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Unconfined Compressive Strength of Lateritic Soil Treated with Bacillus Coagulans for use as Liner and Cover Material in Waste Containment System

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Abstract: The innovative and environmentally friendly Microbial Induced Calcite Precipitation (MICP) technique involves the use of micro-organisms to facilitate soil improvement. Urease positive bacteria in the company of urea and calcium sources formed dissolved ammonium and inorganic carbon, carbon dioxide and subsequent formation of calcite which is a pore filling material that stiffens the soil and improve its strength. The study involved assessing the potential of Bacillus coagulans (B.coagulans) to improve the unconfined compressive strength (UCS) of lateritic soil. The soil samples were treated with 1/3 pore volume *B. coagulans* suspension densities of $0, 1.5 \times 10^8$, 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. Soil specimens were prepared at moulding water content (MWC) of -2, 0, +2 and +4 % relative to optimum moisture content (OMC) and compacted with the British Standard light (BSL) energy. Cementation reagent was allowed to percolate the compacted specimens until partial saturation was achieved. Results show that UCS values increased with rise in B. coagulans suspension density. UCS of natural soil prepared at -2 % OMC decreased from 278.3 kN/m² to 141.45 kN/m² at +4 % OMC. Similar trend were recorded for specimens treated with varying *B. coagulans* suspension densities when prepared at MWC of -2, 0, +2 and +4 % relative to OMC. Also, UCS values improved with rise in dry density. The UCS values of specimens prepared with B. coagulans suspension densities and compacted at MWC of -2, 0 and +2 OMC, respectively, satisfied the minimum requirement of 200 kN/m² and can be apply as liner and cover materials in municipal solid waste containment system.

Keywords: B. coagulans; Lateritic soil; Microbial Induced Calcite Precipitation; Moulding water Content; Unconfined compressive strength.

1. Introduction

The application of sanitary landfills for attenuating the migration of leachate of disposed waste into the ground has been a common practice in developed nations. Because of low permeability requirement, the idea of Compacted Clay Liners (CCLs) has been an acceptable technique for barrier systems to attenuate the migration of contaminants from the landfill into the ground that pollute the underground water. Thus, the reliability of a landfill is subject greatly on the strength and hydraulic performance of their barrier systems. CCL is made in the field founded on the soil's MDD and OMC [1]. The laboratory and field investigations reported by [2] and [3] suggested that either CCL or Geosynthetic Clay Liner (GCL) lie below by a geomembrane can efficiently mitigate the advection and diffusion of the pollutants into the ground that pollute drinking water.

The influence of a waste discarding facility on groundwater quality use for human consumption heavily relies on the kind of barrier which is envisioned to minimize and control pollutant migration [4]. The primary purpose of engineered landfill system in containment facilities is to decelerate contaminant movement into the underlying subsurface for the period of both the active disposal time and the post closure age. Barrier

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system is an important feature of a contemporary engineered landfill. The technology has grown meaningfully in the last eras in nations where landfill has been in practice. The prospective materials used for such purposes are compacted clay, geosynthetic clay liners (GCLs), reused waste, recycled waste e.t.c [5–6].

Lateritic soil may be considered for use as barrier in waste disposal facilities because of its availability in the tropical regions like Nigeria. Researches have shown that when lateritic soil is used alone or stabilized with fly ash, waste wood ash, cement kiln dust, or foundry slag etc. as barrier material has demonstrated satisfactory in terms of chemical resistance, improved workability, reduced vulnerability to desiccation induced shrinkage, shear strength, hydraulic conductivity, compatibility and diffusion parameters [7 -11]. However, too much dependence on the current industrially developed geosynthentic materials for the building of landfill hydraulic barriers has stimulated to high price tag for building a landfill system in developing and under developed countries. This in turn has increased the rate of indiscriminate and unhygienic disposal of industrial, agricultural, municipal and medical solid wastes due to increasing human population, industrialization and economic development.

Too much reliance on the use of industrially made soil additives like lime and cement has also raised the cost of improvement of deficient construction materials [12]. Cement production process produce large quantity of carbon (IV) oxide (CO_2), thereby increasing greenhouse effect and global warming [13]. Replacement of this approach with a more environment friendly techniques like Microbial Induced Calcite Precipitation, MICP will lessen the general environmental effect of the stabilization process and in other engineering applications.

