Evaluation of compacted lateritic soil – *Bacillus coagulans* induced calcite precipitate for landfill application using bacterial foraging optimization algorithm

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**Abstract**: Evaluation of compacted lateritic soil – *Bacillus coagulans* (*B.coagulans*) induced calcite precipitate for landfill application was carried out using Bacterial Foraging Optimization Algorithm (BFOA). Experimental results were obtained through laboratory tests. Measured soil factors include; Coefficient of permeability (hydraulic conductivity) as a dependent factor and void ratio, bulk density, *B. coagulans* suspension, pH, Compactive effort, water content relative to optimum, plasticity index, viscosity of microbes and liquid limit as self-determining (independent) factors. GeneXproTools 5.0 software was used to develop the fitness (objective) function used for Bacterial Foraging Optimization (BFO) to predict hydraulic conductivity of treated lateritic soil with *B. coagulans* suspension density. The fitness function was then integrated using BFO codes in Matlab 2016 version to predict the minimum hydraulic conductivity for a given set of self-determining factors. The result shows a strong association between the predicted hydraulic conductivity values and the measured hydraulic conductivity values in the laboratory using a regressed line with coefficient of determination R²=0.85. It is clear from the optimization results that the hydraulic conductivity values and the self-determining variables have strong correlation. The least hydraulic conductivity value of 2.38×10⁻¹¹ m/s which falls below the permissible regulatory value of 1.0×10⁻⁹ m/s for landfill application was achieved at 100 iterations. Based on all the optimization results, it is recommended that lateritic soil-*B.coagulans* mixtures be compacted with 1.20×10⁸ - 2.40×10⁸ cells/ml *B.coagulans* suspension density compacted using British standard heavy (BSH) energy at 15.3 % moisture content for landfill application

**Keywords**: Bacterial foraging optimization, Bacillus coagulans, Iterations, Lateritic soil, Objective function.
1. Introduction

Soil improvement using soil microbes is a new practice which uses bacterial activity in the improvement of properties of soil. This method applies biochemical mechanism to increase soil engineering performance (i.e. strength and hydraulic properties). Bio-clogging is a process that involves the reduction in hydraulic conductivity of soil and porous rocks by pore filling materials (calcite). Calcite is produced as a result of microbial activity [1]. Microbial activity involves the production of calcite via microbial means, this helps to reduce the soil porosity, hydraulic conductivity, blocks soil pore throats, subsequent establishment of aggregations and as well as biofilms to restrict movement of fluid within the soil matrix [1-2]. Optimization or optimality is an act of minimizing or maximizing an equation/function done by choosing the values of integer variables analytically from inside a tolerable interval [3]. It involves the selection of a best option or amount in several options using mathematical and computer programming approach. The best option is referred to as the optimal value in terms of minimum or maximum among set of outcomes. [3] reported that optimization problems are categorised into two major parts namely, the objective or fitness function, and the set of constraints. Objective or fitness function defines the routine principles for the structure. Constraints define the margins and limits beneath which the structure is investigated.

However, the constraints comprise physical properties of the system to be optimized. The best solutions also referred to as the optimal values are the established values of the choice parameter that fulfill the requirement for the constraints and give a best value of the objective or fitness function [3]. The procedure for optimization is as follows:

Identify decision variables: These are indeterminate factors linked with the problem statement that is requisite for solving the problem. Coming up with specific definition for decision variables is a vital phase in coming up with an optimization model or equation. Also, the outcome of the results and the level of relevance to the subject under study are linked to and heavily rely on the decision variables.

Determine the objective/fitness function: Fitness function demonstrates the decision-maker’s main aim. It defines the purpose for the optimization via the definition of the factors in the equations. Also the subject to minimise or optimised is stated. It is the most important component of the entire estimation processes.

Determine the constraints: Constraints describe the necessities that the preferred problem shall encounter. Constraints are expressed as equalities and in some situations as inequalities. It is a vital component for the estimation of the desire property. Constraints defined the boundaries of the results so as to minimise errors and achieve a feasible results.

There are different forms of optimization techniques which include neural network, Swarm Optimization, Random Search Method, Bacterial foraging optimization, Particle swarm optimization, Ant colony optimization etc [4].

2. Bacterial foraging optimization Theory

The idea of bacteria foraging optimization was first suggested by Prof. K.M. Passino in 2002 [5]. Passino developed a novel nature stimulated calculation technique (Algorithm) after simulating the food scavenging, evolutionary replica and ecological elimination-dispersal activities of an Escherichia Coli (E.Coli) bacteria and called it Bacteria Foraging Optimization Algorithm (BFOA). BFOA is stimulated by the social foraging behaviour of Escherichia coli bacteria in hunt of food [4, 6]. BFOA provides a
universal outline and established rules for generating explanation to a problem than giving the comprehensive arrangement and analysis [7]. Numerical bio-inspired optimization system is a novel associate in the swarm intelligence optimization paradigm [8]. BFOA has been broadly recognized as a universal optimization algorithm of present concern for optimization and regulations in many engineering applications.

