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Evaluation of jet index and erodibility coefficients of lateritic soil treated with bacillus thuringiensis-induced calcite precipitate

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Abstract: *The ability of Bacillus thuringiensis (Bt) induced calcite precipitate to improve the jet index and erodibility coefficient of lateritic soil against scour erosion was evaluated using a fabricated submerge-impinging JET apparatus (JETa). Bio-treated soil samples were prepared using the mixing method of Bt suspension and cementation reagent (C_s) in the ratio of C_s, 50 % Bt : 50 % C_s, based on the natural soil liquid limit (LL). Bt suspension densities of 0, 1.5 ×108, 6.0 × 108, 1.2 × 109, 1.8 × 109 and 2.4 × 109 cfu/ml and four (4) cementation reagent concentrations (i.e., 0.25, 0.5, 0.75, and 1 M) were considered. The samples were compacted using three compaction energies; British Standard heavy, BSH, West African Standard, WAS, and British Standard light, BSL. The jet index (J_i= 0.0221) and erodibility coefficient (k_d= 14.87 cm3/N-s) values recorded indicate that the natural lateritic soil has low resistance to water erosion when compacted with a low energy level (BSL) and moderate resistance to erosivity (optimum J_i= 0.0003 and k_d = 0.0034 cm3/N-s) when bio-treated with Bt (2.4 × 109 cells/ml) - C_s (0.75 M) and compacted using BSH energy. The predictive modelled equation developed for jet index (dependent variable) using multiple linear regression analysis showed a strong correlation between the chosen predictive factors (independent variables). Based on the results highlighted, Lateritic soil bio-treated with Bacillus thuringiensis (Bt) (2.4 × 109 cfu/ml) - cementation solution concentration (C_s) (0.75 M) using the mixing method and compacted with BSH energy can be used to mitigate scour erosion of lateritic soil.*

KEYWORDS: *JET apparatus, soil erodibility coefficients, jet index*

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1. INTRODUCTION

Biocementation is a soil modification approach that utilises biological activity through processes such as microbiological induced carbonate precipitation (MICP), enzymatic induced carbonate precipitation (EICP) and microbial-induced desaturation (MID) to strengthen mechano-physical properties of soil, resulting in a cementation effect within the soil matrix using one or a combination of the following metabolic pathways such as photosynthesis, ureolysis, denitrification, sulphate reduction, ammonification, and methane oxidation (Kumar et al., 2023; Gowthaman et al., 2023; Xue et al., 2023; Kanyi et al., 2023). A good number of soil microbes are able to produce crystalline or non-crystalline inorganic compounds through microbial mineralisation processes. The produced compounds coat soil particles and fill the voids of geo-materials. The viable products of these microbial processes are the precipitation of insoluble salt (i.e., calcification) and iron oxide. According to He et al. (2016), the bonding effect of crystalline precipitates surpasses those of non-crystalline precipitates. Urea hydrolysis remains the widely adopted method due to its high energy proficiency. The process has been utilised in the construction industry to enhance the performance of concrete and soils as construction materials (De Belie and De Muynck, 2009; Haouzi et al., 2019; Hoang et al., 2020; Liu et al., 2021; Hoffmann et al., 2021; Jurado et al., 2022; Khosravifar and Moug, 2023; Eberemu et al., 2023).

To promote microbial urease activity, certain bacterial types are preferred. The urease-positive and Gram-positive organisms have been reported as the most suited for urea hydrolysis (Donovan et al., 2017; Wang, 2020; Wani and Mir, 2020). Dhami et al. (2013) reported the commonly used microbes for ureolysis in the MICP process to include *Bacillus pasteurii*, *Variovorax sp*., *Pseudomonas sp*., *Micrococcus sp*., *Leuconostocmesenteroides*, *Bacillus subtilis*, *Halomonaseurihalina*, *Deleya halophila* and *Myxococcus xanthus*. However, the most widely used microbes belong to the Bacillus species as adopted by several researchers (Whiffin et al., 2007; Osinubi et al., 2020a, b, c; 2021; Yisa et al., 2023).

