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Microbially Treated Lateritic Soil as a Landfill Liner Material

Kavya K. S.[1] and Ajitha A. R.[2]

College of Engineering, Trivandrum, Kerala, 695016
kavyasasidharan07@gmail.com

Abstract. With the growing population and urbanization, there is huge hike in the amount of waste generated on earth. Landfilling is one of the most convenient methods for bulk disposal of waste generated by mankind. Landfill liners serve to prevent the contamination between the waste and the surrounding environment, especially groundwater during landfilling process. Landfill liners are usually made of geocomposites based on clayey soil. Previous studies reveal that bacteriological treatment on sandy soil has greater potential in geotechnical engineering applications, in terms of performance and environment sustainability.

Lateritic soil with an appreciable amount of sand is abundantly found in Kerala. Therefore the study was focused on designing a new landfill liner material using lateritic soil amended by Microbially Induced Calcium Carbonate Precipitation (MICP) method. As per the guidelines of Environmental Protection Agency [1], a soil liner is required to have a hydraulic conductivity below 1 x 10^{-7} cm/s. The effect of MICP treatment on hydraulic conductivity of the lateritic soil was investigated. Bacillus megaterium is chosen as the bacterium for triggering calcite precipitation in soil. The results show that MICP treatment reduces the hydraulic conductivity of lateritic soil by a considerable amount.

Keywords: Landfill Liner, Lateritic, Microbial, Calcite.

1 Introduction

Ground improvement is a fundamental and essential part of civil engineering construction strategies now a days. The two main traditional ground improvement techniques are mechanical compaction and chemical treatment. Mechanical compaction is the process of applying mechanical energy to a soil mass so as to rearrange the particles and making it dense through the reduction of voids between soil grains. The mechanical compaction possesses some drawbacks like requirement of large equipments, high cost and causes disturbance to the surrounding ground and structures. Chemical treatment involves the introduction of foreign materials like chemicals, cement, etc. into the soil which can improve the soil properties. Most of the artificial synthetic materials that are introduced into soil are toxic, which threatens the natural environment and people's health.

The above mentioned limitations in the current practice of soil improvement necessitate exploration of new alternative technologies which are preferably eco-friendly, sustainable and able to fulfil the increasing demands for ground improvement. Microbiologically Induced Calcium Carbonate Precipitation (MICP) is such a technique which can improve ground with the aid of microbial activities taking place within the soil.

With the growing population and urbanization, there is huge hike in the amount of waste generated on earth. Landfilling is one of the most convenient methods for the bulk disposal of wastes. Leachate is a contaminated liquid, which is generated on account of the infiltration of water into landfills and its percolation through waste as well as by the squeezing of the waste due to self-weight. Landfill liners serve to prevent the contamination between the waste and the surrounding environment, especially groundwater during landfilling process. Landfill liners are usually made of geocomposites based on clayey soil. Previous studies reveal that microbial treatment on sandy soil has greater potential in geotechnical engineering applications, in terms of performance and environment sustainability. Lateritic soil is abundantly available in Kerala and MICP treatment shows good performance in reducing the permeability and improving the strength of coarse-grained soils. MICP is also proposed as a potential bioremediation method to immobilize contaminating metals and metalloids in soil. As a preliminary study, an investigation was made to find the effect of MICP treatment on hydraulic conductivity of lateritic soil.

1.1 Microbially Induced Calcium Carbonate Precipitation

MICP is a bio-geochemical process that induces calcium carbonate precipitation within the soil matrix due to the action of micro-organisms present in soil. The microbes can induce MICP in soil through several mechanisms such as urea hydrolysis, denitrification, sulphate reduction, methane oxidation etc.

Urea hydrolysis is the most preferred $CaCO_3$ precipitation mechanism because it can be easily controlled and possesses about 90% of $CaCO_3$ production efficiency in a short period of time. Bacteria cells get attached to the surface of soil particles when bacterial solution is added to the soil. Urease positive bacteria causes hydrolysis of urea during their metabolic process to produce ammonium and carbonate ions. Hydrolysis reaction of urea is represented by Equation 1.

$$CO(NH_2)_2 + H_2O \rightarrow CO_3^{2-} + 4NH_4^+ \quad (1)$$

Bacterial cell surfaces have negatively charged groups that act as scavengers for Ca^{2+} which is derived from the cementation solution ($CaCl_2$) added to soil. The Ca^{2+} ions and CO_3^{2-} ions produced by urea hydrolysis combine together to precipitate $CaCO_3$ crystals in the soil pores (Equation 2).

