



Microbial Induced Modification of Silty Soil Using *Bacillus Coagulans* for Building Foundation

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ABSTRACT

This research was carried out to modify the properties of silty soil with *Bacillus. coagulans* (*B. coagulans*) to make them fit to be used as building foundation. This was achieved using the microbial induced calcite precipitate process by treating the silty soil with *B. coagulans* with suspensions densities of 0 /ml, 1.5×10^8 /ml, 6.0×10^8 /ml, 12×10^8 /ml, 18×10^8 /ml and 24×10^8 /ml at British Standard Light (BSL) compaction energy. The index properties of the soil, compaction characteristic (optimum moisture content (OMC) and maximum dry density (MDD)), shear strength parameters (cohesion and angle of internal friction) and the bearing capacity of the silty soil were determined. The MDD shows an increase in value up to 6.0×10^8 cells/ml of *B. coagulans* suspension density before it drops slightly while the OMC on the other hand shows a decreasing trend with increase in *B. coagulans* suspension density up to 6.0×10^8 cells/ml before increasing slightly. The shear strength parameter which is a key parameters that influence the strength of foundation shows a decrease in value of cohesion with increase in *B. coagulans* suspension density while the angle of internal friction shows an increase in value with increase in *B. coagulans* suspension density. The results of the shear strength parameters when used in Terzaghi's equation for four types of foundation shows a great increase in the bearing capacity of the silty soil which shows a great improvement. The bearing capacity for square footing that gave the highest value increased from 977.98 to 1286.91 KN/m² which is over 31.59% increase in strength which indicate improvement on the silty soil for building foundation. 18.0×10^8 cells/ml of *B. coagulans* suspension density is recommended for modification of soil for building foundation.

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INTRODUCTION

Soil is one of the most important backbones of geotechnical engineering; it serves as a base on which all geotechnical structures depend for their stability. When soil is weak or its natural properties are not up to standard required, the soil needs modification for it to be suitable for geotechnical engineering purposes. Modification of soil is used to prevent the occurrence of landslide and liquefaction in weak soil which usually leads to foundation

deformation and/or failure (Alvarado, 2009). Modification of soil can be chemical or biological modification.

Modification of soil using chemicals involves the use of chemical such as cement, fly ash, bagasse ash etc while biological modification involves the use of microorganism (bacteria) such as *Sporosarcina pasteurii*, *Bacillus coagulans*, *Bacillus pumillus* etc to modify or improve the soil through the influence of calcium carbonate (calcite) precipitate, triggered by the

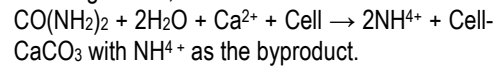


microorganism (bacteria) and this process is termed microbial induced calcite precipitate (MICP) (Osinubi *et al.*, 2019a; Osinubi *et al.*, 2019b; Osinubi *et al.*, 2019c; Osinubi *et al.*, 2020 and Sani *et al.*, 2020a and b).

In microbial induced calcite precipitation (MICP), calcites are the required material responsible for upgrading the soil properties. MICP can take place whenever metabolic stages of microorganisms result in alteration of the surrounding aqueous phase, which lead in the formation of calcite. (Phillips *et al.*, 2013). One of the ways in which this may be done is through the attachment of the microorganisms in the porous subsurface environment. MICP is a byproduct of collective metabolic activities by microbes through any of the following processes: photosynthesis, urea hydrolysis, sulfate reduction, denitrification (nitrate reduction), methane oxidation, or ammonification, which leads to an increase in the saturation of calcium carbonate (Castro-Alonso *et al.*, 2019). From the various stages through which calcite is formed as stated above, studies reported by Zhu and Dittrich (2006) have shown that urea hydrolysis is the most advance technology in use. According to Mujah *et al.*, 2017 ureolysis is the most preferred by researchers because it is easy and more straightforward for the precipitation of calcite (CaCO₃) and 90% of chemical conversion efficiency of calcite can be achieved in less than 24 hours, followed by photosynthesis. According to Zhu and Dittrich (2006) sulfate reduction is another MICP process that is widely studied, although its engineering advantage is commonly given less priority.

The different reactions and byproducts generated in the formation of calcite using the various MICP processes stated above are as follows:

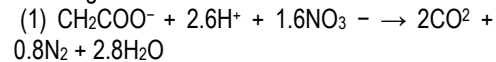
1. Urea hydrolysis (ureolysis) using ureolytic bacteria in the presence of urease-positive microorganisms, this reaction occurs:



2. Photosynthesis using cyano bacteria algae
 $2\text{HCO}_3^- + \text{Ca}^{2+} \rightarrow \text{CH}_2\text{O} + \text{CaCO}_3 + \text{O}_2$ with O₂ as the byproduct.

