Research Article

Evaluating the electrical resistivity of microbial-induced calcite precipitate-treated lateritic soil

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Received: 11 May 2020 / Accepted: 29 July 2020 / Published online: 10 August 2020

Abstract
Organisms or chemicals introduced into soils for soil improvement tend to make such soil reactive and this may affect the parameters that are used to determine the engineering and other properties of the soil. In this study, the electrical resistivity of *Bacillus pumilus* microbial-induced calcite precipitate-treated lateritic soil at different compactive effort was evaluated; lateritic soil was treated with stepped densities of *B. pumilus* suspensions 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, respectively, and compacted with three compaction energies, namely British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy. The treated soil samples were cured for 7, 28 and 56 days to also see the effect of the curing period on the resistivity of the treated lateritic soil. The resistivity test result shows an increase in resistivity value with an increase in *B. pumilus* suspension density and also with an increase in compactive energy. Though there is a marginal increase between BSL and WAS compactive effort. The peak resistivity value was obtained at 2.4×10^9 cells/ml of *B. pumilus* suspension density for all compactive effort considered. The effect of curing days indicates that beyond 28 days there is only a marginal increase in resistivity value because there is little or no increase in the resistivity values obtained.

Keywords *Bacillus pumilus* · Electrical resistivity · Compactive effort · Curing days · Lateritic soil

1 Introduction

Electrical resistivity of soil is a measure of the resistance that a soil type (of a specified volume) offers to the flow of electricity through it. An estimate of soil resistivity and its variation with depth in the soil is critical in the designing of the grounding system in an electrical substation. It is also needed for designing earthen electrodes for high-voltage direct current transmission systems. The soil resistivity value varies substantially with changes in moisture content, chemical content (salts), temperature, etc. [43]. It is measured in Ohm-meter (Om).

The geotechnical community often assumes that natural soil deposits and graded fills are inert due to their ignoring biological presence in soils (that soils are free of organisms) and in a stable state. However, biological presence can modify the engineering properties of soil greatly [9]. Bio-geochemical processes have been used to improve the engineering properties of soil such as physical properties, conduction properties, mechanical properties and chemical composition and are well documented in the literature [8, 9, 14, 19, 20, 38, 40, 42]. Therefore, it becomes necessary to determine the effect of biological processes on properties of treated soils, most especially those that have found popular use in construction, such as laterite.

Laboratory methods including studies of the injection method, injection volume, influence of the calcium source, concentration of cementation reagent, and factors that affect the MICP process have been investigated with the aim of using the findings for various engineering applications to be carried out in the field [32]. Commonly found soil bacteria (*S. pasteurii*, *Bacillus coagulans*

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SN Applied Sciences (2020) 2:1492 | https://doi.org/10.1007/s42452-020-03285-x

and *Bacillus pumilus*) were cultured from a tropical residual soil (lateritic soil) which met the geometric compatibility requirements for this research technique, obtaining positive results [29–31].

Laterites, which are formed in tropical and sub-tropical regions of hot and humid climatic conditions with heavy rainfall, warm temperature and good drainage according to Townsend [39], are very rich in iron and aluminium and occur mostly as the capping of the hill. They, therefore, find extensive use in numerous construction activities such as subgrade material for road construction and brick production material [12]. Similarly, they are categorized as natural resources of importance in geoenvironmental applications [10] because of their adequate chemical resistance and low desiccation-induced shrinkage potential [25]. Most tropical laterites are predominantly composed of kaolinite, non-swelling, non-expanding 1:1 clay minerals which are engineering materials [23]; some often contain swelling 2:1 clay mineral sand and, therefore, constitute problematic engineering structures.

Great success has been recorded in strength and durability of an MICP-treated soil, but little work has been done to determine the electrical resistivity of an MICP-treated soil. The aim of this study is to evaluate the electrical resistivity of *B. pumilus* microbial-induced calcite precipitate-treated lateritic soil at different compactive effort. Microbial-induced calcite precipitate (MICP) is a technology by which microorganisms are used to improve the geotechnical properties of soils, by the production of calcite that binds the soil particle as a result of the introduction of bacteria (*B. pumilus*) and cementation reagents into the soil [7, 15, 27]. Successes in this research can be upscale to field applications of the MICP technique to improve the electrical resistivity of soil. van Paassen [41] carried out the first full-scale field application of the MICP technique, producing very promising findings. Despite the promising finding of field applications, the lack of understanding of the long-term mechanical properties of bio-cemented soil has delayed its extensive acceptance for practical engineering applications [11, 18]. This research considered curing the MICP-treated soil for 56 days to see the sustainability of the resistivity value.

2 Materials and methods

2.1 Soil

The lateritic soil sample used in this study was collected by the method of disturbed sampling from Abagana (Lat 6.186549° and Long. 6.980070°), Njikoka Local Government Area of Anambra state, South East Nigeria. The soil samples were collected at a depth of 1.5 m below the natural earth surface to minimize organic matter.

2.2 Microorganisms

Bacillus pumilus which was identified by the Microgen ID was used in this study. The *B. pumilus* 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, and 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 min 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 1.5×10^8cells/ml, 6.0×10^8cells/ml, 12×10^8cells/ml, 18×10^8cells/ml and 24×10^8cells/ml, respectively [17]. 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.