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (2)$$

2 Materials

MICP treatment on lateritic soil was performed using Bacillus megaterium bacterium and $CaCl_2$ solution which was used as the cementation reagent.

2.1 Lateritic Soil

Laterite is commonly referred as a soil type as well as a rock type. It is rich in iron and aluminium, and is commonly considered to have formed in hot and wet tropical areas. Nearly all laterites are of rusty-red coloration, because of high iron oxide content. The texture of laterite soil is mostly gravel. It is acidic due to heavy rainfall and leaching out of bases and possesses low cation exchange capacity. Laterites are developed by intensive and prolonged weathering of the underlying parent rock. Tropical weathering (laterization) is a prolonged process of chemical weathering which produces a wide variety in the thickness, grade, chemistry and ore mineralogy of the resulting soils.

Lateritic soils are red to reddish brown in colour and vary in type from a poorly graded sand to a highly plastic clay. These soils have some secondary iron cementing between particles and a specific gravity in the range of 2.73 to 3.12. When this material is undisturbed, it is fairly well drained, however after being disturbed it is relatively impermeable and plastic. Typically these soils excavate as a fine grained material with a percentage of soil components of about 40 to 50 % sand, 30 to 40 % silt and 20 to 30 % clay. The significant difference between a laterite and lateritic soil is the presence of gravel components in a laterite and their possible absence in a lateritic soil. An important physical consideration of a lateritic soil is that it will not harden irreversibly upon drying while laterite gets harden irreversibly upon drying [2].

Lateritic soil is abundantly available in Kerala. Soil map of Kerala is shown in Figure 1.

Lateritic soil for the study is collected as disturbed samples from a site in College of Engineering Trivandrum, shown in Figure 2. The soil samples are collected from a depth of 3 m below the natural earth surface to avoid the influence of organic matter. The properties of the soil sample collected is presented in Table 1.

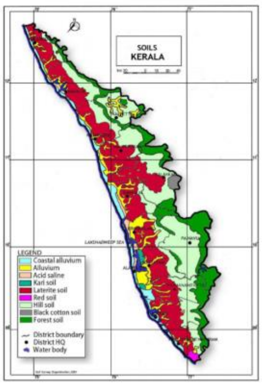

Fig 1. Soil map of Kerala [3]

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Fig 2. Lateritic soil at a site in College of Engineering, Trivandrum

Table 1. Properties of the soil used for the study.

Property	Value
Insitu water content	21.40 %
Percentage of gravel	27.40 %
Percentage of sand	33.00 %
Percentage of coarse sand	8.60 %
Percentage of medium sand	15.40 %
Percentage of fine sand	9.00%
Percentage of silt and clay	39.60 %
Specific gravity	2.56
Maximum dry density	1.82 g/cc
Optimum moisture content	15.00 %
Liquid limit	61 %
Plastic limit	36 %
Plasticity index	25 %
USCS soil classification	SM

2.2 Microorganism

The urease-producing microorganism used in the current study is Bacillus megaterium. Bacillus megaterium is a gram-positive bacterium that can be found in a broad habitat range, however, it is mainly found in soil. It has been proven to have the ability to induce calcite precipitation in natural soils. Bacillus megaterium is one of the largest known eubacteria. The selection of B. megaterium as the urease-producing microorganism in the current study was based on these considerations;

a) Bacillus megaterium can be found in abundance in natural tropical soils.
b) It is an anerobic species.
c) It is non-pathogenic.
d) It lives on and get its nourishment from dead organisms or decaying organic material.
e) The large and elongated rod-shaped cell may provide the advantage of avoiding being flushed out during injection of the cementation reagent or by intense tropical rain.
f) Bacillus megaterium can form endospores that are highly resistant to extreme environmental conditions.