3. Sulfate reduction using sulfate-reducing bacteria
 $\text{SO}_4^{2-} + 2[\text{CH}_2\text{O}] + \text{OH}^- + \text{Ca}^{2+} \rightarrow \text{CaCO}_3 + \text{CO}_2 + 2\text{H}_2\text{O} + \text{HS}^-$ with CO₂ and HS⁻ as the byproducts.

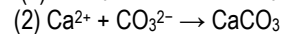
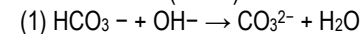
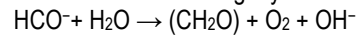
4. Denitrification (nitrate reduction) using nitrate-reducing bacteria



When the reaction is complete, with CO₂ + N as byproducts;

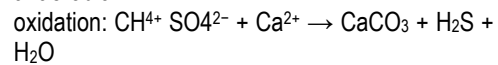
(2) $\text{Ca}^{2+} + \text{CO}_2(\text{aq}) + 2\text{OH}^- \rightarrow \text{CaCO}_3(\text{s}) + \text{H}_2\text{O}$ when the reaction is incomplete, with NO and N₂O as byproducts.

5. Ammonification using myxobacteria



(3) With NH₃ as the byproduct.

6. Methane oxidation using methanogens anaerobic



Aerobic oxidation: $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$, with H₂S being the by products for both the anaerobic and aerobic reactions (Osinubi, *et al.*, 2020).

Fig.1 below shows bacterial metabolism and subsequent CaCO₃ precipitation under high pH and high Ca²⁺ extracellular condition

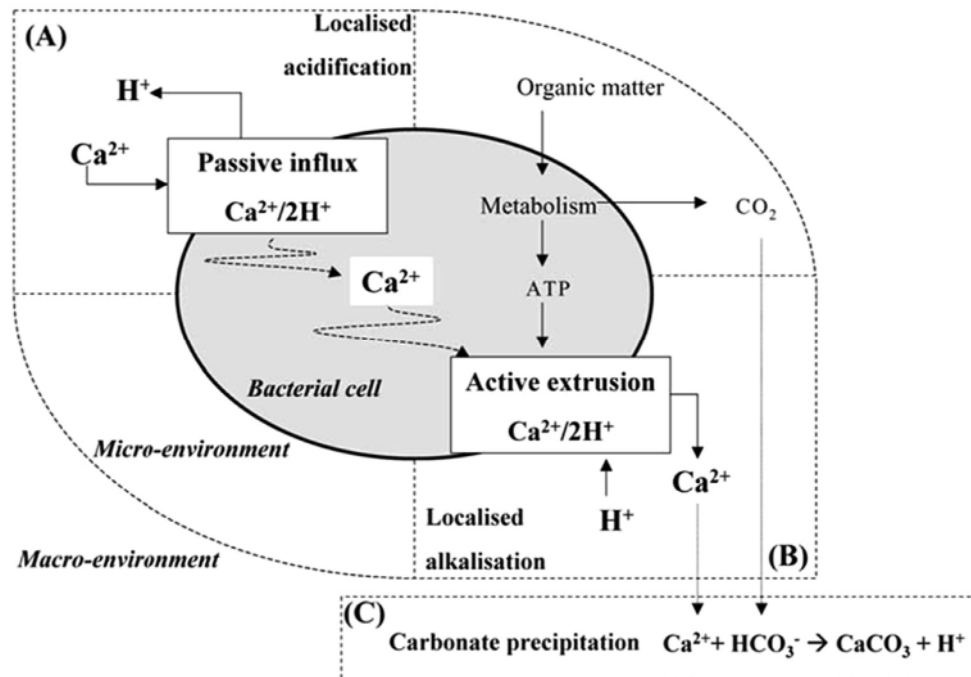


Fig. 1: Schematic diagram of bacterial metabolism and subsequent CaCO_3 precipitation under high pH and high Ca^{2+} extracellular conditions (Hammes and Verstraete, 2002)

According to Cheng *et al.*, (2013) particle size distribution, shape, mineralogy, density and texture of the mineral aggregates affect the cementation process in bio-mediated treatment process. However, excellent results is achieved by this technique in preventing leakages in water retaining structures and decreasing the permeability of some soils by means of bioclogging has led to a lot of interesting researches and applications of bio sealing in a lot of civil engineering works (Whiffin, et al., 2007). According to Kucharski *et al.*, (2006), the use of microorganisms to improve the strength of granular soil which is referred to as bio cementation started in Australia in 2001. The technique was widely accepted by civil engineers after a bag of sand was turned into columns of calcareous sandstone when treated by Australian research group.

