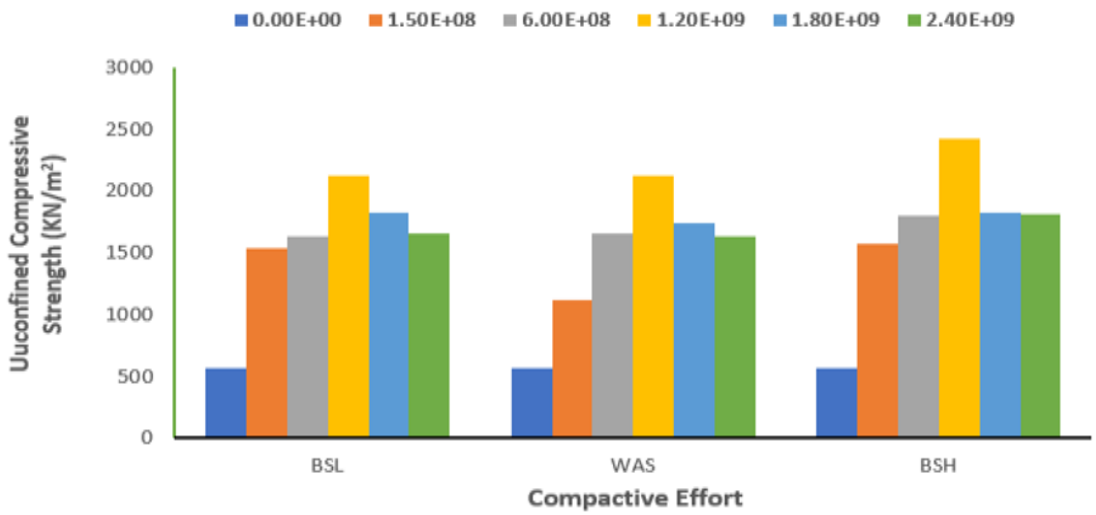

Figure 10: Variation of unconfined compressive strength of lateritic soil – B. *pumilus* mixtures prepared using different mix ratios with compactive effort for 7 days curing period

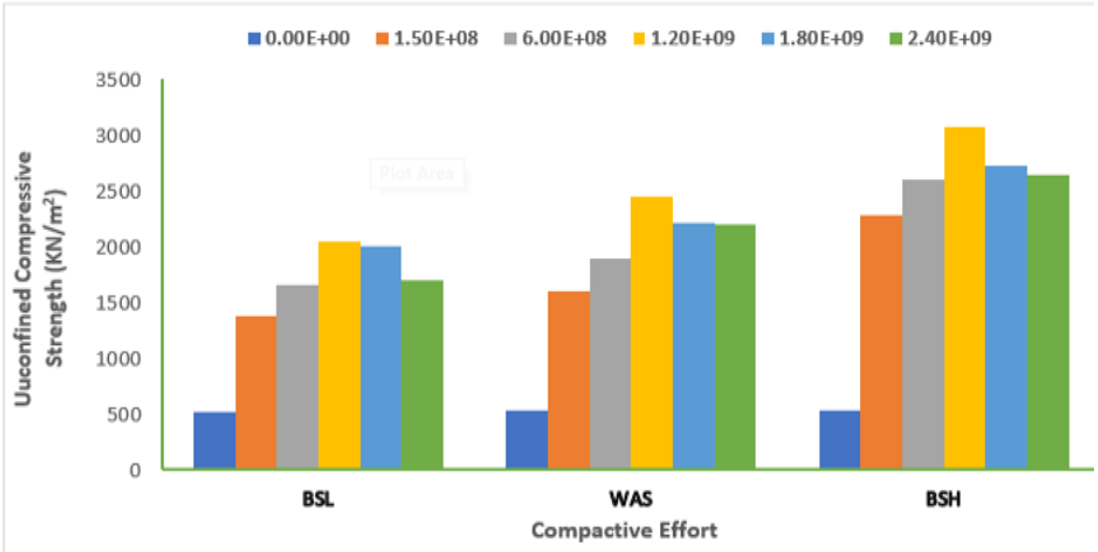

Figure 11: Variation of unconfined compressive strength of lateritic soil – B. *pumilus* mixtures prepared using different mix ratios with compactive effort for 14 days curing period

