Compatibility of Landfill Leachate with Compacted Bio cemented Lateritic Soil Using Microbial Induced Calcite Precipitation Technique

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ABSTRACT

A new soil improvement method known as microbial induced calcite precipitation (MICP) has received tremendous attention of researchers in the related fields. This paper reports the results of the compatibility of compacted bio-cemented lateritic soil with municipal solid waste (MSW) leachate. Lateritic soil was treated with Sporosarcina pasteurii (S. pasteurii) suspension densities up to 2.40 x 10⁹ cells/ml and compacted using British Standard light, BSL (or standard Proctor) energy. The permeation with leachate only yielded minimum hydraulic conductivity values of 5.02 x 10⁻¹⁰ m/s for the natural soil and 5.78 x 10⁻¹⁰ m/s for specimen treated with S. pasteurii suspension density of 2.40 x 10⁹ cells/ml. The micrographs of specimens treated with S. pasteurii suspension density of 2.40 x 10⁹ cells/ml and permeated with leachate only depicted the development of bio-film when compared with micrograph of the untreated soil. Test results showed significant reduction in the concentration of the MSW leachate chemical specie considered after interaction with S. pasteurii for 150 days either through bio-transformation or bio-degradation process.

Keywords: Bio-cementation, Bio-degradation, Bio-film, Lateritic soil, Leachate, S. pasteurii.

1 INTRODUCTION

There are several methods utilised in the improvement of soils for engineering use. However, environmental and sustainability issues associated with these methods have led to the discovery of a technique known as microbial induced calcite precipitation (MICP). MICP has recently attracted the interest of multidisciplinary researchers from microbiology, chemistry and civil engineers as a natural biological motivated procedure that makes the use of ureolytic bacteria to hydrolyse urea to produce calcite and related carbonate ions (Mujah et al., 2016). The product responsible for the soil improvement in MICP is the calcite or the by-product of the reaction between a urease producing micro-organism in the presence of calcium source (Keykha et al., 2017). MICP has been reported in literature as an alternative and sustainable soil improvement method in terms of strength and stiffness, remediation of chemical species in soil, soil liquefaction resistance and erosion control (Whiffin et al., 2007; DeJong et al., 2013; Osinubi et al. 2017b; 2018a; 2019a; Mujah et al. 2019). Several biological procedures that can lead to calcite precipitate have also been reported; however, urea hydrolysis has been more widely used because the mechanism is straightforward and can produce up to 90% chemical conversion efficiency of precipitated amount of calcite in less than 24 hours (Cheng et al., 2016; Mujah et al., 2017). Suitable materials for use in MSW containment facilities are required to have volumetric shrinkage strain not exceeding 4 % (Albrecht and Benson, 2001). Unconfined compressive strength exceeding 200 kN/m², to endure stability against forces capable of destroying its material connection (Daniel and Wu, 1993). Hydraulic conductivity with a maximum value of 1x10⁻⁹ m/s; to ensure that the chemical specie in the leachate resulting from the waste can effectively be attenuated as well as contained, to properly protect the groundwater/drinking water aquifer from pollution (Pal et al. 2017). In addition to these parameters, the
material must satisfy compatibility requirements with the MSW leachate. A liner material is compatible with leachate when a long interaction between the two materials does not compromise the three parameters stated above (Shackelford and Kristin, 2014; Osinubi et al., 2017a). This study focused on evaluation of the compatibility of compacted lateritic soil - S. pasteurii mixtures with MSW leachate considering the interactions between: (i). the natural soil and MSW leachate; (ii). lateritic soil treated with S. pasteurii suspension density of 2.40 x 10⁹ cells/ml and MSW leachate; (iii). S. pasteurii and synthetic leachate; (iv). S. pasteurii and MSW leachate.

MATERIALS AND METHODS

2 MATERIALS

Soil: The lateritic soil used in the study was obtained from Abagan (Latitude 6°10'15'' N and Longitude 6°58'10'' E), Anambra state, Nigeria, at depths between 0.5 m and 3.0 m using the disturbed sampling method.

Bacteria: The species of bacteria used in this research is S. pasteurii, which are commonly found in soils. The urease positive bacteria is rod-shaped, spore-forming and Gram-positive; it was cultured and grown from the lateritic soil sample.

Cementation reagent: The composition of cementation reagent reported by researchers (e.g., Stocks-Fischer et al., 1999; Dejong et al., 2006; Tirkolaei and Bilsel, 2017; Mujah et al., 2019 and Osinubi et al., 2020a) was used in the study. The reagent was composed of 20 g Urea, 10 g NH₄Cl, 3 g Nutrient broth, 2.8 g CaCl₂ and 2.12 g NaHCO₃ per litre of de-ionized water. In all the studies cited, 3g/l of nutrient broth was added into the cementation reagent because it is the most viable amount for survival of bacteria (Sharma and Ramkrishnan, 2016).