Foraging theory is established on the theory that animals quest for and get food for leaving in a manner that make best use of their energy intake E per unit time T use in searching. Mathematically represented as \( \frac{dE}{dT} \). Optimal expansion of such function makes available nutrient bases to live and extra period for supplementary vital actions (such as mating, reproducing, fighting, sleeping). Ideal foraging concept forms the foraging problem as an optimization problem through the use of computational and also analytical approaches [5]. [5] proposed that generally, animals have different methods of search for food in their surroundings by either cruise or ambush approach. In the case of cruise method to searching of food or nutrients, the forager changes position constantly over the environment, continuously hunting for prey. In the case of ambush search, the forager (such as a rattlesnake) rests motionless and pauses waiting for prey to pass cross its range of striking [5].

The techniques of Bacterial foraging optimization (BFO) has been successfully applied in many engineering fields [4-11].

2.1. Steps for Bacterial Foraging Optimization Algorithm

2.1.1 Chemotaxis

Chemotaxis processes mimic the behaviour of an E.coli cell via swimming and tumbling using flagella [4,6]. Assume \( \theta \) signifies the ith bacterium at jth chemotactic, kth reproductive, and ith elimination–dispersal step. C (i) is said to be a scalar and designates the size of the phase occupied in the arbitrary direction stated by the tumble (run length unit). Formerly, in computational chemotaxis, bacterium movement could be signified by

\[
\theta^i(j + 1, k, l) = \theta^i(j, k, l) + C(i) \frac{\Delta(t)}{\sqrt{\Delta^2(t)\Delta(t)}}
\]

where \( \Delta \) designates a unit length vector in the random direction [4].

2.1.2 Swarming

Motivating group performance has been described for numerous species of bacteria, where swarms are made in semisolid nutrient medium [4]. Swarming involves the arranging of an assembly of E.coli cells moving in a ring toward a nutrient slope when positioned within a semisolid medium with its own nutrient chemo-effector [4]. The cells when motivated by a high level of succinate release an attractant aspartate, which aids them to conglomerate into clusters and transfer as concentric arrangements of swarms with high bacteriological concentration [12].

2.1.3 Reproduction

In this step, the smallest healthy bacteria eventually die whereas the ones in good health asexually fragment into two bacteria, which are at that moment positioned in the same location. This retains the swarm size constant [4].
2.1.4 Elimination and Dispersal
In other to estimate elimination and dispersal phenomenon in BFOA, [5] suggested that selected bacteria occupying best points are reserved and the remaining population of the bacterial are killed. The bacteria with best locations are eventually moved to a new location within the surroundings [13].

The aim of the study is to evaluate the potentials of compacted lateritic soil –Bacillus coagulans (B.coagulans) induced calcite precipitate for use as liner and cover material in waste containment system with the aid of BFOA. Also, to determine the optimal combination of compaction energy, water content and B.coagulans needed to achieve the optimal hydraulic properties for the intended application.

3. Material and Methods

3.1 Bacteria Foraging Optimization Procedure

Experimental results were obtained through laboratory tests. Measured soil factors include; Coefficient of permeability (hydraulic conductivity) as dependent factor and void ratio (d1), bulk density (d2), B. coagulans suspension density (d3), pH (d4), Compactive effort (d5), water content relative to optimum (d6), plasticity index (d7), viscosity of microbes (d8) and liquid limit (d9) as self-determining (independent) factors. GeneXproTools 5.0 was used to develop the fitness (objective) function used for Bacterial Foraging Optimization to predict hydraulic conductivity of treated lateritic soil with B. coagulans suspension density. The fitness function was integrated using codes in Matlab 2016 version to predict the minimum hydraulic conductivity for a given set of self-determining factors. The fitness function used is shown in equation 2.