Soil erosion is a human or natural induced process that detaches and transports the topsoil layer, leading to soil deterioration. Soil deformation resulting from surface runoff has become a huge global concern. The factors that accelerate soil erosion include inappropriate exposure and exploration of land due to human activities, heavy rainfall, landforms, as well as climate change (Wang et al., 2013; Igwe et al., 2023). Severe soil erosion eludes the protective, supportive and productive functions of the soil.

Prevention of surface erosion at road shoulders, abutments, bridge piers, dams and embankments requires good knowledge of different methods of evaluating erodibility potential and the magnitude of soil erosion. The measure of soil detachment rate is most effectively evaluated using erodibility factors (Saerahany et al., 2016; Abbas et al., 2019; Athulya et al., 2022). A lot of methods, such as small flumes, large flumes, a submerged JET (Jet Erosion Test), and a laboratory hole erosion test, have been utilised to evaluate soil erodibility parameters (e.g., critical shear stress,τ_c jet index, J_i, and coefficient of soil erodibility, k_d) (Benseghier et al., 2020). However, the submerged JET is widely adopted because of the ease of measuring erodibility variables in different types of soils (Abbas et al., 2019; Coffman, 2009; Brunier-Coulin et al., 2017; Benseghier et al., 2023).

In this research, the potential of *Bacillus thuringiensis* (Bt) induced calcite precipitate to improve the jet index and erodibility coefficient of lateritic soil against scour erosion was evaluated using a fabricated submerge-impinging JET apparatus (JETa).

II. MATERIALS AND METHODS

2.1 Materials

Soil: Soil samples were obtained by disturbed sampling technique at depths of 0.5 m - 3 m at a location with coordinates of 6^o 12' 15" N and 7^o 0' 40" E on latitude and longitude, respectively, at Abagana, in Anambra State, Nigeria. According to Okorafor*et al.,* (2017), the soils in this region are basically ultisols (a strongly weathered red soil typically consisting of sub-soil horizon and appreciable quantity of clay of humid and warm climates and is relatively acidic) and alfisols (similar to ultisols but severity of weathering and acidity is relatively less) which naturally are fragile and easily leached making them susceptible to erosion.

Microorganism: *Bacillus thuringiensis* (Bt) was isolated from the soil and cultured using biochemical confirmatory test kits to identify and characterise Bt in the laboratory. It was used throughout the research.

Cementation solution: The study adopted equimolar of urea and calcium chloride to obtain their mass concentration in solution as suggested by Murtala *et al.* (2016) in addition to constituents such as ammonium chloride (10 g), sodium bicarbonate (2.12 g) and nutrient broth (3 g) dissolved per dm^3 of de-ionised water for effective cementation solution suitable for MICP process (Stocks-Fischer et al., 1999). Four different concentrations of cementation solutions (C_s) (i.e., 0.25, 0.5, 0.75 and 1 M) were used. The C_s is composed of nutrient broth, ammonium chloride (NH_4Cl), urea ($CO(NH_2)_2$), sodium bicarbonate ($NaHCO_3$) and calcium chloride ($CaCl_2$).

2.2 Methods

2.2.1 Bacteria inoculation

The constituents that make up the bacterial media (nutrient broth, 3 g, urea, 10 g) were weighed and dissolved in 1 litre of distilled water, cotton flogged and sterilised in an autoclave at a temperature of 110 $^{\circ}$C for 10 minutes. The media was allowed to cool completely before inoculation of the bacteria. After the media had cooled, the conical flasks were labelled using a masking tape, then a standardised inocular (bacteria) of the bacterial isolate was inoculated. A standardised inocular is a bacterial suspension whose turbidity is compared with that of the McFarland turbidity standard. The McFarland turbidity standard scale ranges from 0.5 to 9, each scale representing a bacteria cell density. After inoculation of the media with the standardised bacteria, the conical flasks were incubated in an incubator at a temperature of 37^{o} C for 24 hours before use.