Leachate: The MSW leachate used in this study was obtained from an unengineered dump site located in Zaria.

3 METHODS

Urease production: The test organisms inoculated on urea agar slant, was incubated at 37°C for 24 hours and were able to break down urea agar slant. This made the culture media alkaline in nature and changed its colour to red-pink thus indicating that the test organism was urease positive.

Bacteria cell suspension density: The S. pasteurii suspension densities used are: 0/ml, 1.50 x 10⁹/ml, 6.0 x 10⁹/ml, 1.20 x 10⁹/ml, 1.80 x 10⁹/ml and 2.40 x 10⁹ cells/ml, equivalent to 0, 0.5, 2, 4, 6 and 8 McFarland standards, respectively. The maximum volume of organisms added to the soil was one-third (1/3) of the pore volume as reported by Rowshankanbakh et al. (2016).

Index properties: Natural moisture content, specific gravity, Atterberg limits and sieve analysis were conducted in accordance with test procedures outlined in BS 1377:1990. Thereafter, the amount of S. pasteurii for varying suspension densities and cementation reagent were calculated. The methods adopted involved the use of 75 % of liquid limit (LL) for the natural soil to be S. pasteurii suspension (bac) and 25 % of liquid limit of the natural soil to be cementation reagent (cem) thus making a total of 100 % LL (i.e., 75 % S. pasteurii - 25 % cementation reagent). Each test was carried out in duplicate for S. pasteurii suspension densities stated in section above. The treated soil specimens were air-dried in the laboratory at an ambient temperature of 24 ± 2°C before carrying out Atterberg limits tests.

Compaction characteristics: Specimens were compacted with British Standard light (BSL) energy in accordance with the procedures outlined in BS 1377 (1990) to obtain moisture – density relationships. The BSL compaction energy is obtained from 2.5 kg rammer falling through 30 cm onto three layers with each receiving 27 blows.

Preparation of specimen: 3000 g of the crushed air-dried soil sample passed through BS No. 4 sieve (4.76 mm aperture) was thoroughly mixed with +2 % moulding water content wet of optimum moisture content (OMC) containing 1/3 of its pore volume as the S. pasteurii suspension density. Compacted specimens were permeated with 2/3 of their pore volume of the cementation reagent under gravity in three 6 hours’ interval circles each to initiate and facilitate the MICP process.

Compatibility test: The compatibility of the natural and treated lateritic soil with MSW leachate was studied using hydraulic conductivity test in a rigid wall permeameter, under the falling head condition as recommended by Head (1994) in conjunction with the
During the permeation period, specimens compacted using BSL (or standard Proctor) energy were placed in an immersion tank for 48 hours to ensure full saturation before permeating with water only and leachate only. The first set of saturated untreated specimens were immediately connected to the permeant (tap water only) for a period of 91 days. The second set of saturated treated specimens was immediately connected to MSW leachate only for a period of 91 days. During the permeation period, readings were taken every 24 hours to compute the hydraulic conductivity values.

### Compatibility of S. pasteurii with synthetic leachate:
Synthetic leachate used in this study was prepared by mixing 250 ml of distilled water with CuSO₄, PbNO₃, and Cd in five concentrations in the range 1–5 % by weight per volume (Osinubi et al., 2019b). S. pasteurii was inoculated into each concentration, and the growth pattern of the organism was observed for a period of 30 days using spectrophotometer. The measured unit weight of the synthetic leachate was 7.5 kN/m².

### Compatibility of S. pasteurii with MSW leachate:
Compatibility of S. pasteurii with MSW leachate was investigated by inoculating pure culture of the test organism into five (5) different MSW leachates obtained from different un-engineered dumpsites in the study area. Literature has reported varying unit weights for MSW leachate, however, typical value in which the sampling condition were similar is 12 kN/m² measured in situ as reported by Zornberg et al. (1999) for leachate sampled below 10 m depth. The growth of the S. pasteurii was monitored every 3 days up to a maximum of 150 days. The concentration of each chemical specie in the leachate was measured before and after the interaction of the organism with the leachate using PG instruments ‘AA 500 Spectrophotometer’.

### Microanalysis:
Microanalysis using scanning electron microscope (SEM) was conducted on both natural and MICP treated lateritic soil to investigate the changes in morphological features due to the formation and distribution of calcite bonds on the inter particle surface in the micro-structure of the soil. The test was carried out using Phenom World Pro desktop SEM equipped with a software tool that could automate data collection and duplicate analysis. (Phenom World, 2017).