3.2 Fitness/Objective function

\[
y = d_1 - \frac{5.25}{d_9} + 2.52 + d_6 - d_7 + \cos(Cos(d_3d_6) - 8.14 \left[\frac{0.18}{\cos(\sin(Tanh(d_4 - d_5))\right]d_7}}
\]

\[
+ \cos\left[\frac{d_6}{\cos(d_8 + d_2) + (d_7 + d_2)\right] - d_2 + \tan[\sin(d_5(\cos(-5.95d_6) - 3.82d_3)] + d_7
\]

\[
R^2 = 85.5\%
\]

Where; y = Coefficient of permeability (hydraulic conductivity), d1 = Void ratio, d2 = Bulk density, d3 = B. coagulans suspension density, d4 = pH, d5 = Compactive effort, d6 = water content relative to optimum, d7 = Plasticity index, d8 = Viscosity of microbes, d9 = Liquid limit
3.3 Constraints
The constraint considered include B. coagulans suspension density \(d_3\), Compactive effort \(d_5\) and water content relative to optimum \(d_6\).

\[
0 \leq d_3 \leq 2.4E-09 \\
-1 \leq d_5 \leq 1 \\
13.8 \leq d_6 \leq 15.3
\]

4 Results and Discussion

4.1 Bacterial Foraging Optimization

BFO method was applied to determine the minimum hydraulic conductivity based on laboratory results using the possible combination of the self-determining variables (Void ratio \(d_1\), bulk density \(d_2\), B. coagulans suspension density \(d_3\), pH \(d_4\), Compactive effort \(d_5\), water content relative to optimum \(d_6\), plasticity index \(d_7\), viscosity of microbes \(d_8\) and liquid limit \(d_9\)) measured in the laboratory that give rise to the minimum hydraulic conductivity value. GeneXproTools 5.0 was used to develop the fitness (objective) function for optimizing hydraulic conductivity. The various output for the model developed are contained in Table 1.

| S/No | Variable                  | Quantity   |
|------|---------------------------|------------|
| 1    | Fitness                   | 856.11     |
| 2    | MSE                       | 2.82E-02   |
| 3    | RMSE                      | 0.168      |
| 4    | MAE                       | 0.136      |
| 5    | RSE                       | 0.146      |
| 8    | Correlation Coefficient   | 0.924      |
| 9    | R-square                  | 0.854      |
| 15   | Number of gens            | 4          |

MSE = Mean Square Error; RMSE = Root Mean Square Error; MAE = Mean Absolute Error; RSE = Residual Standard Error.

The relationship between the predicted hydraulic conductivity (Target) against the measured values from the laboratory used for the model is shown in figures 1 and 2. The result shows a strong association between the predicted values and the measured values in the laboratory using a regressed line with coefficient of determination \(R^2=0.85\). This indicate that the self determining variables used to develop the model has strong effect on the hydraulic conductivity of lateritic soil-B. coagulans mixtures and should be carefully studied and considered during the design and construction phase of a waste containment system.
Results of measured hydraulic conductivity and predicted hydraulic conductivity values from Fitness function generated by GeneXpro Tools 5 is presented in table 2 with absolute percentage error of 0.68-30.12%. The graphical plots of hydraulic conductivity against iteration number for (A) 50 (B) 100 (C) 500 and (D) 1000 iterations are shown in figure 3. Table 3 presents summary of the optimization results for 50, 100, 500, 750, 1000, 1500 and 2000 iterations. It is clear from the optimization results that the hydraulic conductivity values and the self-determining variables are close to each other irrespective of the number of iterations. However, the least hydraulic conductivity value of $2.80 \times 10^{-11}$ m/s was recorded from 750 iterations and above, this suggest that the minimum iteration required to minimize hydraulic conductivity of lateritic soil-$B.coagulans$ mixtures is 750 iterations. This results falls within the range of optimal values from overall acceptable zone generated from laboratory result. Therefore, the compactive effort, moisture content and $B.coagulans$ suspension density should be considered primarily during design and construction of the compacted clay liner in the field or in any related geotechnical engineering applications. Also, [14] suggested that hydraulic head difference should be strictly controlled.
in the course of construction of landfill to mitigate the movement of contaminant into the ground water. Higher hydraulic gradient can significantly encourage the migration of contaminant. The application of BFOA has proven be a good mechanism for this application. However, the development of a proper objective function with the required variables that have direct impact on the hydraulic performance of a containment system is key to achieving the expected result in the field. Hence care should be taken in developing the objective function and setting of the appropriate equation constraints in order to arrive at expected output in the field.

**Table 2.** Results of Measured and predicted hydraulic conductivity values from Fitness function generated by GeneXproTools 5.