Silty soils highly absorbed water which shows it is moisture sensitive and their stability is govern considerably by the degree of densification achieved during compaction. Silty soils are often hydrophobic and difficult to cost-

effectively moisture condition during compaction. Deformation of wet silt subgrade is problematic during pavements' constructions as well as under regular vehicular traffic loads. (Mohammad, *et al.*, 2013).

Silt particles are intermediate in size and chemical and physical properties lies between clay and sand. Silt particles have low capacity to retain plant nutrients, or to allow the soil solution for plant uptake. Silt particles tends to be spherical in shape, which give a high silt soil a soapy or slippery feeling when rubbed between the fingers. When wet is more difficult to form into a string than clays. Because of the spherical shape, silt also retains a large amount of water, but it releases the water readily to plants. Silt soils are generally considered very fertile for the growth of plants, due to their water properties and ease of cultivation, engineers don't like working with silt soil due to their relatively easy release of water and lack of ability for the particles to stick together (Sheard, 1993).

Silt particles are mostly found in semi-arid zones referred to as a granular material of a



size between sand and clay, which mineral origin is feldspar (Assallay, 1998) and quartz. Silt behaves differently from clay and sand. Silt may be a soil (often mixed with sand or clay) or as sediment mixed in suspension with water and in a body of water such as a river. It can also exist as soil deposited at the base of water bodies, like mudflows from landslides. Silty soil mostly has floury feel when it is dry, and a slippery feel when wet. Sandy silt in particular will tends to dilate and decrease in pore pressure due to increase in strain during shear. (Brandon *et al.*, 2006; Mohammad *et al.* 2013). Cohesion between silt particles is almost zero and most of their shear strength values are dependent on the internal friction. This study will center it focus on microorganism induced modification of silty soil using *bacillus coagulans* for building foundation. This will be achieved by determine the index properties of natural and *bacillus coagulans* induced calcite precipitation, determine the compaction characteristic of natural and *bacillus coagulans* induced calcite precipitation and determine the shear strength parameters of natural and *bacillus coagulans* induced calcite precipitation

2. MATERIALS AND METHODS

Soil

Silty sandy soil sample to be used for this research will be obtained from Wudil Local Government Area (latitude 11° 786N and longitude 8° 840E) in Kano State, Nigeria.

Microorganisms

B. coagulans which was identified by the Microgen ID was used in this study. The *B. coagulans* was used for this study because it was identified from the lateritic soil used and it will enhance bio-stimulation which is obtaining bacteria from the soil culture it in mass and reintroduce it into the soil for MICP process. The bacteria were cultured in liquid media consisting of 3 g Nutrient Broth, 330 mM of urea, 186.7 mM of NH_4Cl , 25.3 mM of NaHCO_3 per litre of glass distilled water, with a pH measured at 9.7. Liquid media were sterilized by autoclaving for 20 minutes at 121°C. The bacterial cell densities were determined using McFarland Turbidity scale using 0, 0.5, 2, 4, 6 and 8 being equivalent to

1.5×10^8 cells/ml, 6.0×10^8 cells/ml, 12×10^8 cells/ml, 18×10^8 cells/ml and 24×10^8 cells/ml, respectively (McFarland, 1907). The growth phase of the inoculating culture was controlled. The *B. pumilus* suspensions were prepared in stepped suspension densities of 0 cells/ml (which is the control), 1.5×10^8 cells/ml, 6.0×10^8 cells/ml, 12.0×10^8 cells/ml, 18.0×10^8 cells/ml and 24.0×10^8 cells/ml, respectively for the MICP treatment and was used in treating each soil sample.

Cementation Reagents

Cementation reagents served as the raw materials for calcite formation in the MICP process. The cementation reagents that were employed in this study comprise 333 mM of urea ($\text{CO}(\text{NH}_2)_2$) and 25.2 mM of calcium chloride (CaCl_2). The cementation reagents also contained 3 g nutrient broth, 186.7 mM ammonium chloride (NH_4Cl), and 25.3 mM of sodium bicarbonate (NaHCO_3) per litre of deionized water which is an alkaline culture medium (Stocks-Fischer *et al.*, 1999; Stoner *et al.*, 2005; Dejong *et al.*, 2006; Qabany *et al.*, 2011).

Compaction

Each soil sample was compacted in the compaction mould using British Standard Light (BSL) or Standard Proctor (SP) compaction energies in accordance with BS 1377 (1990) to determine the compaction characteristics ((Optimum Moisture Content (OMC) and Maximum Dry Density (MDC)) of the natural soil. Soil samples were passed through 4.76mm sieve. Soil samples were mixed with *B. coagulans* suspension density at 25% of the natural OMC of all compactive effort used while the remaining 75% was for the cementation reagent. Soil samples were allowed to air dry on trays and afterwards tests were carried out on them. Tests to determine the moisture-density relationships were carried out in accordance with BS 1377 (1990) for the three energies considered.