These characteristics of B. megaterium provide enormous advantages for its usage as a calcite precipitating agent in lateritic soil. Bacillus megaterium bacteria culture (MTCC No. 6544) in freeze-dried form was obtained from Microbial Type Culture Collection and Gene Bank (MTCC), Chandigarh. The freeze-dried culture is obtained in a sealed glass tube, shown in Figure 3. The composition of nutrient broth for bacterial growth is obtained from the catalogue of MTCC [4], Chandigarh and is detailed in Table 2.

Fig. 3. Bacteria culture in freeze dried form obtained in sealed glass tube

Table 2. Composition of nutrient broth for growth of bacteria

Component	Quantity per litre of distilled water (g)
Beef extract	1
Yeast extract	2
Peptone	5
Sodium chloride	5

2.3 Cementation Reagent

The composition of cementation solution used is given in Table 3 and the composition has been selected with reference to a work done by Soon N. W. et. al.[5] on MICP technique, for improving the engineering properties of a typical tropical residual soil using Bacillus megaterium bacterium.

Table 3. Properties of the soil used for the study.

Component	Quantity (g/L)
Urea	20.00
Calcium chloride	2.80
Nutrient broth	3.00

3 Methodology

3.1 Preparation of Bacterial Solution

To prepare the nutrient broth, 250 mL distilled water is taken in a conical flask and the components are added to it proportionately. The solution is shaken well and heated slightly so that all the components get completely dissolved, shown in Figure 4.

Fig. 4. Nutrient broth being heated.

The mouth of the flask is then plugged with cotton and is kept in a pressure cooker for sterilization. After sterilization, freeze-dried culture in powder form is put into the nutrient broth. The culture is then incubated at 37^0 C for 48 hours. After the incubation period the solution turns turbid from its clear form, which confirms the growth of bacteria in the broth. The sterilized nutrient broth before the growth of bacteria is shown in Figure 5. The concentration of bacterial solution after different growth period was determined by counting the number of bacteria colonies under a microscope.

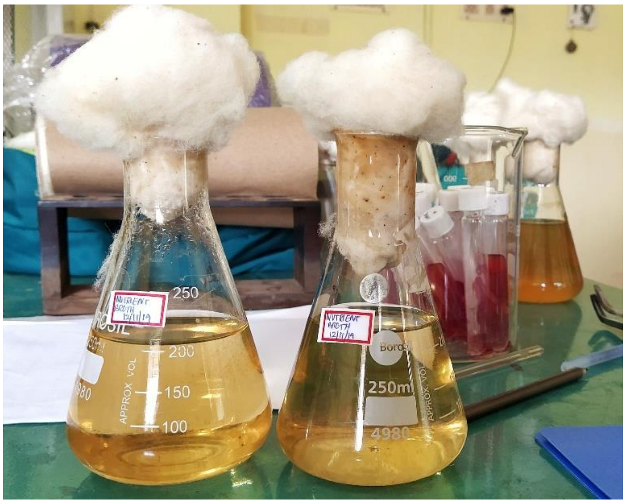

Fig. 5. Nutrient solution after sterilisation

3.2 MICP Treatment on Soil and Testing of Treated Soil Samples

Oven dried soil finer than 425 μ was taken for the study. Samples are prepared at optimum moisture content of 15%. The moulding water comprised of bacterial solution and cementation solution. The volume of bacterial solution is equal to 1/3rd of pore volume of soil and the remaining volume is of cementation solution.

In the first stage, soil is treated by MICP through three different methods; i.e., injection, surface percolation and premixing. The concentration of bacterial solution is kept same for all the cases, i.e., 1.5 x 10^8 cells/mL. The different methods of MICP treatment in soil is discussed below.

Injection Method

Soil specimens are prepared at maximum dry density inside the moulds. Then the bacterial solution is injected to the top of the specimen at a pressure of 20 kPa. The pressure of injection was ensured by allowing the flow of bacterial solution into the soil from a height of 2 m. After a contact period of 24 hours which ensures saturation of Bacillus megaterium within the soil mass, cementation solution is injected into soil. The soil specimen is kept air tight for a curing period of 7 days before testing. The line sketch of test setup is shown in Figure 6.