2.3 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 ($CO(NH_2)_2$) 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 [7, 34, 36, 37].

2.4 Compaction

Each soil sample was compacted in the compaction mould using British Standard Light (BSL) or Standard Proctor (SP), West African Standard (WAS) and British Standard heavy (BSH) compaction energies in accordance with BS 1377 [5] to determine the compaction characteristics (Optimum Moisture Content (OMC)) and Maximum Dry Density (MDC)) of the natural soil. Soil samples were passed through 4.76 mm sieve. Soil samples were mixed with *B. pumilus* 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 [5] for the three energies considered.

2.5 MICP treatment

After compaction, the samples in the compaction mould were saturated under gravity with the various *B. pumilus* suspension densities. Each specimen was left for 3 h 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 anymore. 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 h for 2 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 the electrical resistivity test. Three samples were tested for each suspension density, and the average value was taken as the electrical resistivity of the soil.

2.6 Index properties

The index properties of the soil were determined in accordance with specifications outlined in BS. 1377 [5]. Soil passing through British Standard No. 40 sieve (425 µm aperture) was used to determine Atterberg limits consisting of liquid limit, plastic limit, and plasticity index, and the linear shrinkage was also determined. The various *B. pumilus* suspension densities were 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 ± 2 °C, before being used to carry out the test. The soil samples were treated in stepped densities of *B. pumilus* cells/ml considered. Three samples were tested for each suspension density, and the average value was taken.

2.7 Specific gravity

Dried treated samples mixed for index properties were used for the test in accordance with specification outlined in BS. 1377 [5].

2.8 Calcite content determination

The calcite content was estimated using the acid washing method as described by Burbank et al. [4] and Choi et al. [6]. Moreover, 5 g of the treated sample used in volumetric shrinkage strain test was cut from surface to core of the specimen and weighed (denoted as W_1) and placed in a 50 ml beaker; 20 ml of 2 M of hydrochloric acid (HCL) was added into a beaker and stirred with a glass rod until the calcium carbonate was dissolved in the acid; it was then transferred to Whatman filter paper and washed with distilled water for 10 min. The filtrate was oven-dried at 35 °C/105 °C. The dried weight (W_2) was recorded. The calcite content was computed as follows:

$$W_D\ (\mathrm{g}) = W_1 - W_2 \tag{1}$$

where W_D is the weight of the calcite content (CC), W_1 is the weight of the sample before acid washing, and W_2 is the weight of the sample after acid washing

Or

$$\mathrm{CC}\,(\%) = 100 - \frac{W_2}{W_1} \times 100 \tag{2}$$

2.9 Electrical resistivity measurement

The electrical resistivity of the soil is determined by measuring the resistance between two points in the soil, and this is done by measuring the voltage across a pair of electrodes by transmitting a controlled DC or AC current (*I*) between two electrodes pushed into the ground while measuring the potential (*V*) between two other electrodes. The setup for the measurement of electrical resistivity is shown in Fig. 1 and the Schematic of M.C. Miller Soil Box **utilized** is shown in Fig. 2. The resistivity of the samples was measured after the samples were cured for 7 days, 28 days and 56 days to also see the effect of long-time

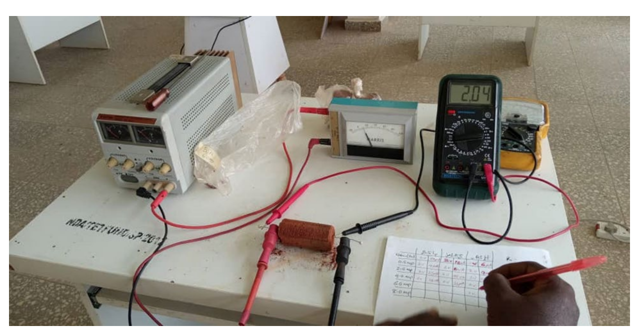


Fig. 1 Soil resistivity testing system utilized in this research

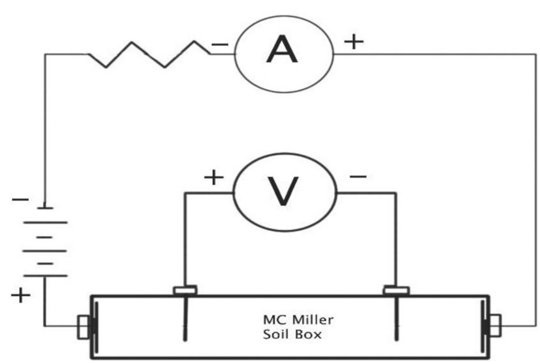


Fig. 2 Schematic of M.C. Miller Soil Box

Table 1 Oxide composition of lateritic soil

Oxide	Concentration %
SiO_2	56.5
Al_2O_3	19.00
CaO	0.33
TiO_2	2.89
V_2O_5	0.061
Cr_2O_3	0.051
Fe_2O_3	15.41
MnO	0.075
CuO	0.056
ZrO_2	0.290
L.O.I	4.54

After Osinubi et al. [28]

curing on the resistivity value of *B. pumilus* treated soil at the stepped suspension density considered.