MICP Treatment

After compaction, the samples in the compaction mould were saturated under gravity with the various *B. coagulans* suspension



densities. Each specimen was left for three hours to ensure that the pores within the soil matrix are filled with the bacteria suspension before the introduction of the cementitious reagent also by gravity into the pores of the soil matrix until they were completely saturated. Saturation was ascertained by the cementitious reagent dripping from the bottom of the compaction mould and the applied reagent on the surface of the sample does not permeate into the soil any more. A series of compacted soil samples were repeatedly treated (one each) with different bacterial suspension densities (control; 1.5×10^8 cells per ml; etc.) every 6 hours for two days and the cementitious reagent with alkaline culture medium was injected into the soil to initiate the MICP process. Upon completion of the treatment, the soil specimen was used for shear box test to determine shear strength parameters. Three samples were been tested for each suspension density and the average value was taken as the angle of internal friction (ϕ) and cohesion (c) of the soil.

Index Properties

The index properties of the soil were determined in accordance to specifications outlined in BS, 1377 (1990). Soil passing through British Standard No. 40 sieve (425 μ m aperture) was used to determine Atterberg limits consisting of liquid limit, plastic limit, plasticity index and the linear shrinkage was also determined. The various *B. coagulans* suspension density was mixed at 25% of the natural liquid limit value while the cementation reagent was mixed at 75% of the same natural liquid limit value. The treated soil specimens were then air-dried at the laboratory temperature of $23 \pm 2^\circ\text{C}$, before being used to carry out the test. The soil samples were treated in stepped of *B. coagulans* cells/ml considered. Three samples were been tested for each suspension density and the average value was taken

Specific Gravity

From dried treated samples mixed for index properties were used for the test in accordance to specification outlined in BS. 1377 (1990).

Shear Strength

The shear strength test on natural and treated soil will be done in accordance with BS 1377

Bearing Capacity

The bearing capacity of the silty soil was determined using Terzaghi's equation considering strip footing, square footing and circular footing. The equations used to generate the bearing capacities for strip, square and circular footing using shear strength parameters obtained from the laboratory are shown in equations 1 – 3.

$$q_u = \dot{c}N_c + qN_q + \frac{1}{2}\gamma BN_\gamma \quad (1)$$

$$q_u = 1.3\dot{c}N_c + qN_q + 0.4\gamma BN_\gamma \quad (2)$$

$$q_u = 1.3cN_c + qN_q + 0.3\gamma BN_\gamma \quad (3)$$

For the rectangular footing considered the general bearing capacity equation was used which is shown in equation 4

$$q_u = \dot{c}N_c F_{cs} F_{cd} F_{ci} + qN_q F_{qs} F_{qd} F_{qi} + \frac{1}{2}\gamma BN_\gamma F_{\gamma s} F_{\gamma d} F_{\gamma i} \quad (4)$$

Where

c = cohesion

q =

effective stress at the level of the bottom of the foundation

γ = unit weight of soil

B = width of foundation (=

diameter for a circular foundation

$F_{cs} F_{qs} F_{\gamma s}$ = shape factors

$F_{cd} F_{qd} F_{\gamma d}$ = depth factors

$F_{ci} F_{qi} F_{\gamma i}$ =

load inclination factors

$N_c N_q N_\gamma$ =

bearing capacity factors

RESULTS AND DISCUSSION

Specific gravity

The variation of specific gravity of silty soil with *B. coagulans* is shown in Figures 1. The specific gravity of the soil generally decreased with increased *B. coagulans* suspension density. Its value decreased from 2.63 for the natural lateritic soil to 2.32 at 2.4×10^9 cells/ml. This decrease may be caused by the calcites formed during the MICP process which caused the soil

particles to be flocculated within the soil matrix and hence loosely parked particles. This result is similar to findings by Osinubi *et al.* (2017);

Osinubi *et al.*, (2018) and Sani *et al.*, (2020a and b).

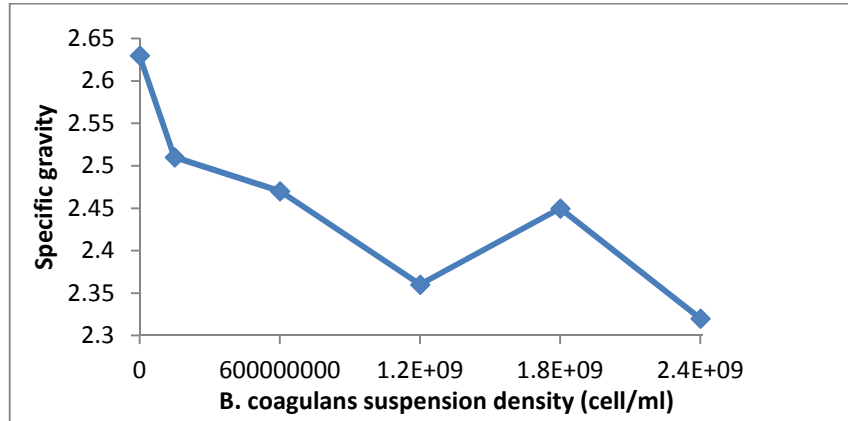


Figure 1: Variation of the specific gravity of lateritic soil with *B. coagulans* suspension treatment