MICP, a new innovative and ecologically pleasant technique that involves the use of microorganisms to facilitate soil improvement processes. MICP is lately being considered due to its numerous applications that include soil improvement [14 -15], sequestration of contaminants [16], mitigation of seismic liquefaction [17] and crack remediation in stone monuments [18].

Previous researches on soil improvement focused on the use of conventional additives such as cement, lime, bitumen, agro-industrial waste pozzolanic materials, etc. which are either expensive or not environmentally friendly and therefore not sustainable. Therefore, this study is targeted at assessment of UCS of lateritic soil treated with *B. coagulans* (which is a more sustainable and environment-friendly technique of soil improvement) for use in waste containment application. This involved treating the soil with *B. coagulans* with 1/3 pore volume at varying suspension density for specimens prepared at MWC of -2, 0, +2 and +4 % relative to OMC, respectively. The specific objectives were to evaluate the suitability of *B. coagulans* as agent for strength development of lateritic soil for landfill purpose as well as statistical analysis of the laboratory tests results.

2. Materials and Methods

2.1 Materials

2.1.1. Soil sample. Sample was obtained from Abagana, Anambra state, Nigeria.

2.1.2. Micro-organism. B. coagulans a urease positive bacteria was used.

2.1.3 Cementation reagent. The content include 3 g Nutrient broth, 2.8 g CaCl₂, 10 g NH₄Cl, 2.12 g NaHCO₃ and 20 g urea per litre of distilled water as reported by [19].

2.2 Methods

2.2.1 Isolation of the bacterium species from lateritic soil. Isolation of the bacterium species from lateritic soil was done by serial dilution.

2.2.2. Culture medium and growth conditions. The process adopted is as reported by [19] using the medium (Tris \pm YE). The stock and pilot cultures comprises of the resulting ingredients per litre of distilled water: Tris \pm HCl, 130 mM (pH 9.0); (NH₄)2SO₄, 10 g; and yeast extract, 20 g; to which 1.5 % agar was added to achieve a solid medium for the stock culture.

2.2.3 Index properties. Investigations were done on the natural and treated soil based on British Standards [20] and [21], respectively.

2.2.4 Compaction. Specimens were compacted with BSL energy based on the procedures outlined in [20].

2.2.5 Calcium carbonate content. The measurement method used is in accordance with that proposed by [22] and [23] called the acid wash method. In this method, 5 g of natural and soil - *B. coagulans* mixtures were mixed with 20 mL 1-M hydrochloric acid (HCl) acid to dissolve calcium carbonate (gravimetric acid washing technique). Then all the solution and insoluble solids were washed by distilled water on filter paper with a coarse pore size in a No. 200 sieve for 10 mins. This washing method was able to remove all soluble calcium from the soil particles. Then all solid particles remaining on the sieve were oven-dried and weighed. The weight difference between the original soil sample (X) and post washing sample (Y) was the mass of calcium carbonate content (CCC). The CCC was calculated as

$$CCC = 100 - \frac{Y}{X} \times 100 \tag{1}$$

2.2.6 Unconfined compressive strength (UCS). The UCS tests were done on the soil in accordance with [20]. Specimens were treated before compaction with *B.coagulans* suspension at one-third (1/3) pore volume (as endorsed by [24]) in stepped densities of $0, 1.5 \times 10^8, 6 \times 10^8, 1.2 \times 10^9, 1.8 \times 10^9$ and 2.4×10^9 cells/ ml, respectively, using McFarland Standards (McFarland (10-7) Standards are turbidity standards that are used to measure approximately the population of bacteria cells present in a liquid suspension). [24] reported that decreasing the volume of injected voids up to (1/3) of the pore volume did not meaningfully influence on the treated soil which is economically viable for engineering applications. Soil specimens were prepared at MWC of -2, 0, +2 and +4 % relative to OMC and compacted with BSL. Cementation reagent was allowed to percolate into the compacted specimens until saturation was achieved. The specimens were cured and thereafter placed in a load frame machine with driven strain controlled rate at 0.10%/min until failure occurred. The UCS of the specimens was determined at the point on the stress-strain curve at which failure happened.