Five different scales of McFarland turbidity standard were used (i.e., 0.5, 2, 4, 6 and 8). The equivalent bacterial cell density for the adopted McFarland turbidity scale is presented in Table 1.

Table 1: McFarland turbidity scale and its equivalent bacterial cell density

Scale	Bacterial cell density (equivalent) *(Cfu/ml)
0.5	1.5×10^8
2	6.0×10^8
4	1.2×10^9
6	1.8×10^9
8	2.4×10^9

*Cfu /ml: - Colony forming unit per millilitre

2.2.2 *Jet erosion test apparatus (JETa) features and operational methods*

. The fabricated equipment is made up of a water reservoir tank, a plastic submergence cell (300 mm height x 270 mm diameter), a surface pump, polyvinyl chloride (PVC) pipes, two steel inlet pipes (one for water inlet into the submergence cell and the other serves as the impinging jet inlet as well as the scour depth gauge) and a pressure gauge mounted to the device frame instead of the submergence cell contrary to the original and mini-JET devices. This offers greater flexibility in controlling the valves regulating the pressure gauge. The pressure gauge is connected to a surface pump that draws out water from the reservoir tank. The rubber hose links the inlet pipe from the pump and the jet flow pipe with the nozzle, which also serves as the depth gauge profiler (see Plate I).

Plate I: The fabricated jet erosion test apparatus (JETa).

The JETa uses a pressure gauge as opposed to the head tank utilised in the original JET equipment. This is to give room for a wider range of pressure heads during experimentation. The device functions in a similar way as any jet experiment device, mostly available in fluid mechanics laboratories. The JETa submergence cell is made of plastic material, whereas the original JET device is made of acrylic (see Plate II). This is to help keep the cost of producing the equipment as low as possible.

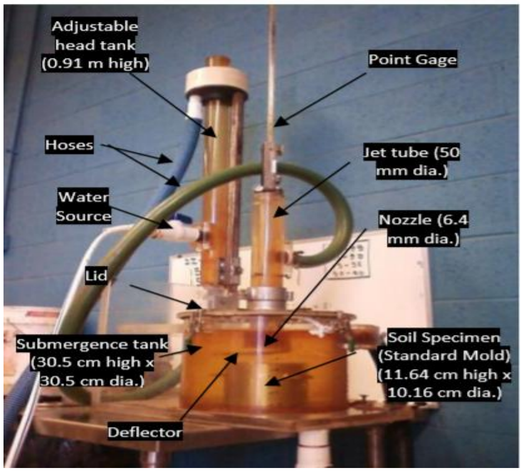


Plate II: Original JET equipment Al-Madhhachi et al. (2013).

Another modification made on the JETa is the provision of three distinct detachable nozzle size diameters (3, 4 and 6 mm) fitted at the tip of the jet flow pipe, which also doubles as the scour depth gauge (see Plate III). The modification is to allow for variations in the nozzle's height, J_h to diameter, d_o, ($\frac{J_h}{d_o}$) ratios.

Plate III: different nozzle sizes

The $\frac{J_h}{d_o}$ for the fabricated JETa, is set similar to the mini-JET device during operational setup. This is to maintain a similar operational approach to previous research involving JET devices. The value of 10.2 is reported as the $\frac{J_h}{d_o}$ for the mini-JET device (Saerahany et al., 2016). The unit of k_d (soil erodibility coefficient) is also reported in cm^3/Ns to conform with earlier studies (Saerahany et al., 2016; Al-Madhhachi et al., 2013; Vessaire et al., 2020; Choo et al., 2020).