| S/No | Measured hydraulic conductivity (m/s) | Predicted hydraulic conductivity (m/s) | Absolute error | % Error |
|------|--------------------------------------|----------------------------------------|----------------|---------|
| 1    | 5.75E-10                             | 7.48E-10                               | 1.7E-10        | 30.12   |
| 2    | 5.85E-10                             | 5.47E-10                               | 3.8E-11        | 6.51    |
| 3    | 7.52E-10                             | 7.47E-10                               | 5.1E-12        | 0.68    |
| 4    | 8.64E-10                             | 7.37E-10                               | 1.3E-10        | 14.71   |
| 5    | 9.56E-10                             | 1.18E-09                               | 2.2E-10        | 23.13   |
| 6    | 9.99E-10                             | 1.19E-09                               | 2.0E-10        | 19.65   |
| 7    | 1.03E-09                             | 1.02E-09                               | 8.1E-12        | 0.79    |
| 8    | 1.14E-09                             | 1.33E-09                               | 1.9E-10        | 16.96   |
| 9    | 1.36E-09                             | 9.72E-10                               | 3.9E-10        | 28.62   |
| 10   | 1.46E-09                             | 1.42E-09                               | 3.8E-11        | 2.58    |
| 11   | 2.12E-09                             | 1.85E-09                               | 2.7E-10        | 12.72   |
| 12   | 2.56E-09                             | 2.36E-09                               | 2.0E-10        | 7.92    |
Figure 3. Plots of Hydraulic conductivity against Iteration number using Bacterial foraging optimization algorithm for (A) 50 (B) 100 (C) 500 and (D) 1000 iterations.

Table 3. Bacterial Foraging Optimization Results

| No of Iteration | y    | d_1 | d_2 | d_3 | d_4 | d_5 | d_6 | d_7 | d_8 | d_9 |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 10              | 2.84e-11 | 0.415 | 2.193 | 6.708 | 7.301 | 0.969 | 15.300 | 26.090 | 33.991 | 37.996 |
| 50              | 2.82e-11 | 0.406 | 2.191 | 3.095 | 7.250 | 0.730 | 15.300 | 26.100 | 33.991 | 37.983 |
| 100             | 2.81e-11 | 0.404 | 2.191 | 6.423 | 7.293 | 0.960 | 15.299 | 26.100 | 34.000 | 38.000 |
| 250             | 2.82e-11 | 0.400 | 2.193 | 6.383 | 7.300 | 0.850 | 15.299 | 26.099 | 34.000 | 37.998 |
| 500             | 2.81e-11 | 0.408 | 2.193 | 6.620 | 7.305 | 0.851 | 15.299 | 26.100 | 33.990 | 37.996 |
| 750             | 2.80e-11 | 0.406 | 2.193 | 5.955 | 7.301 | 0.866 | 15.300 | 26.100 | 33.984 | 37.984 |
| 1000            | 2.80e-11 | 0.405 | 2.193 | 3.361 | 7.264 | 0.874 | 15.300 | 26.095 | 33.986 | 38.000 |
| 1500            | 2.80e-11 | 0.409 | 2.193 | 4.048 | 7.240 | 0.967 | 15.300 | 26.087 | 33.967 | 37.985 |
| 2000            | 2.80e-11 | 0.408 | 2.193 | 6.375 | 7.296 | 0.968 | 15.300 | 26.090 | 33.976 | 37.987 |

Where y = Least Hydraulic conductivity (m/s), d_1 = Void ratio, d_2 = Bulk density, d_3 = B. coagulans suspension density, d_4 = pH, d_5 = Compactive effort, d_6 = Water content relative to optimum, d_7 = Plasticity index, d_8 = Viscosity of microbes, d_9 = Liquid limit

5. Conclusion

Lateritic soil – Bacillus coagulans (B.coagulans) induced calcite precipitate was analysed for hydraulic behaviour using Bacterial Foraging Optimization Algorithm (BFOA). Laboratory experiments were carried out to generate results used for BFOA. GeneXproTools 5.0 software was used to develop the fitness (objective) function used for BFO to predict hydraulic conductivity of treated lateritic soil with B. coagulans suspension density for use as a hydraulic barrier material. The fitness function was then integrated using BFO codes in Matlab 2016 version to predict the minimum hydraulic conductivity for a given set of self-determining factors. The results showed a strong association between the predicted and the measured hydraulic conductivity values in the laboratory using a regressed line with coefficient of determination R=0.85. It is clear from the optimization results that the hydraulic conductivity values and the self-determining variables have strong correlation irrespective of the number of iterations. The least hydraulic conductivity value of 2.80×10^{-11} m/s was recorded after 750 iterations and above which fell below the permissible regulatory value of 1.0×10^{-9} m/s for waste containment barrier application. Based
on all the optimization results, it is recommended that lateritic soil-$B.\text{coagulans}$ mixtures be compacted with $1.20 \times 10^{-9} - 2.40 \times 10^{-9}$ cells/ml $B.\text{coagulans}$ suspension density using British standard heavy (BSH) at 15.3\% moisture content for waste containment barrier application. Therefore, the compactive effort, moisture content and $B.\text{coagulans}$ suspension density should be considered primarily during design and construction of the compacted clay liner in the field or in any related geotechnical engineering applications.

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