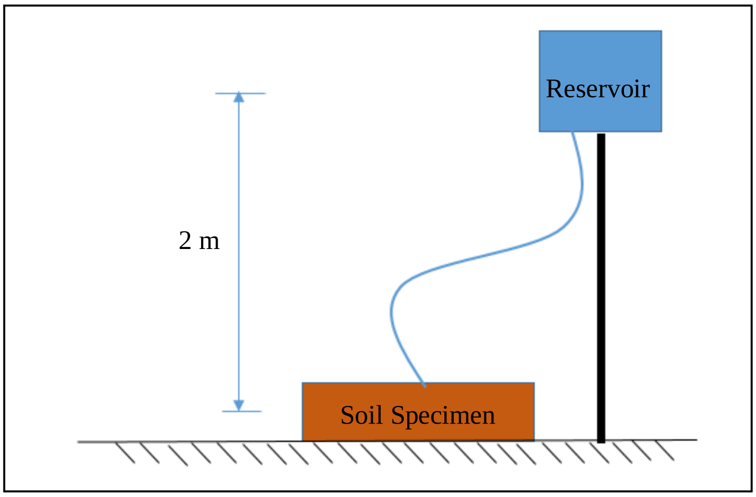

Fig 6. Test setup for injection method of MICP treatment

Surface Percolation Method

In this method, soil is filled into the mould at maximum dry density. Then the bacterial solution is simply sprayed over the top of the specimen so that it can freely percolate into the soil specimen. After a contact period of 24 hours which ensures saturation of Bacillus megaterium within the soil mass, cementation solution is sprayed over the soil. The specimens are kept for 7 days curing in air tight condition. After the curing period the specimen is subjected to testing.

Premixing Method

In premixing method, soil is thoroughly mixed with bacterial solution and kept aside in an air-tight polythene bag for 24 hours for ensuring saturation of Bacillus megaterium within the soil mass. After 24 hours, the specimens are prepared at maximum dry density and then the cementation solution is allowed to freely percolate into the soil specimens. Then the specimens are kept for 7 days curing in air tight condition before testing.

4 Results and Discussion

4.1 Determination of Best Method of Execution of MICP in Lateritic Soil

In order to determine the best method of execution of MICP in lateritic soil, hydraulic conductivity of soil samples treated by three different methods are compared against each other. The concentration of bacterial solution is kept same for all these tests (1.5 x 10^8 cells/mL) and the samples are tested after a curing period of 7 days.

The results of the hydraulic conductivity tests of soil treated with bacterial solution with concentration of 1.5 x 10^8 cells/mL after 7 days of curing is presented in Table 4. It can be observed that due to MICP treatment hydraulic conductivity of the soil sample gets reduced. The loss of permeability of soil is due to the occupation of $CaCO_3$ crystallization in the soil pores.

Table 4. Permeability of soil samples treated with bacterial solution with concentration of 1.5 x 10^8 cells/mL after a curing period of 7 days.

Condition of sample	Method of execution of MICP in soil	Permeability (cm/s)
Insitu	-	6.1 x 10^{-5}
MICP treated	Premixing	7.3 x 10^{-6}
MICP treated	Surface percolation	5.3 x 10^{-5}
MICP treated	Injection	7.8 x 10^{-6}

Diagrammatic representation of comparison of hydraulic conductivity of soil samples treated through three different methods of MICP is shown in Figure 7. Permeability of soil samples reduced from the order of 10^{-5} cm/s for insitu soil to 10^{-6} cm/s for MICP treated samples prepared through injection and premixing method. Premixing method produced sample with the least permeability. This may be because during premixing calcite precipitation occurs uniformly in all soil voids which leads to bio-clogging. There is no considerable amount of reduction in permeability for samples prepared through surface percolation method. This may be because of the compaction effort that cemented the soil to such an extent, which created a low infiltration rate of the bacterial solution into the soil.

Since hydraulic conductivity is the primary criterion adopted while designing a liner material, premixing is assumed as the best method for MICP treatment in lateritic soil. Further studies were conducted on premixed soil samples.