Index Properties

The soil was determined to be an A-3 soil according to ASHTO soil classification and it was a non-plastic soil.

Compaction characteristics Maximum Dry Density

The variation of the Maximum Dry Density (MDD) of MICP treated silt soil with *B. coagulans* suspension density is shown in Figure 2. The MDD shows a sharp increase with increasing *B. coagulans* suspension density up to

6.0×10^9 cells/ml and thereafter decreases slightly to 2.4×10^9 cells/ml. The MDD increased from 1.59 to 1.7 Mg/m³ and then decreased to 1.68 Mg/m³, 1.67 Mg/m³ and 1.67 Mg/m³. The increase in MDD is due to improvement in the density of the silt soil and also as a result of high quantity of calcite that bridged the soil particles together by clogging of the pores spaces within the silty soil. Similar trend was also reported by Abo-El-Enein *et al.* (2012), Osinubi *et al.*, (2017), Osinubi *et al.*, (2018) and Sani *et al.*, (2020a and b).

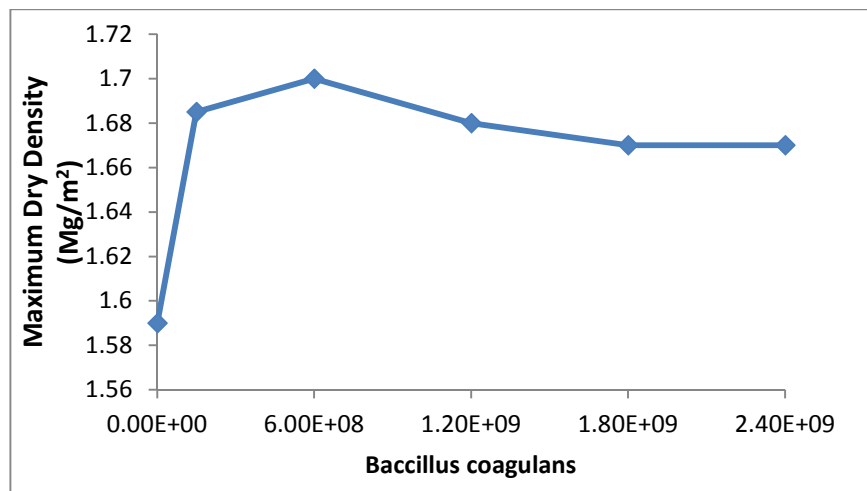


Figure 2: Variation of the MDD of the silt soil with *B. coagulans* suspension density treatment

Optimum Moisture Content

The variation of Optimum Moisture Content (OMC) with *B. coagulans* cells/ml is shown in Fig. 3. The OMC generally decreased with increased *B. coagulans* suspension density treatment up to a minimum value at 12.0×10^8 cells/ml and thereafter increases. The OMC decreased from 14.6% to 13.3% and thereafter increases to 14.0% at 2.4×10^9 cells/ml. The decrease in OMC recorded for at the initial stage could be caused by the urease enzyme produced by *B. coagulans* that reacted with the

cementation reagent to form larger surface areas that had greater affinity for water thereby leading to lower moisture content. The increase beyond 12.0×10^8 cells/ml can be attributed to the quantity of calcite that bridged the soil particles together by clogging of the pores spaces within the soil thereby allowing for more affinity of water hence absorption. Similar findings were reported by Abo-El-Enein *et al.* (2012), Osinubi (2017), Osinubi *et al.*, (2018) and Sani *et al.*, (2020a and b).