The testing procedure during the experimental setup followed a similar methodology to earlier researchers (Al-Madhhachi et al., 2013; Saerahany et al., 2016). The testing could be done on disturbed and undisturbed soil samples in the laboratory. The prepared soil sample for testing is placed centrally in the submergence cell, with the centre of the prepared sample aligned directly with the jet flow pipe andthe nozzle. Before the start of the impinging jet test, at zero seconds, the depth gauge is used to ascertain the jet nozzle height to the soil sample surface. After which, the desired constant pressure head is set on the pressure gauge (in units of bar) based on the calibrated discharge velocities using the pump control valve. The water source is opened with the rubber hose connected to the second water inlet pipe, which is not aligned with the prepared sample. The water is let into the submergence cell through this inlet pipe until the nozzle is completely submerged to avoid impinging right on the sample. When the nozzle is submerged, the rubber hose is transferred from the water inlet pipe to the jet flow pipe with the nozzle with the valve closed. The valve is then opened for the impinging jet test to start, and the scour depths are taken periodically over the specific time of testing using the scour depth gauge. The first scour depth was taken after 30 seconds, while others were recorded after 5 minutes intervals over a period of 30 – 60 minutes.

2.2.3 Calibration of JETa

The equipment was to enable the JETa to produce consistent results over a period of time. Al-Madhhachi et al. (2013) enumerated two ways to achieve this that include evaluating the JETa performance and determination the discharge coefficient, C$_d$. These are conducted in the laboratory with soil samples prepared in line with provisional standard practices such as BS 1377 (1990).

The orifice discharge coefficient, C$_d$, for the original jet apparatus, as reported in literature, ranges from 0.95 – 1.0, while that of the mini jet ranges from 0.7 – 0.75 (Saerahany et al., 2016). The value of C$_d$ is determined as the slope of the graph of the actual discharge ($Q_a = C_d A_o \sqrt{2gh}$) plotted against theoretical discharge ($A_o\sqrt{2gh}$) where, A_o is the area of the orifice ($A_o = \frac{\pi}{4} {d_o}^2$) where d_o is the nozzle diameter attached to the jet apparatus, h is the hydraulic head, and g is the acceleration due to gravity. The actual flow rate for JETa was obtained by taking the amount of water discharged over time in an experiment conducted at different heads of pressure. The plot of actual discharge versus the theoretical discharge at the end of the experiment produced discharge coefficient values in the range of 0.58 - 0.72. This means the JETa discharge coefficient is similar to that of the mini jet apparatus. Thus, further analysis based on these findings could be done to evaluate erodibility parameters.

2.2.4 Determination of erodibility coefficient of soil

The method adopted to evaluate the erodibility of the compacted natural and bio-treated lateritic soil is the jet index method ASTM D 5852 (2000). The method developed by Hanson (1990) measures the scour depth over a specific time in relation to velocity-time relationships. The soil samples were prepared in a standard compaction mould in line with BS 1377 (1990) using three compaction energy levels (British Standard heavy, BSH, West African Standard, WAS, and British Standard light, BSL). The laboratory jet erosion test procedure followed the JETa operational procedure described in the previous section. The layout of the experiment is shown in Plate IV.


A B

Plate IV: (A) prepared soil in the mould (B) compacted soil positioned in the submergence cell

The test can be conducted on compacted and undisturbed soil samples in the laboratory. The test results evaluate the soil resistance to erosional forces and provide a general description of material properties in building predictive and performance relationships (Al-Madhhachi et al., 2013). Several researchers have adopted the jet index method to compute soil erodibility parameters for different purposes (Coffman, 2009; Lovern et al., 2013; Al-Madhhachi et al., 2013; Saerahany et al., 2016; Shanahan and Montoya, 2016).

The method was devised from the original jet device. Therefore, the procedure and working principles are similar to the working operations of the JETa discussed in the preceding sections. The analysis involved in the method is generally easy and direct. The jet index (J_i) is determined as the gradient of the fitting line of least squares of the plotted scour depth over a specific time against the velocity-time function (Saerahany et al., 2016).

There are several factors affecting the scouring jet of an impinging jet device. These include the height of the nozzle above the original soil surface, its diameter, and the jet velocity. The jet velocity is given as $U_o = C_d\sqrt{2gh}$ where C_d = nozzle discharge coefficient. The JETa C_d is taken to be 0.72. The maximum scour depth, D_s, for every time interval was also determined.