The resistance (R) is calculated using Ohm's Law as given in Eq. (3).

$$R = \frac{V}{I} \tag{3}$$

where V is the voltage (V) and I is the current (amp).

For the case of a pair of electrodes in homogeneous, isotropic conducting media, the relationship between resistance and resistivity is linear and the material resistivity (ρ) can then be defined as in the following Eq. (4):

$$\rho = RA/l \tag{4}$$

where l is the length (m) between electrodes and R is the resistance (Ω).

In the actual field measurement of electrical resistivity, there are many different kinds of electrode arrays or configuration that one could adopt. Some of the typical electrode arrays are Wenner, Schlumberger, dipole–dipole and pole-pole. In this research, however, the disc electrode method in accordance with BS 1377 was adopted to enable undisturbed or disturbed samples of soil to be measured in the laboratory. By using this disc electrode method of measurement, the resistivity of the soil (ρ) in Ω.m is determined by the formula given in Eq. (5).

$$\rho = \left(\frac{A}{l}\right)R \tag{5}$$

where A is the cross-sectional area (m^2) of the sample, l is the length (m) and R is the resistance (Ω).

The technical requirement of electrical resistivity is that it has a relationship with the soil type, degree of compaction and soil moisture content. Electrical resistivity increases with the degree of compaction (compaction energies). Electrical resistivity can be considered as a quick and clean quality control tool for field compaction. For each site, laboratory tests could be carried out to determine the site-specific relation between the electrical resistivity and the degree of compaction and water content [22].

3 Results and discussion

3.1 Oxide composition of lateritic soil

The results of X-Ray Fluorescence (XRF) carried out in the Nigeria Geological Survey Laboratory Kaduna, Kaduna State to determine the oxide composition of lateritic soil is shown in Table 1.

The silica–sesquioxide ratio of 1.65, which is between 1.33 and 2.00 classifies the natural material as lateritic soil in accordance with the specifications given by Joachin and Kandiah [16].

3.2 Specific gravity

The variation of the specific gravity of lateritic soil with *B. pumilus* is shown in Fig. 3. The specific gravity of the soil generally decreased with increased *B. pumilus* suspension density. Its value decreased from 2.86 for the natural lateritic soil to 2.63 at 1.8×10^9 cells/ml and thereafter increased to 2.68 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. [24, 26].

3.3 Index properties

The index properties of the lateritic soil and treated lateritic soil are summarized in Table 2. The natural soil is reddish-brown in colour and had 35.3% passing through

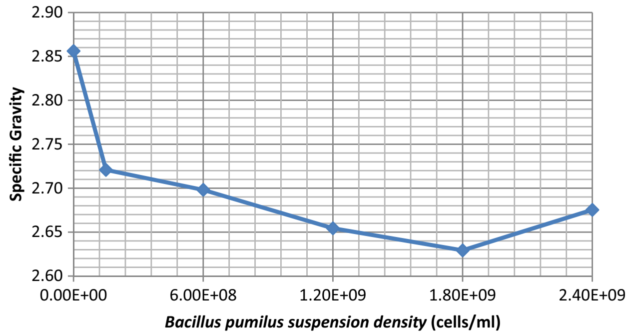


Fig. 3 Variation of the specific gravity of lateritic soil with *B. pumilus* suspension treatment

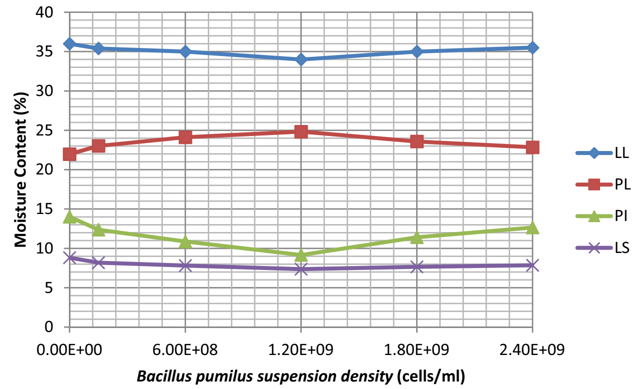


Fig. 4 Variation of the Atterberg limits of lateritic soil at various *B. pumilus* suspension density treatments

BS sieve no. 200. It was classified as clayey sand (SC) under the USCS [3] and A-4(0) under the AASHTO system [1] with the dominant clay mineral being kaolinite.

The variation of Atterberg limits [liquid limit (LL), plastic limit (PL), plasticity index (PI)] and linear shrinkage (LS) of the lateritic soil treated with cementitious reagent at various suspension densities of *B. pumilus* is shown in Fig. 4. It was observed that there was a decrease in the liquid limit values from 36 to 34% at 1.2×10^9 cells/ml of *B. pumilus* suspension density and thereafter it increased to 35.5 at 2.4×10^9 cells/ml of *B. pumilus* suspension density. A plasticity index value of 14.02% was recorded for the natural soil which dropped to a value of 9.17% at 1.2×10^9 cells/ml of *B. pumilus* suspension density and thereafter increased to a value of 12.66% at 2.4×10^9 cells/ml of *B. pumilus* suspension density. The linear shrinkage decreased from 8.82% for the natural soil to 7.27% at 1.2×10^9 cells/ml of *B. Pumilus* suspension density and thereafter slightly increased to 7.86% at 2.4×10^9 cells/ml of *B. pumilus* suspension density.