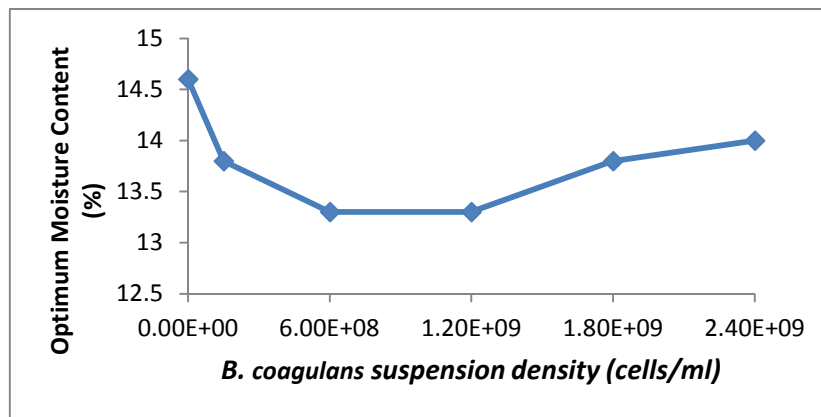


Figure 3: Variation of the OMC of the silt soil with *B. coagulans* cells/ml suspension density treatment

Cohesion

The variation of cohesion with *B. coagulans* cells/ml is as shown in Fig. 4. The general trend of the cohesion shows a general decrease with increase in *B. coagulans* suspension density treatment and lowest cohesion values were obtained at 18.0×10^8 cells/ml. The result indicates there is a great improvement in the silt soil by reducing the clayey nature of the silt soil from 35 kN/m² to 26 kN/m². The result also indicates that Calcites were formed through the MICP process that improves the property of the soil.

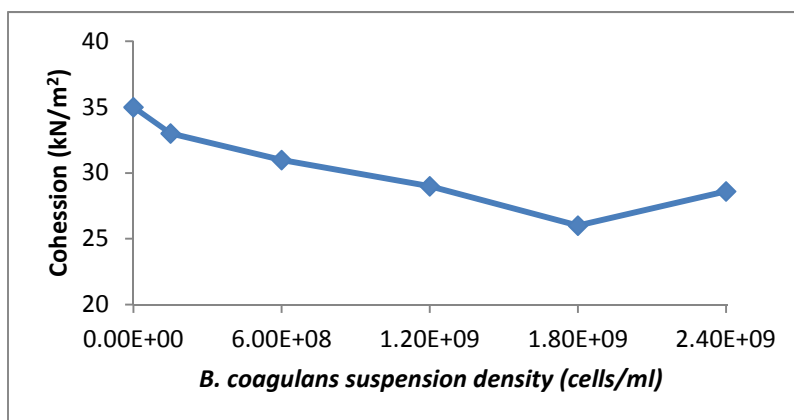


Figure 4: Variation of the Cohesion of the silty soil with *B. coagulans* cells/ml suspension density treatment

Angle of Internal Friction

The variation of angle of internal friction with *B. coagulans* cells/ml is as shown in Fig. 5. The general trend of the angle of internal friction shows a general increase with increase in *B. coagulans* suspension density treatment and highest angle of internal friction values were obtained at 18.0×10^8 cells/ml. The angle of internal friction value increased from 31° to 39° .

The result indicates that higher angle of internal friction value obtained is a function of the calcites precipitations that were formed through the MICP process. The enzyme urease triggered the MICP biochemical reaction by hydrolyzing urea and the ammonium (NH_4^+) produced increased the pH and caused the bicarbonate

(HCO_3^-) to precipitate with calcium ion (Ca^{2+}) from the calcium chloride supplied to form calcium calcite (CaCO_3). The calcite generated was responsible for binding silty soil particles and clogging the pores in the silty soil specimens. Bio-cementation is achieved when the calcite crystals precipitate on the surface or form bridges between the existing soil grains. These calcite crystals formed are responsible for the bond between the silt soil particles and forbid movement of its grains, and therefore improves the angle of internal friction and lower the cohesion of silty soil (Harkes *et al.*, 2010; Mujah *et al.*, 2017; Osinubi *et al.*, 2019d and Sani *et al.*, 2020a and b).