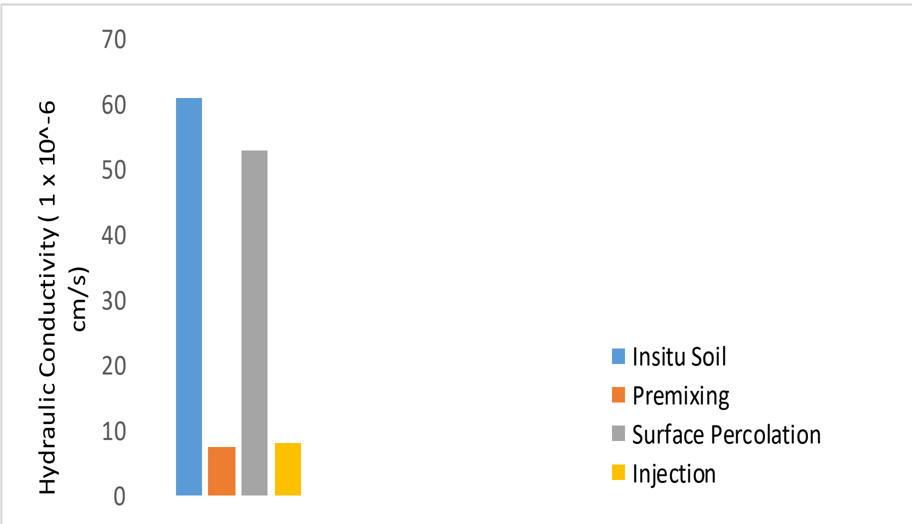

Fig 7. Comparison of hydraulic conductivity of soil samples

4.2 Variation of Hydraulic Conductivity with Concentration of Bacterial Solution

The effect of concentration of bacterial solution on hydraulic conductivity of pre-mixed MICP soil sample after a curing period of 1 month is shown in Figure 8. It is clear that the hydraulic conductivity of soil reduced with increase in the initial concentration of bacterial solution. The hydraulic conductivity of soil reduced from 6.1 x 10^{-5} cm/s to 0.4 x 10^{-7} cm/s at a bacterial solution concentration of 18 x 10^{8} cells/mL after a curing period of 1 month.

Bacteria get attached to the soil and act as nucleation sites for calcite precipitation to occur. Hence, more the bacterial concentration more will be the amount of calcite precipitation which results in higher reduction of permeability of soil.

Lateritic soil treated with 18 x 10^{8} cells/mL of bacterial solution after a curing period of 1 month possessed hydraulic conductivity below 1 x 10^{-7} cm/s and UCS above 200 kPa. Hence the MICP treated lateritic soil satisfies primary requirements of a landfill liner material under the above said conditions.

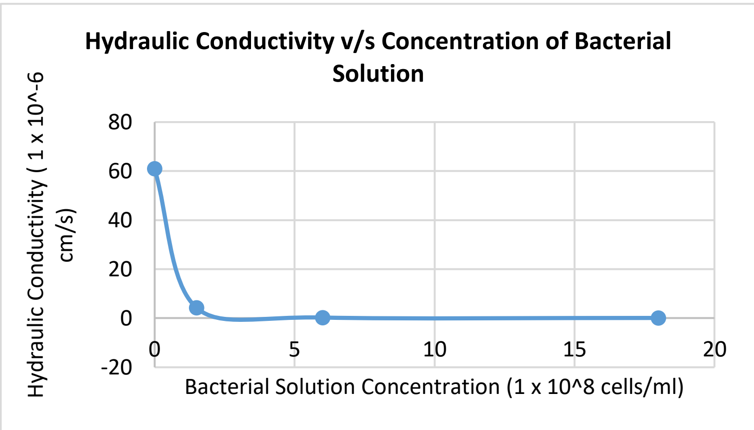

Fig 8. Effect of concentration of bacterial solution on hydraulic conductivity of premixed MICP soil sample after a curing period of 1 month

5 Conclusions

The following points can be summarized from the study conducted on lateritic soil finer than 425 µ treated with MICP technique.

1. Premixing proved to be the best method of execution of MICP in lateritic soil, when compared to injection and surface percolation method.

2. Hydraulic conductivity of lateritic soil reduces with increase in initial concentration of bacterial solution. Permeability of soil reduced from 6.1 x 10^{-5} cm/s to 0.4 x 10^{-7} cm/s at a bacterial concentration of 18 x 10^{8} cells/mL after a period of 1 month.
3. Lateritic soil finer than 425 μ treated with 18 x 10^{8} cells/mL of bacterial solution after a curing period of 1 month satisfies the primary requirements of a liner material. The hydraulic conductivity and unconfined compressive strength obtained of the same satisfies the requirements of a landfill liner as per guidelines of EPA 2013 [1].

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