3. Results and Discussion

3.1. Index Property

The untreated soil was classified as A-4(2) or SC soil in accordance with AASHTO classification system [25] and Unified Soil Classification System (USCS) [26] respectively. A summary of the characteristics of the untreated lateritic soil is shown in table 1. The particle size graph for the untreated soil is revealed in figure 1.



Figure 1. Particle size graph for the untreated soil

Table 1. Properties of the untreated lateritic soil	
Property	Quantity
Percentage Passing No. 200 Sieve	35.4
Natural Moisture Content, %	11.4
Liquid Limit, %	37.5
Plastic Limit, %	19.3
Plasticity Index, %	18.2
Specific Gravity	2.62
AASHTO Classification	A-4(2)
USCS	SC
Maximum Dry Density, Mg/m ³	1.83
Optimum Moisture Content, %	15.3
Unconfined compressive Strength(kN/m ²)	
-2% relative to OMC	278.3
0% relative to OMC	263.7
+2% relative to OMC	222.0
+4% relative to OMC	141.4

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3.2. Calcium carbonate content

One of the guiding principles for microbial soil improvement technique is the development of binding material called calcium carbonate which stiffens the soil and improves its workability. Measurement of calcium carbonate content (CCC) was done using the acid wash method [22-23]. The variation in calcium carbonate content with B. coagulans suspension density is shown in figure 2. It was observed that the quantity of calcium carbonate content formed within the soil matrix increased with increase in the population of the microbes from 0 cells/ml to 2.4 x 10⁹ cell/ml considered. The marginal increase in the value of CCC from 3.6 to 3.9 % may be associated with increase in the quantity of urease enzymes produced by B. coagulans. As the population of B. coagulans increased it is presumed that more urease enzyme was released by the microbes which enhanced the formation of calcium carbonate. [27] and [28] reported that increased

bacteria density results on greater enzyme activities because the surfaces of the microbes serve as nucleation sites that induced calcite precipitation in the soil.



Figure 2. Graph of calcium carbonate content with B. coagulans suspension density

3.3. Influence of Bacillus coagulans suspension on UCS

The plot of UCS of the compacted soil specimens with B. *coagulans* suspension density is presented in figure 3. Generally, UCS values in rise from 278.3, 263.7, 222 and 141.4 kN/m² for the untreated soil to highest values of 1835.5, 1373.9, 507.5 and 177.6 kN/m² for specimens prepared and compacted at OMC-2, OMC, OMC+2 and OMC+4, respectively. As the B. *coagulans* suspension density increased, greater quantity of calcite formed (see Figure 2) bound the soil particles together thereby increasing the strength values. The increment in UCS value can be qualified to the increasing quantity of bacteria cells that precipitated higher amount of calcium carbonate during urea hydrolysis. Similar trend was reported by [29] who used MICP technique for sand consolidation and mortar crack remediation.

[30] suggested that an arbitrary least UCS value of 200 kN/m² should be attained by compacted soil for liner and cover purposes to care the bearing stress in landfill. Satisfactory UCS values were gotten at MWC in the range 13.3 - 17.3% for both the natural soil and soil modified with B. *coagulans* suspension density of 2.4×10^9 cells/ml.



Figure 3. Graph of UCS of lateritic soil with *B. coagulans* suspension density

3.4. Influence of MWC relative to optimum moisture content on UCS

A graphical correlation between UCS and MWC is presented in figure 4. The UCS of specimens generally declined with rise in MWC regardless of the B. *coagulans* suspension density used. Similar findings were reported by [1, 10, 30-34]. For the natural soil, the UCS value deceased from 278.29 kN/m² for specimens prepared at -2 % OMC to 141.45 kN/m² when prepared at +4 % OMC. Similar trend were recorded for specimens treated with 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ ml B. *coagulans* suspension densities, when prepared at MWC of -2, 0, +2 and +4 % relative to OMC respectively. The observed trend was probably associated with the reduction in the stiffness of the soil with higher MWC. As the water content increased, the bonds between the particles were weakened thereby reducing the frictional resistance and increasing the cohesion of the soil matrix. As B. *coagulans* suspension density increased, no significant changes were observed, which implies that the quantity of water added to the soil prior to compaction significantly affected the UCS of the treated soil.