This result is contrary to the reports by Osinubi et al. [24] where it was reported that the liquid limit value rose with an increase in *B. pumilus* treatment. However, similar studies [33, 35], which used cement to stabilize lateritic soil reported the effects of Ca^{2+} on the liquid limit of the clay soil, showed a decrease in the liquid limit value. The Atterberg test result may not be unconnected with the flocculation and agglomeration of the clay particles which occurred as a result of the production of calcites in the MICP process. This result is similar to findings by Osinubi et al. [24, 26] where it was reported that the plastic limit value rose with an increase in *B. pumilus* suspension density treatment on lateritic soil.

3.4 Compaction characteristics

3.4.1 Maximum dry density

The variation of the maximum dry density (MDD) of MICP-treated soil with *B. pumilus* suspension density for

Table 2 Properties of the natural and treated lateritic soil

Property	*B. pumilus* (suspension density/ml)					
	0	1.5E8/ml	6.0E8/ml	12.0 E8/ml	18.0E8/ml	24.0E8/ml
Natural moisture content (%)	11.8					
Percentage passing no. 200 sieve (wet sieving)	35.3					
Liquid limit (%)	36	35.4	35	34	35	35.5
Plastic limit (%)	21.98	23.02	24.12	24.83	23.58	22.84
Plasticity index (%)	14.02	12.38	10.88	9.17	11.42	12.66
Linear shrinkage (%)	8.82	8.19	7.82	7.37	7.66	7.86
Specific gravity	2.86	2.72	2.70	2.65	2.63	2.68
AASHTO classification	A-4(0)	A-4(0)	A-4(0)	A-4(0)	A-4(0)	A-4(0)
USCS	SC	SC	SC	SC	SC	SC
Colour	Reddish brown					
Dominant clay mineral	Kaolinite					

the three compactive effort is shown in Fig. 5. The MDD decreased with increasing *B. pumilus* suspension density for all compactive energies considered after an initial increase to 2 Mg/m^3 at 1.5×10^8 cells/ml of *B. pumilus* suspension density for BSL and increase to 2 Mg/m^3 and 2.05 Mg/m^3 at 6.0×10^8 cells/ml of *B. pumilus* suspension density each for WAS and BSH, respectively. The MDD decreased to 1.87 Mg/m^3, 1.86 Mg/m^3 and 1.98 Mg/m^3 for samples compacted at BSL, WAS and BSH, respectively, when treated with up to 2.4×10^9 cells/ml of *B. pumilus* suspension density. The reduction in MDD is probably due to the lower specific gravity values as the *B. pumilus* suspension density increased. A similar trend was also reported by Abo-El-Enein et al. [2] and Osinubi et al. [24, 26].

3.4.2 Optimum moisture content

The variation of optimum moisture content (OMC) with *B. pumilus* cells/ml at different compactive effort considered is shown in Fig. 6.

The OMC generally increased with increased *B. pumilus* suspension density treatment after an initial drop in the OMC value at 1.5×10^8 cells/ml for both BSL and BSH compaction. The OMC increased to 14% and 13.2% at 2.4×10^9 cells/ml for both BSL and WAS compacted samples while the BSH compaction increases to 12% at 1.2×10^9 cells/ml and thereafter decreases. The increase in OMC recorded for all effort considered could be caused by the urease enzyme produced by *B. pumilus* that reacted with the cementation reagent to form larger surface areas that had a greater affinity for water thereby leading to higher moisture content. This can also be attributed to the quantity of calcite that bridged the soil particles together by clogging of the pore spaces within the soil thereby allowing for more affinity of water and hence absorption. Similar findings were reported by Abo-El-Enein et al. [2] and Osinubi et al. [24, 26].

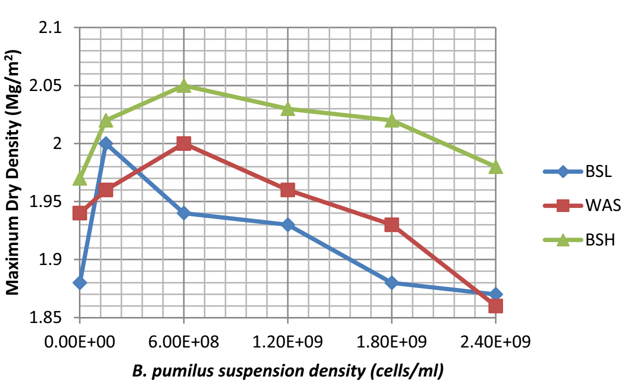


Fig. 5 Variation of the MDD of the lateritic soil with *B. pumilus* suspension density treatment at different compactive effort