### RESULTS AND DISCUSSION

#### Urease test
The urease test qualifies an organism for use as ureolytic organism in the hydrolysis of urea. The result of urease test conducted on S. pasteurii is shown in Fig. 1. Urea hydrolysis was used in MICP because of its high efficiency in the conversion of the chemical reaction into calcite within a very short period. Therefore, for a test organism to be used in this method, it must secrete urease enzyme. The pink colour observed on Fig. 1 indicates that S. pasteurii organism is urease positive. Its reaction with urea in the cementation reagent results in the precipitation of calcite which is the required product of MICP.

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Table 2: Oxide composition of the natural lateritic soil

| Oxide  | SiO₂ | Al₂O₃ | CaO | TiO₂ | V₂O₅ | Fe₂O₃ | ZrO₂ | LOI | Total  |
|--------|------|-------|-----|------|------|-------|------|-----|--------|
| Concen. (%) | 56.5 | 19.00 | 0.33 | 2.89 | 0.06 | 15.41 | 0.29 | 4.54 | 99.02  |

*Legend (LOI) = Loss on ignition.

**Atterberg limits:** The variation of Atterberg limits with *S. pasteurii* suspension density is shown in Fig. 2. The LL initially decreased from 44.0 % for the natural soil to a minimum value of 36.5 % before increasing to 38.0 % when treated with *S. pasteurii* suspension density of 2.40 x 10⁹ cells/ml. The PI gradually decreased from a value of 22.5 % for the natural soil to 17.8 % for the treated soil at *S. pasteurii* suspension density of 2.40 x 10⁹ cells/ml. It is pertinent to state that decrease in PI value is desirable for any method adopted for the improvement of soil for engineering use. The results obtained suggest that the method employed for soil improvement in this study is appropriate.

![Fig. 2 Variation of Atterberg limits of lateritic soil with *S. pasteurii* suspension density](image)

**Hydraulic conductivity:** The variation of hydraulic conductivity (k) lateritic soil - *S. pasteurii* mixtures under permeation conditions with water and leachate only for 90 days is shown in Fig. 3. For the natural soil, it was observed, that the least k value of 2.38 x 10⁻⁹ m/s recorded on the 6th day marginally changed throughout the test period. However, the k value of specimen treated with *S. pasteurii* density of 2.40 x 10⁹ cells/ml slightly increased from 2.87 x 10⁻⁹ m/s on the 1st day to 5.28 x 10⁻⁹ m/s on the 77th day before slightly decreasing to 3.25 x 10⁻⁹ m/s at the end of the test on the 90th day. The least k value of 1.88 x 10⁻⁹ m/s was recorded on the 3rd day. The results recorded showed that the k values of the specimens tested are greater than the design maximum k criterion of 1 x 10⁻⁹ m/s. Furthermore, the k value of the natural soil permeated with leachate only between the 1st and 78th day was virtually constant at 1.75 x 10⁻⁹ m/s; between the 79th and 90th day, the k value decreased from 9.02 x 10⁻¹⁰ m/s to 5.09 x 10⁻¹⁰ m/s. The least k value of 5.02 x 10⁻¹⁰ m/s was recorded on the 88th day. For specimen treated with *S. pasteurii* suspension density of 2.40 x 10⁹ cells/ml, the k value marginally decreased with test period. It decreased from 7.50 x 10⁻⁹ m/s up to the 83rd day, when a value of 9.04 x 10⁻¹⁰ m/s was recorded and it further decreased to 5.78 x 10⁻¹⁰ m/s at the end of the test on the 90th day when the least value was recorded. Although chemical equilibrium was not achieved from the results, continuous decrease in k value with time is envisaged. The reduction in k recorded for the treatments considered aside the precipitation of calcite in the voids could also probably be attributed to the formation of bio-film from the interaction between *S. pasteurii* and other organisms in the soil and the leachate, since the leachate was filtered through 53 µm sieve aperture before testing.
Compatibility of *Sporosarcina pasteurii* with synthetic leachate

The initial concentration of chemical species before inoculation of *S. pasteurii* and final concentration of chemical species after 150 days' interaction with five different MSW leachates are summarized in Tables 3 and 4. An increase was recorded in the range of 12.75 to 56.91 % in pH values of the leachate after interaction was recorded, with leachate 4 and 1 having the lowest and highest increase respectively, the observed trend has been reported in literature to be a favorable requirement for effective MICP process. The concentration of Ca²⁺, K⁺ and Na⁺ decreased considerably at the end of the period of interaction between the leachates and *S. pasteurii* with Na⁺ recording the highest reduction. This could be due to bio degrading ability of *S. pasteurii* on the chemical specie (Achal et al., 2013; Kumari et al., 2014; Anbu et al., 2016 and Osinubi et al., 2019b). In addition, the observed reduction could probably be because a selective media was used in the isolation and growth of the pure culture of *S. pasteurii*, which suggests that the organism fed on Na⁺. On the other hand, Mg²⁺, Fe, Mn and Cu²⁺ were observed to increase in concentration after the interaction period, which also could not be unconnected with the bio transformation ability of *S. pasteurii* during MICP processes (Achal et al., 2011; 2012; Rajasekar et al., 2017 and Osinubi et al., 2020b). Furthermore, Cr and Pb marginally decreased after the interaction period, which also could not be recorded, with leachate 4 and 1 having the lowest concentration of chemical species in the five (5) MSW leachates considered.