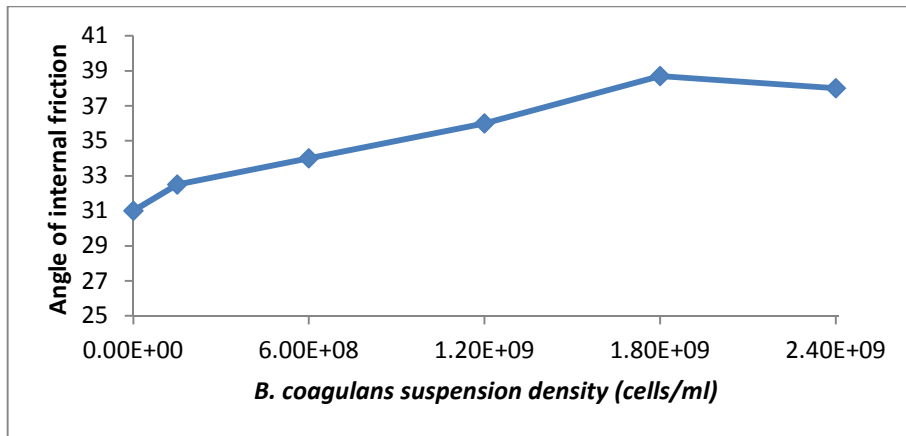
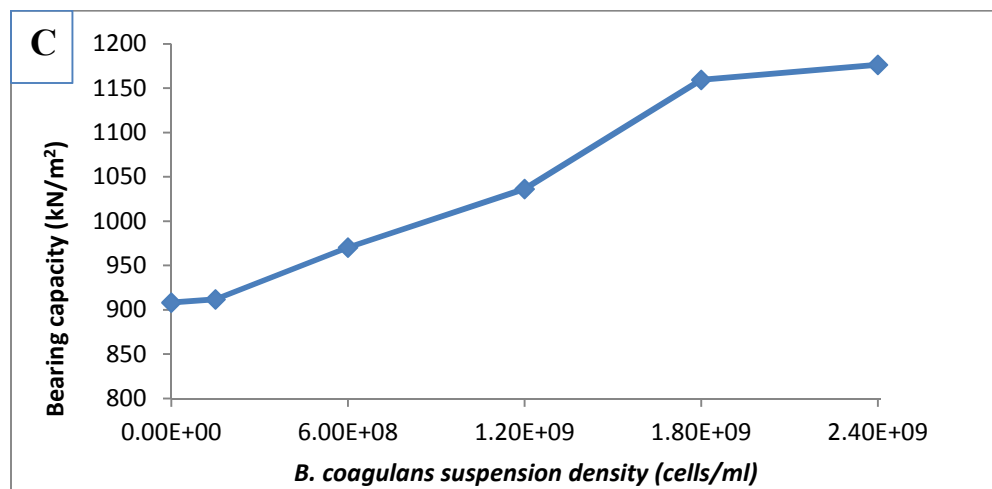
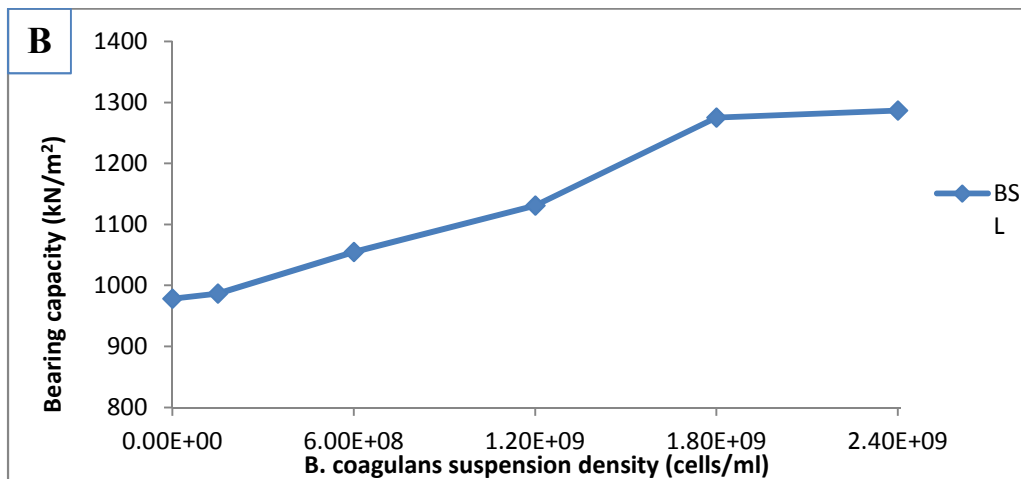
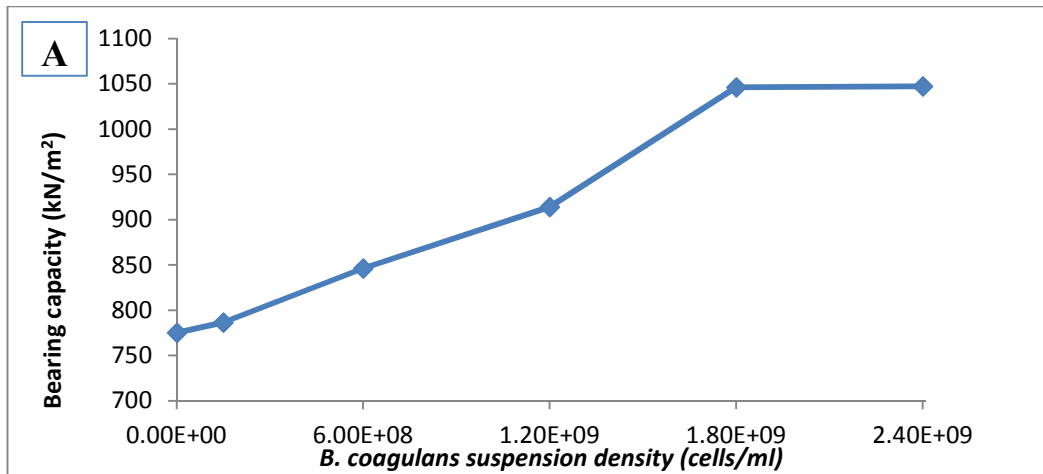