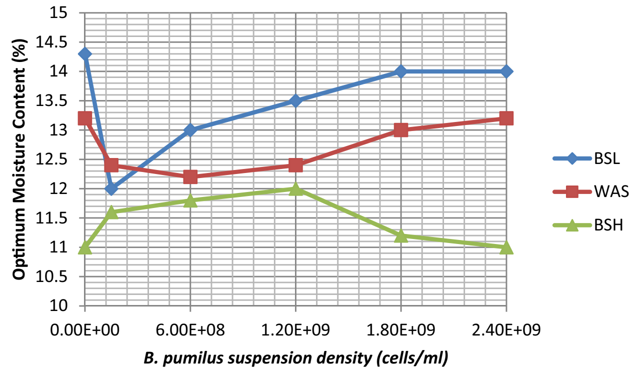


Fig. 6 Variation of the OMC of the lateritic soil with *B. pumilus* cells/ml suspension density treatment at different compactive effort

3.5 Calcite content test

The variation of calcite content for lateritic soil mixed with stepped *B. pumilus* suspension density is shown in Fig. 7. After the MICP treatment for all densities of *B. pumilus* suspension, the sample was extruded from the mould to see the formation of calcite content across the treated sample. Generally, the calcite content of the lateritic soil initially increased with an increase in *B. pumilus* suspension density. It was also observed that a higher concentration of calcite was formed at 1.8×10^9 cells/ml. The picture of the calcite crystal formed as a result of the MICP process is shown in Fig. 8 which is whitish in colour and is responsible for the increase in resistivity of the soil.

3.6 Electrical resistivity

The variation of Resistivity with *B. pumilus* cells/ml at different compactive effort considered and for 7 days curing is as shown in Fig. 9. The general trend of the resistivity shows a general increase with an increase in *B. pumilus* suspension density treatment for all compactive effort considered, and the highest resistivity values were obtained

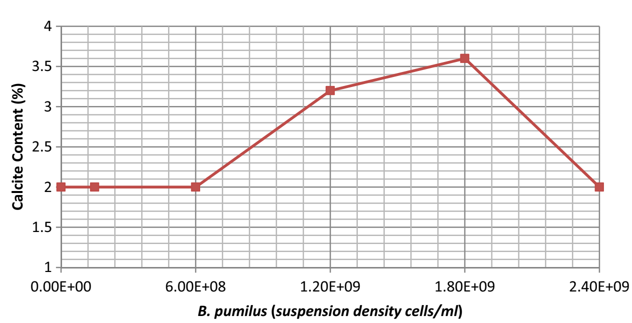


Fig. 7 Variation of calcite content of lateritic soil with *B. pumilus* suspension density cells/ml

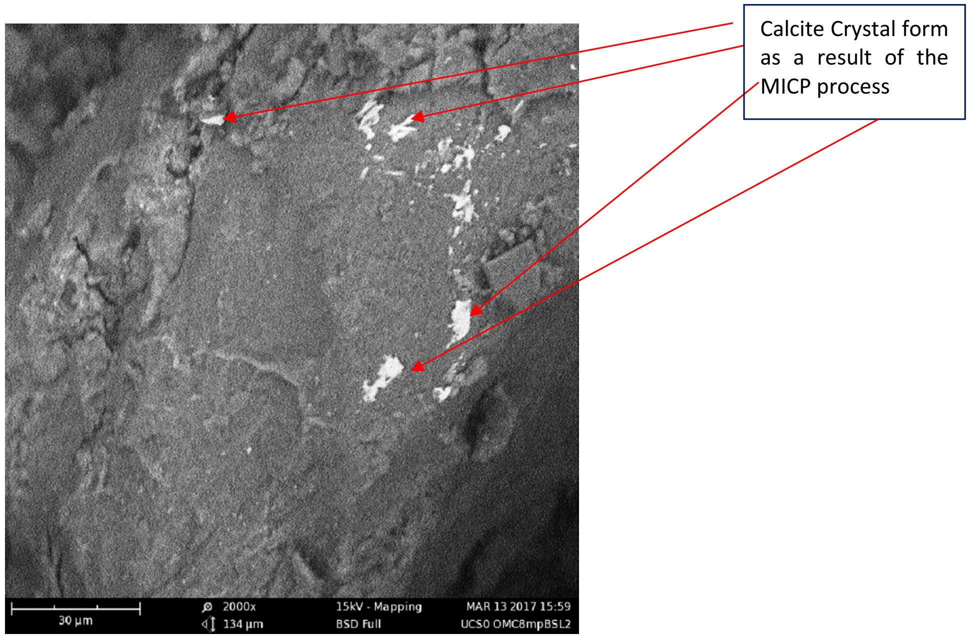


Fig. 8 Picture showing the calcite crystal formed as a result of the MICP process

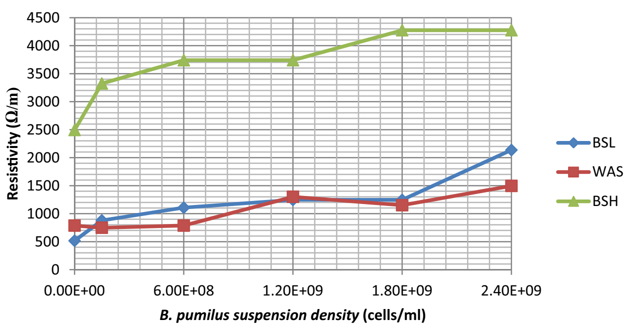


Fig. 9 Variation of the resistivity of the lateritic soil with *B. pumilus* cells/ml suspension density treatment at 7 days curing for different compactive effort