Figure 4. Graph of UCS of lateritic soil – B. coagulans mixtures with moulding water content.

3.5. Influence of dry density on UCS

The impact of dry density on UCS for varying B. *coagulans* suspension density is shown in figure 5. The observed trend depicts upturn in the strength of the compacted soil with higher dry density. It implies that a direct relationship exist between UCS and the density of the treated soil. The increase could be due to urease enzymes released by B. *coagulans* in the existence of urea and calcium source which hydrolysed urea to precipitate calcite in the pores of the soil. Inter-granular cementing material formed from urease hydrolysis may have caused the filling of the void spaces in the interior the soil matrix which densified the treated soil [29,35-37].



Figure 5. Graph of UCS of lateritic soil – B. coagulans mixtures with dry density

3.6 Regression analysis

Regression analysis generally establishes relationship between variables (i.e., one dependent variable and one or more independent variables). A multi-linear regression model generated from laboratory measured values is shown in equation (2), with UCS as dependent parameter and *B. coagulans* suspension (BS), Moulding water content (MWC), Dry density (DD), Viscosity of the microbes (Visc), pH, plasticity index (PI) and Calcite content (CC) as self-determining parameters. The model equation shows negative coefficients for MWC, DD, Visc, pH and PI while BS and CC has positive coefficient. The implication of such results indicate that as BS and CC increased, the UCS value increase, while increase in MWC, DD, Visc, pH and PI while recorded a reduction in UCS values with rise in the MWC from -2 to 4 % OMC. It implies that the quantity of water added to the treated soil should be carefully monitored during field geotechnical applications to achieve desirable UCS values. A plot of measured UCS values alongside projected values from the model indicate a strong interaction amid the measured and projected values using polynomial relationship with correlation coefficient R= 0.918 (see figure 6).

UCS =
$$7332.54 - 254.58 \text{ MWC} + 9.21 \times 10^{-8} \text{ BS} - 1625.02 \text{ DD} - 65.36 \text{ Visc} - 251.32 \text{ pH} - 58.53 \text{ PI} + 210.70 \text{ CC}$$
 (2)

 $R^2 = 72.7\%$

where:

BS = B. coagulans suspension, MWC = Moulding water content, DD = Dry density, Visc = Viscosity of the microbes, pH, PI = Plasticity index, CC = Calcite content.

The coefficients in standardized form for each of the parameter used in this investigation at 95 % confidence of interval is as presented in figure 7. The graph shows a graphical influence of each of the self-determining parameters on the UCS of the treated soil.



Figure 6. Graph of measured UCS values against predicted UCS values



Figure 7. Graph of standardized coefficients against variables at confidence level of 95 %

4. Conclusion

An evaluation of the influence of B. *coagulans* on the UCS of lateritic soil using MICP technique (which is a more sustainable and environment-friendly technique of soil improvement) was carried out in this study. The soil samples were treated with 1/3 pore volume B. *coagulans* suspension densities of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. Soil specimens were prepared at MWC of -2, 0, +2 and +4 % relative to OMC and compacted using the BSL energy. Generally, UCS values increased from 278.3, 263.7, 222 and 141.4 kN/m² for the untreated soil to peak values of 1835.5, 1373.9, 507.5 and 177.6 kN/m² for samples compacted at OMC -2, OMC, OMC+2 and OMC+4, respectively. The strength of specimens generally declined with higher MWC. For the untreated soil, UCS value decreased from 278.29 kN/m² for specimens prepared at -2 % OMC to 141.45 kN/m³ at +4 % OMC. Similar trend was also recorded for specimens treated with varying B. *coagulans* suspension density when prepared at MWC of -2, 0, +2 and +4 % relative to OMC. UCS values rise with higher dry density. Statistical analysis showed that the self-determining parameters greatly influenced the UCS values. The UCS values recorded satisfied the regulatory minimum value of 200 kN/m² for all suspension density considered when specimens were

compacted at MWC of -2, 0 and +2, respectively. The treated soil can be used as liner and cover material in waste containment application. Further studies on volumetric shrinkage, hydraulic conductivity and micro analysis are recommended to establish the suitability of B. *coagulans* as soil improvement agent in waste containment application.

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