Figure 5: Variation of the Angle of Internal Friction of the silty soil with *B. coagulans* cells/ml suspension density treatment

Bearing Capacity

The variation of ultimate bearing capacity of the silty soil with *B. coagulans* cells/ml for strip footing, square footing, rectangular footing and circular footing is as shown in Fig. 6 A – D. The general trend of the bearing capacity for all shapes considered is of increase in the bearing capacity with increase in *B. coagulans* cells/ml to a peak value at 24.0×10^8 cells/ml treatment. The maximum bearing capacity increases from 775.34 – 1047.11 kN/m², 977.98 – 1286.91 kN/m², 908.31 – 1176.59 kN/m² and 967.99 – 1259.23 kN/m² for strip, square, rectangular and circular footing respectively.



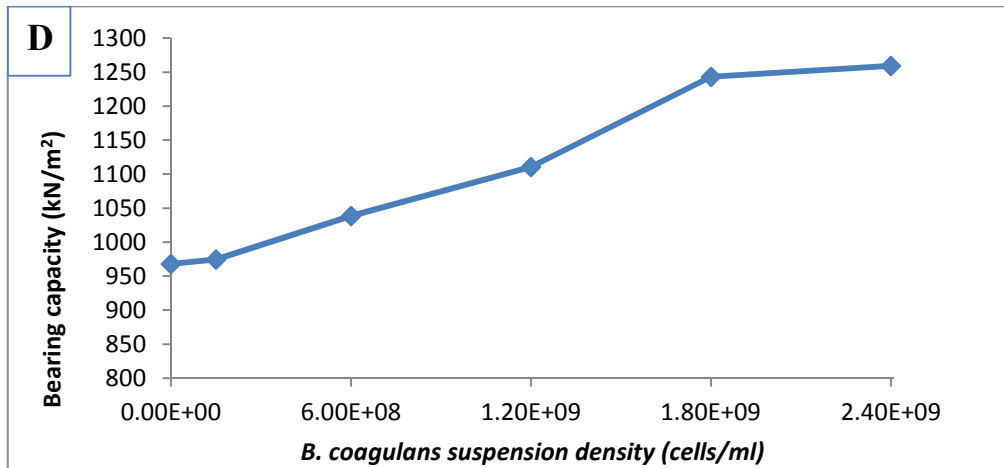


Figure 8: Variation of the Bearing Capacity of the silty soil with *B. coagulans* cells/ml suspension density treatment for (A) Strip Footing (B) Square Footing (C) Rectangular Footing (D) Circular Footing

CONCLUSION

Based on the results of the study on microbial induced modification of silty soil using *bacillus coagulans* for building foundation, it can be concluded that:

1. The specific gravity of the soil decreases with increase in *B. coagulans* suspension density
2. The Atterberg limits test conducted shows that the soil is a non-plastic soil.
3. The compaction characteristic shows that the maximum dry density increases with increase in *B. coagulans* suspension density and thereafter decrease at peak value of 1.7 Mg/m³ at 6.0×10^8 cells/ml *B. coagulans*. The optimum moisture content OMC on the other hand decreases with increase in *B. coagulans* suspension density to a minimum value at 6.0×10^8 cells/ml *B. coagulans*. The OMC decreased from 14.6% to 13.3% and thereafter increases to 14.0% at 2.4×10^9 cells/ml.
4. The cohesion of the soil shows a decrease in value with an increase *B. coagulans* suspension density with a minimum value of 26 kN/m² obtained at 18.0×10^8 cells/ml. The result indicates there is a great improvement in the silty

soil by reducing the clayey nature of the silty soil.

5. The angle of internal friction shows a general increase with increase in *B. coagulans* suspension density treatment. The angle of internal friction value increased from 31° to 39° with maximum value obtained at 18.0×10^8 cells/ml.
6. The ultimate bearing capacity of the silty soil with *B. coagulans* cells/ml for strip footing, square footing, rectangular footing and circular footing considered shows an increase with increase in *B. coagulans* cells/ml. The square footing gave the highest value of 1286.90 kN/m² followed by circular with 1259.23 kN/m² then rectangular with 1176.59 kN/m² and lastly strip footing with 1047.10 kN/m².
7. 18.0×10^8 cells/ml of *B. coagulans* suspension density is recommended for modification of soil for building foundation.

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