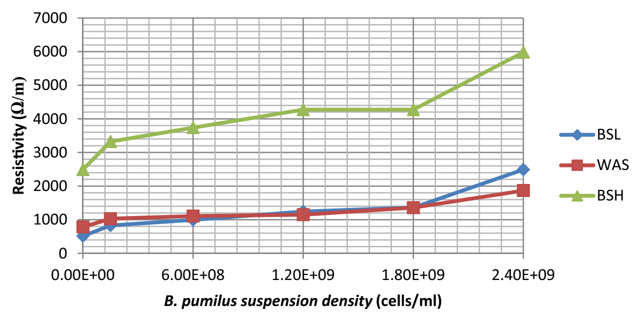


Fig. 10 Variation of the resistivity of the lateritic soil with *B. pumilus* cells/ml suspension density treatment at 28 days curing for different compactive effort

at BSH compactive effort. The result indicates that the resistivity value is a function of both compactive effort and bacteria density. It also indicates that calcites were formed through the MICP process. The resistivity value of the natural soil cured for 7 days increases from a value of 515.929 (Ω/m) to 2137.42 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for BSL compactive effort, 787.47 (Ω/m) to 1496.19 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for WAS compactive effort and 2493.657 (Ω/m) to 4274.841 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for BSH compactive effort.

The variation of resistivity with *B. pumilus* cells/ml at different compactive effort considered and for 28 days of curing is as shown in Fig. 10. The general trend of the resistivity shows a general increase with an increase in *B. pumilus* suspension density treatment for all compactive effort considered, and higher resistivity values were obtained at BSH compactive effort while BSL and WAS compactive effort gave relatively same resistivity values. The samples were cured for 28 days to see the long-time effect of curing on the resistivity value. The resistivity value obtained for the 28 days curing were higher than those obtained for the 7 days curing. The result obtained also indicates that higher resistivity value is a function of compactive effort and also the calcites that were formed through the MICP process. The resistivity value of the natural soil cured for 28 days increased from a value of 515.929 (Ω/m) to 2493.66 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for BSL compactive effort, 787.47 (Ω/m) to 1870.24 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for WAS compactive effort and 2493.657 (Ω/m) to 5984.776 (Ω/m) at 2.4×10^9 cells/ml of *B. pumilus* suspension density for BSH compactive effort.

To further test the long-time effect of curing on the resistivity value of *B. pumilus* suspension density treatment for the soil was cure for 56 days. The variation of resistivity with *B. pumilus* cells/ml at different compactive effort considered cured for 56 days is shown in Fig. 11. The same trend obtained for 7 days and 28 days was recorded for 56 days curing. Beyond 28 days, there is only a marginal increase in resistivity value because there is little or no increase in resistivity value obtained. 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 soil particles and clogging the pores in the 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 soil particles and forbid movement of its grains, and therefore improves the strength and stiffness properties of the soil [13, 21, 27]. At the end of the bio-cementation no further gain in strength which makes the resistivity at some point to be constant after long-time curing but there is no decrease in resistivity which shows that the treatment with MICP is sustainable for a long time period.

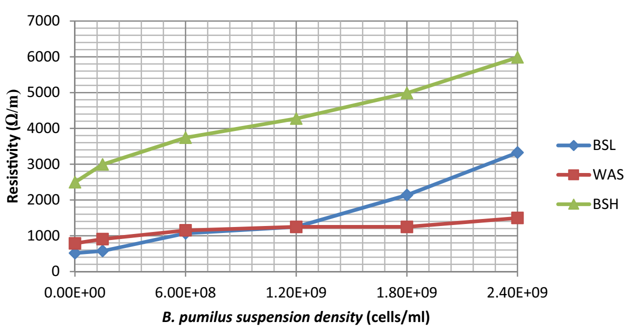


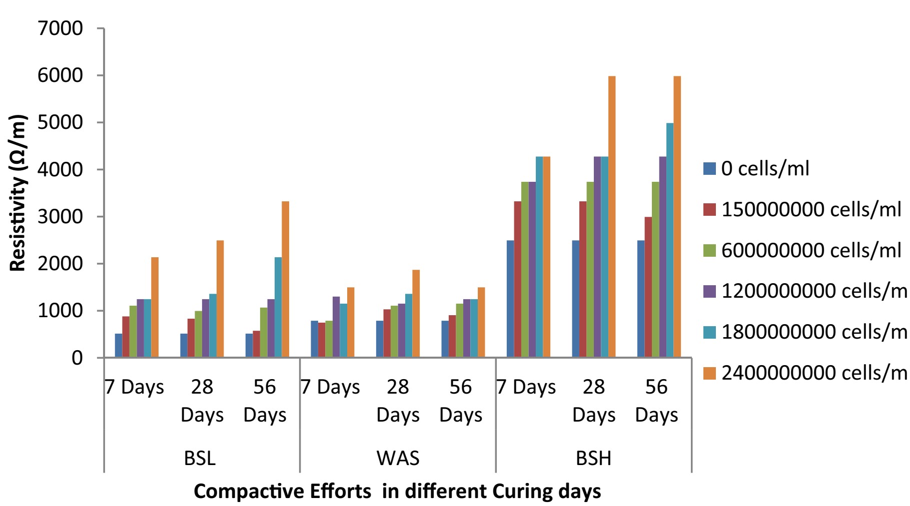
Fig. 11 Variation of the resistivity of the lateritic soil with *B. pumilus* cells/ml suspension density treatment at 56 days curing for different compactive effort