Scanning Electron Microscopy: The micrographs for all the specimens at x1000 magnification for natural soil permeated with water (A) and leachate (A1) only are shown in Fig. 5. Micrograph A1 has lesser micro cracks than in A, which is supportive of the higher hydraulic conductivity values recorded for natural soil permeated with water only than those permeated with leachate only. Micrographs for soils treated with *S. pasteurii* suspension density of 2.40 x 10⁹ cells/ml and permeated with water (B) and leachate (B1) only depict visible calcites as well as spongy material (bio-film); probably responsible for the recorded decrease in hydraulic conductivity values during permeation with leachate only, when compared to those permeated with water only. The SEM results show that permeation of lateritic soil treated with *S. pasteurii* suspension density of 2.40 x 10⁹ cells/ml with MSW leachate facilitated the formation of bio-film, which contributed to decrease in hydraulic conductivity values.

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CONCLUDING REMARKS

From the study carried out and the results presented, the following conclusions can be made: Treatment of an A-4(3) soil with S. pasteurii resulted in decreased plasticity index (PI) values which is desired in soil improvement for engineering use. The results presented suggest that lateritic soil - S. pasteurii mixture is compatible with the leachate. The toxicity effect of the synthesized leachate on the growth pattern of S. pasteurii indicates that 4 % chemical specie concentration gave the best performance. S. pasteurii bio-degraded and bio-transformed the concentration of the chemical species in the MSW leachates considered. Investigation using the same treatment compacted at higher energy is recommended.

Table 3: Initial concentration of chemical specie before inoculation of S. pasteurii

| Parameter | Leachate 1 | Leachate 2 | Leachate 3 | Leachate 4 | Leachate 5 |
|-----------|------------|------------|------------|------------|------------|
| pH        | 5.50       | 6.91       | 6.68       | 8.16       | 7.12       |
| Ca²⁺ (mg/l) | 1240       | 665        | 965        | 1055       | 1290       |
| K⁺ (mg/l)  | 1055       | 335        | 485        | 775        | 330        |
| Na⁺ (mg/l) | 44050      | 60850      | 38500      | 62800      | 7600       |
| Mg²⁺ (mg/l) | 8.482      | 27.27      | 27.714     | 8.948      | 3.188      |
| Fe (mg/l)  | 0.4996     | 0.6383     | 0.2865     | 0.1622     | 0.1726     |
| Mn (mg/l)  | 0.0467     | 0.0093     | 0.1599     | 0.0412     | 0.0477     |
| Cu²⁺ (mg/l) | 0.029      | 0.0109     | 0.0017     | 0.0012     | 0.0002     |
| Zn (mg/l)  | 0.0084     | 0.0253     | 0.0047     | 0.0081     | 0.0237     |
| Cr (mg/l)  | 0.0482     | 0.0432     | 0.0727     | 0.0340     | 0.0734     |
| Pb (mg/l)  | 0.0728     | 0.0205     | 0.0091     | 0.0418     | 0.0619     |

Table 4: Final chemical specie concentration after 150 days’ interaction with S. pasteurii

| Parameter | Leachate 1 | Leachate 2 | Leachate 3 | Leachate 4 | Leachate 5 |
|-----------|------------|------------|------------|------------|------------|
| pH        | 8.63       | 8.51       | 8.50       | 9.20       | 8.36       |
| Ca²⁺ (mg/l) | 44.19      | 130.65     | 125.49     | 147.49     | 101.04     |
| K⁺ (mg/l)  | 756        | 240        | 400        | 585        | 225        |
| Na⁺ (mg/l) | 4500       | 3300       | 4800       | 5200       | 6200       |
| Mg²⁺ (mg/l) | 32.38      | 31.512     | 35.76      | 37.57      | 32.392     |
| Fe (mg/l)  | 62.51      | 25.94      | 60.04      | 55.57      | 56.20      |
| Mn (mg/l)  | 3.76       | 3.05       | 9.64       | 5.26       | 2.25       |
| Cu²⁺ (mg/l) | 2.66       | 1.66       | 4.32       | 1.94       | 2.36       |
| Zn (mg/l)  | 7.26       | 2.55       | 8.60       | 5.14       | 3.78       |
| Cr (mg/l)  | 0.048      | 0.017      | 0.069      | 0.064      | 0.076      |
| Pb (mg/l)  | 0.070      | 0.011      | 0.009      | 0.0412     | 0.0453     |
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