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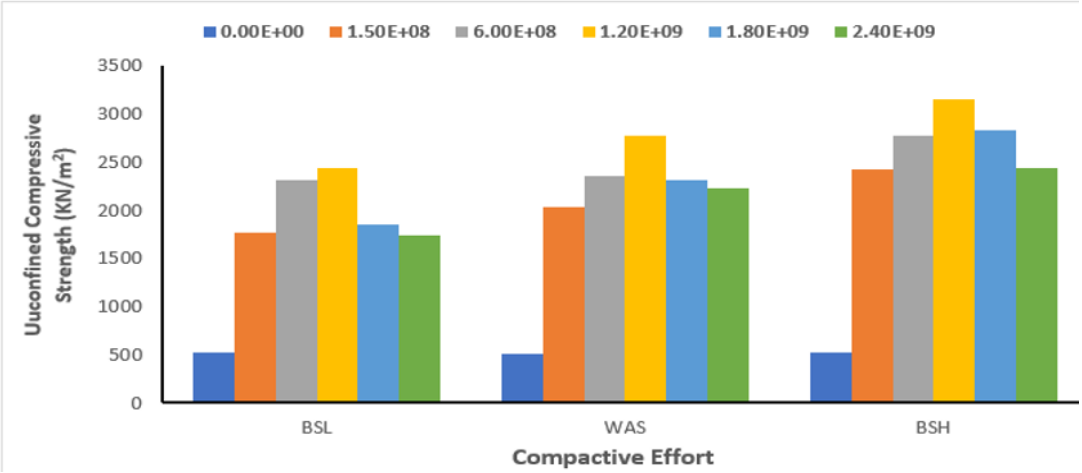

Figure 12: Variation of unconfined compressive strength of lateritic soil–B. *pumilus* mixtures prepared using different mix ratios with compactive effort for 28 days curing period

The general trend of UCS values indicate the expected increases with increase in compactive effort, with the BSH compactive effort producing the highest UCS for all treatments considered. The increase in strength can be attributed to the reaction of the 75 % B_p – 25 % C causing the fines in the soil to bind and form coarser particles with larger surface areas and to be firmly bonded. This shows an enhancement due to the presence of calcite produced from the MICP process. The calcite formed tends to bind the soil grains together and then improved the stiffness as well as reduce the soil compressibility. This result agrees with the findings reported by Cheng and Cord-Ruwisch (2012), Sani *et al*. (2020) as well as Yusuf *et al*. (2025).

Conclusion

The suitability of the shear strength of lateritic soil bio-treated with Bacillus *pumilus* for usage in Civil engineering project was assessed by laboratory testing. BSL, WAS and BSH energies (or standard Proctor) was used to compact specimens prepared at molding water contents –2, 0, +2, and –4% of the OMC. Specimens of lateritic soil – Bacillus *pumilus* suspension density mixtures produced satisfactory Unconfined Compressive Strength (UCS) values for all the treatments and all the moulding water contents considered. With a peak value of 1884.58 kN/m² at a Bacillus *pumilus* suspension density of 18.0 × 10^8 cells/ml and 4% molding water content in comparison to OMC, Bacillus *pumilus* improved the strength of the natural lateritic

Based on the results recorded the following inferences can be made:

1. Specimens of lateritic soil treated with different mix ratios of B. *pumilus* suspension density of 120 x 10^8 cells/ml – cementation reagent using 25% B*p* – 75% Cr, 50% B*p* – 50% Cr and 75% B*p* – 25% Cr mix ratio gave peak UCS values of 2, 454 kN/m², 3,112 kN/m² and 3,184 kN/m², respectively, when specimens were compacted with BSH energy.
2. The variation of unconfined compressive strength (UCS) of lateritic soil with B. *pumilus* suspension density when compacted with BSL, WAS and BSH energy and cured for 7, 14, and 28 days yielded Peak UCS value of 3,183 N/m² at B. *pumilus*

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suspension density of 12 x 10^8 cells/m – 0.75 M cementation reagent concentration for samples compacted with BSH energy and cured for 28 days.

3. A considerable increase in strength was observed when the specimens were bio-treated with 75 % B_p – 25 % C_r mix ratio and cured for 28 days recorded UCS values of 2,897 N/m^2, 3,572 N/m^2 and 3,710 N/m^2 for specimens compacted with BSH energy.
4. Peak UCS values of 2,471 N/m^2, 2,816 N/m^2 and 3,183 N/m^2 were obtained for specimens compacted with BSH energy at 12 x 10^8 cells/ml – 0.75 M.

Recommendation

Based on the results obtained, it is recommended that:

The natural lateritic soil considered in this study which was classified as A-2-6 (2) or CL soil bio-treated with 75% Bp – 25% Cr mix ratio using B. *pumilus* suspension density of 12 x 10^8 cells/ml and compacted with at least BSL energy to improve its unconfined compressive strength (shear strength, stiffness) and reduce its hydraulic conductivity.

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