To access the effect of the curing period on the resistivity, Fig. 12 was plotted to compare the resistivity variation at different curing days for different compactive energy used. The results show that at BSL beyond 28 days curing there is a decrease in resistivity value except for treatment with 1.8×10^9 cells/ml and 2.4×10^9 cells/ml of *B. pumilus* suspension density. The result for the WAS compaction shows that there is no increase in resistivity values beyond 28 days and at most treatment a constant value was obtained with that of the 28 days curing except for 2.4×10^9 cells/ml of *B. pumilus* suspension density that shows a slight decrease in the resistivity value. The results of the BSH compaction on the other hand show that beyond 28 days curing period the resistivity value remains constant for *B. pumilus*-treated soil for all suspension density except for 6.0×10^8 cells/ml of *B. pumilus* suspension density that shows a slight decrease in resistivity value and 1.8×10^9 cells/ml of *B. pumilus* suspension density that shows a slight increase in resistivity value.

3.7 Relationship between resistivity and other properties considered

The relationship between resistivity and specific gravity, liquid limit, plastic limit, plasticity index and linear shrinkage was determined using single regression of second-order polynomial model, and the coefficient of determination R^2 is as shown in Figs. 13, 14, 15, 16 and 17. The coefficient of correlation R is the square root of the coefficient of determination R^2.

Fig. 12 Variation of the resistivity of the lateritic soil with *B. pumilus* cells/ml suspension density treatment at different curing days and different compactive effort