To further evaluate the coefficient of erodibility, Hanson (1991) proposed the equation (1) shown below:

$$k_d = 0.003e^{385J_i} \quad (1)$$

Where k_d is the coefficient of soil erodibility (cm^3/N-s), and J_i is the jet index. Although the method is direct and unambiguous, it only determines the coefficient of erodibility. k_d, it does not evaluate the critical shear stress τ_c.

2.2.5 Statistical analysis

The regression studies to assess the goodness of fit and prediction of the J_i (dependent variable) was carried out using Microsoft Excel 2016. The equations were modeled using a combination of the following independent variables; compaction energy, CE (kJ/m^3), cementation solution concentration, C_s (M), *Bacillus Thuringiensis* suspension density, Bt (cfu/ml), Liquid Limit, LL (%), Plasticity Index, PI (%), calcium Carbonate Content, CCC (%), unconfined compressive strength, UCS (kN/m^2), void ratio, *e*, hydraulic conductivity, k (m/s), water content, m (%) and Urease Activity, UA (mM). All the variables were laboratory measured except for compaction energy, CE, which was arbitrary assigned deterministic values of –1, 0 and 1 for BSL, WAS and BSH compaction efforts, respectively.

III. RESULTS AND DISCUSSION

3.1 Effect of bacillus thuringiensis suspension density on jet index and erodibility coefficient

Impinging jet tests were carried out on the compacted natural and bio-treated lateritic soil (Plate V and VI) prepared using three energies namely, British Standard heavy, BSH (2723.5 kJ/m^3), West African Standard, WAS (1009.2 kJ/m^3), and British Standard light, BSL (605.9 kJ/m^3) using the fabricated JETa.

Plate V: (A) Compacted natural lateritic soil (B) Compacted soil specimen positioned in the submergence cell (C) Recording of time interval during the impinging jet experiment (D) Measurement of scour (E – F) Scoured natural lateritic soil.

Plate VI: Compacted bio-treated lateritic soil specimens: (A) Before experiment (B – C) After experiment.

The compacted lateritic soil specimens were subjected to a constant pressure head in the submergence cell and the scour depths were recorded at 5 minutes intervals for a period of 30 minutes. The collected data were analysed following the procedures outlined in section 2.2.4 to evaluate the erodibility variables. For instance, the J_i was evaluated by plotting the values of $^{D_s}/_{t}$ against $U_o(t)^{-0.931}$ with D_s (scour depth) and t (time) in centimetres and seconds, respectively (Hanson,1991). The gradient of the plotted graph through zero describes the J_i value, as shown in Fig.1.

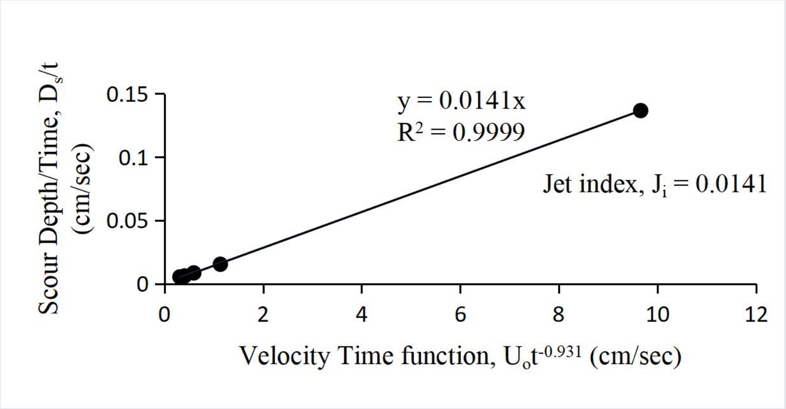
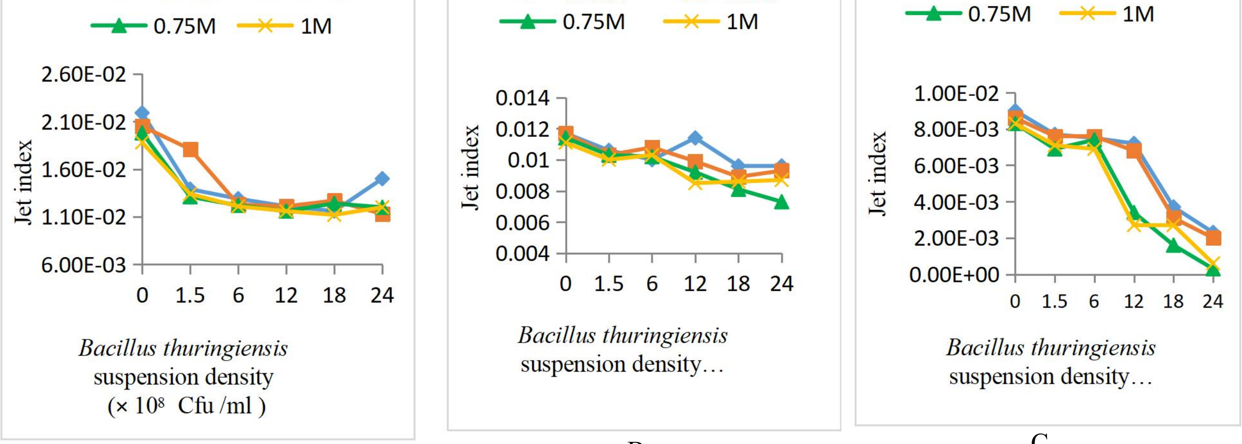


Fig. 1: scour depth over specific time versus velocity-time function for compacted lateritic soil (BSH).

As indicated in Fig. 1 the J_i = 0.0141. According to Hanson (1991), J_i values range from 0 – 0.3 with values of 0.02, 0.01 and 0.001, signifying low, moderate and high resistance to erosion, respectively. The result for the compacted soil indicates that the soil offers moderate resistance to erosion. J_i is, therefore, an erosion evaluation index.

The variation of the jet index (J_i) values of the compacted bio-treated lateritic soil with *Bacillus thuringiensis* suspension density for the three compaction energies considered are presented in Fig. 2.



A B C

Fig. 2: Variation of jet index of compacted lateritic soil with *Bacillusthuringiensis* suspension density for different compaction energy: (A) BSL (B) WAS (C) BSH.

The $J_i$values decreased with increase in cementation and *Bacillusthuringiensis* (*Bt*)suspension density and cementation solution concentration (C_s) regardless of the compaction energy used. However, lower J_i values were recorded at higher compaction energy. According to Hanson (1991), J_i values are in the range 0 – 0.3, with the values of 0.02, 0.01, and 0.001 signifying low, moderate, and high resistance to erosion, respectively. The results also indicated that the natural lateritic soil and soils treated with C_s (0.25 and 0.5 M) only recorded low resistance to water erosion while soils treated with C_s (0.75 and 1 M) only recorded moderate resistance to water erosion when compacted using BSL energy level and subjected to constant pressure of 1 bar (100 kPa). However, the J_i and erodibility coefficient (k_d) values improved considerably with peak J_i and k_d values of 0.012 and 0.3045cm^3/N-s, respectively, recorded for specimens bio-treated with *Bt* (2.4 × 10^9Cfu /ml) - C_s (0.75 M) when compacted with BSL energy.

Similarly, bio-treated lateritic soil compacted with higher energies and subjected to the same pressure head recorded moderate resistance J_i index values compared with the natural soil but improved significantly to within the moderate resistance and high resistance range for WAS and BSH compaction energies. The optimum J_i and k_d values of 0.0003 and 0.0034 cm^3/N-s, respectively, were recorded for specimens bio-treated with *Bt* (2.4 × 10^9Cfu /ml) - C_s (0.75 M) when compacted using BSH energy (see Table 2).