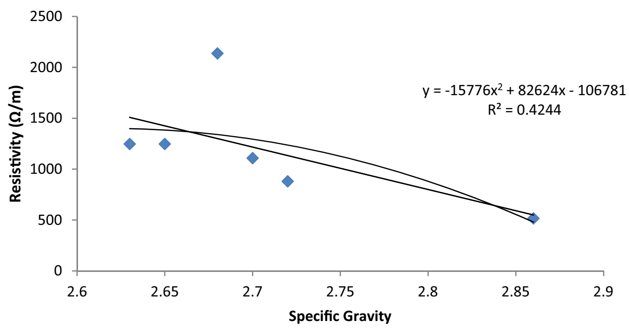


Fig. 13 Correlation of resistivity with specific gravity

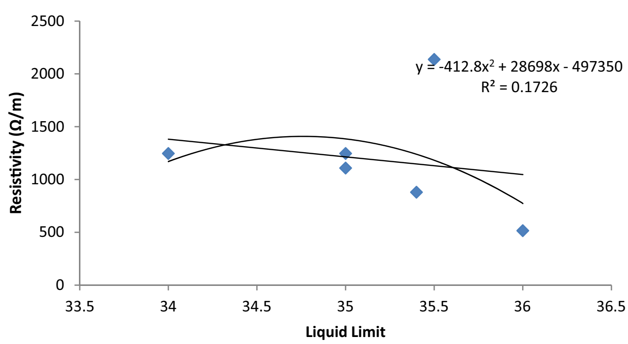


Fig. 14 Correlation of resistivity with liquid limit

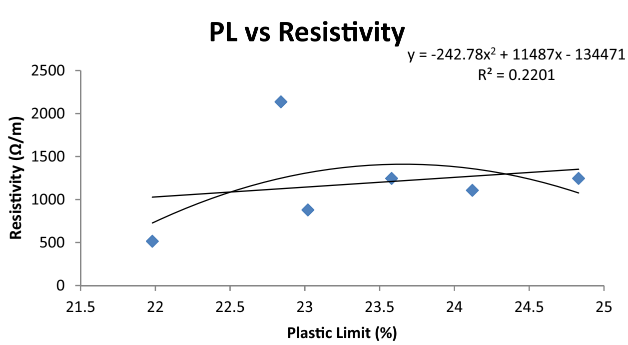


Fig. 15 Correlation of resistivity with plastic limit

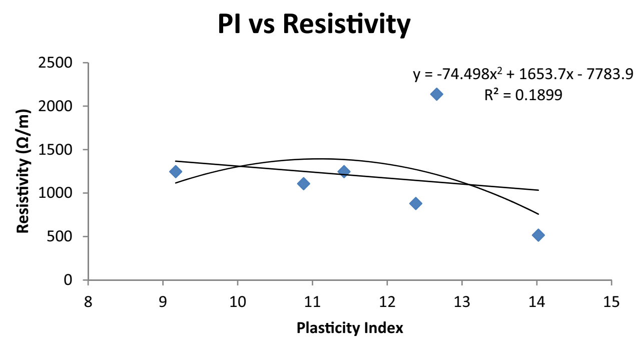


Fig. 16 Correlation of resistivity with plasticity index

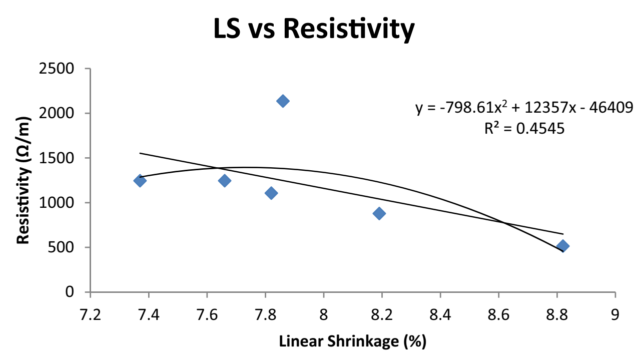


Fig. 17 Correlation of resistivity with linear shrinkage

The result shows that, generally, the relationship between the resistivity and all the parameters considered shows a decrease with an increase in those parameters except for the plasticity limit. The graph shows that the relationship between resistivity and specific gravity gave a coefficient of determination $R^2=0.424$ which is equivalent to the coefficient of correlation $R=0.651$. The relationship between resistivity and liquid limit gave a coefficient of determination $R^2=0.172$ which is equivalent to the coefficient of correlation $R=0.415$. The relationship between resistivity and plastic limit gave a coefficient of determination $R^2=0.220$ which is equivalent to the coefficient of correlation $R=0.469$. The relationship between resistivity and plasticity index gave a coefficient of determination $R^2=0.189$ which is equivalent to the coefficient of correlation $R=0.435$. The relationship between resistivity and linear shrinkage gave a coefficient of determination $R^2=0.454$ which is equivalent to the coefficient of correlation $R=0.674$.

The results show that resistivity has more correlation with the linear shrinkage of the soil with $R=0.674$ followed by the specific gravity of the soil with $R=0.651$. The resistivity has a weak correlation with plastic limit, plasticity index and liquid limit with an R value less than 0.5.

4 Conclusion

Based on the results of the study on evaluating the electrical resistivity of *B. pumilus* microbial-induced calcite precipitate-treated lateritic soil at different compactive effort, it can be concluded that:

1. The specific gravity of the soil decreases with an increase in *B. pumilus* suspension density

2. The Atterberg limits test shows that liquid limit, plasticity index and linear shrinkage decrease with an increase in *B. pumilus* suspension density to a minimum value of 34%, 9.17% and 7.27%, respectively, at 1.2×10^9 cells/ml of *B. Pumilus* suspension density. The plastic limit on the other hand increases with an increase in *B. pumilus* suspension density to a maximum value of 24.83 at 1.2×10^9 cells/ml of *B. pumilus* suspension density.
3. The compaction characteristic shows that the maximum dry density decreases with an increase in *B. pumilus* suspension density after an initial increase but higher MDDs were recorded at BSH compaction energy. The optimum moisture content OMC, on the other hand, increases with increase in *B. pumilus* suspension density after an initial decrease except the sample compacted with BSH that reduces after 1.2×10^9 cells/ml of *B. pumilus* suspension density. BSL compaction gave a higher OMC while BSH compaction gave lower OMC values.
4. The resistivity test result shows an increase in resistivity value with an increase in *B. pumilus* suspension density and also with an increase in compactive energy. Though there is a marginal increase between resistivity values of BSL compactive effort and that of WAS compactive effort.
5. The resistivity values obtained also show that resistivity values increase with curing days, i.e. the values increase between 7 days curing and 28 days curing but beyond 28 days curing period no significant increase in resistivity value.
6. The resistivity result also shows that long-time curing does not reduce the resistivity value which indicates that the MICP process can sustain the resistivity of the treated soil through the lifetime of the structural foundation.
7. The statistical analysis using correlation shows that resistivity has a good relationship with linear shrinkage and specific gravity of the soil with *R* values above 0.65.
8. The peak resistivity values were obtained at 2.4×10^9 cells/ml of *B. pumilus* suspension density for all compactive effort considered.

Acknowledgements The authors gratefully acknowledge the immense support received from the Department of Civil Engineering, Nigerian Defence Academy (NDA) Kaduna, Nigeria for providing their Geotechnical Laboratory where the experimental works of this research were conducted and also thanks the Department of Microbiology Ahmadu Bello University for providing their Laboratory where the micro-organism was identified and cultured to produce the *Bacillus pumilus* suspension density and the cementitious reagent needed for the research.

Funding This research was sponsored by Tertiary Education Trust Fund (TETFUND) under the year 2015 TETFUND RESEARCH PROJECTS (RP) INTERVENTION: RELEASE OF FUND 15TH BATCH with reference TETFUND/DRSS/NDA/KADUNA/2014/RP/VOL. 1 Dated 14th March 2019.

Compliance with ethical standards

Conflict of interest The first author has received research grant from Tertiary Education Trust Fund (TETFUND). The second author did not receive any grant from any company and the third author also did not receive any grant from any company. No conflict of interest for second and third authors.

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