Table 2: Typical coefficient of soil erodibility data obtained using JETa from jet index method

S/N	Cs (M)	*Bt* (cells/mL)	Jet index (J_i)	Erodibility coefficient k_d (cm^3/N-s)	Category
			BSL		
1	0.25	0.00E+00	0.0219	13.768	Low resistance
2	0.5	0.00E+00	0.0205	8.0313	Low resistance
3	0.75	0.00E+00	0.0198	6.3141	Moderate resistance
4	0.75	2.40E+09	0.012	0.3045	Moderate resistance
5	1	2.40E+09	0.012	0.3045	Moderate resistance
			WAS		
6	0.25	0.00E+00	0.0117	0.2713	Moderate resistance
7	0.5	0.00E+00	0.0117	0.2713	Moderate resistance
8	0.75	0.00E+00	0.0114	0.2417	Moderate resistance
9	0.75	2.40E+09	0.0073	0.0499	Moderate resistance
10	1	2.40E+09	0.0087	0.0855	Moderate resistance
			BSH		
11	0.25	0.00E+00	0.009	0.0959	Moderate resistance
12	0.5	0.00E+00	0.0086	0.0822	Moderate resistance
13	0.75	0.00E+00	0.0083	0.0733	Moderate resistance
14	0.75	2.40E+09	0.0003	0.0034	Highly resistance
15	1	2.40E+09	0.0006	0.0038	Highly resistance

The increase in erodibility resistance (k_d) after bio-treatment may be attributed to the low hydraulic conductivity and the high shear strength of the compacted bio-treated soil, occasioned by the formation of calcite within the soil matrix thereby enhancing its performance against water jet pressure that would have caused soil detachment (Zhaoyu et al., 2020; Athulya et al., 2022). On the other hand, the increase in jet index (J_i) values at higher compaction energy may be attributed to increased packing density and cohesion of the soil particles due to bio-calcification during urea hydrolysis, thereby leading to greater resistance of the soil particles to wear and tear, thus increasing the soil erodibility resistance capabilities (Benseghier et al., 2023).

3.2 Regression analysis for jet index

The statistical assessment of the goodness of fit and prediction of the J_i dataset was evaluated using multiple linear regression analysis to come up with the best modelled equation. Three equations were modeled using a combination of the following predictors; compaction energy, CE (kJ/m^3), cementation solution concentration, C_s (M), *Bacillus Thuringiensis* suspension density, Bt (Cfu /ml), Liquid Limit, LL (%), Plasticity Index, PI (%), calcium Carbonate Content, CCC (%), UCS (kN/m^2), void ratio, e, hydraulic conductivity, k (m/s), water content, m (%) and Urease Activity, UA (mM). The predictive models are presented in Table 2.

Table 2: Jet index (J_i) modelled equations

S/N	Model	R^2
1	$J_i = 0.0158 + 0.0043CE + 0.0005C_s - 1.9 \times 10^{-12}Bt - 6.7610^{-5}LL + 0.0001PI + 4.46 \times 10^{-5}CCC + 4.91 \times 10^{-8}UCS - 0.0001e - 7.61 \times 10^{-5}UA$ (1)	85.58
2	$J_i = 0.0154 + 0.0042CE + 0.0004C_s - 1.93 \times 10^{-12}Bt - 6.8 \times 10^{-5}LL + 0.0001PI + 6.26 \times 10^{-5}CCC + 1.5 \times 10^{-7}UCS + 5935.55k - 7.56 \times 10^{-5}UA$ (2)	85.62
3	$J_i = 0.0114 + 0.0036CE + 0.0013C_s - 1.63 \times 10^{-12}Bt + 0.0003m + 7.79 \times 10^{-5}PI - 8.79 \times 10^{-5}CCC - 7.96 \times 10^{-7}UCS - 0.0012e - 8.54 \times 10^{-5}UA$ (3)	85.57

Although the three equations showed a strong correlation between chosen predictive factors and the J_i, however, equation (2) in Table 2 was adopted due to the higher R^2 value of 85.62 compared to R^2 values of 85.58 and 85.57 recorded for the chosen predictive parameters for equations (1) and (3), respectively.

The plot of the adopted predicted and the laboratory measured J_i values also depict a strong correlation with an R^2 of 87.944 % (see Fig. 3).

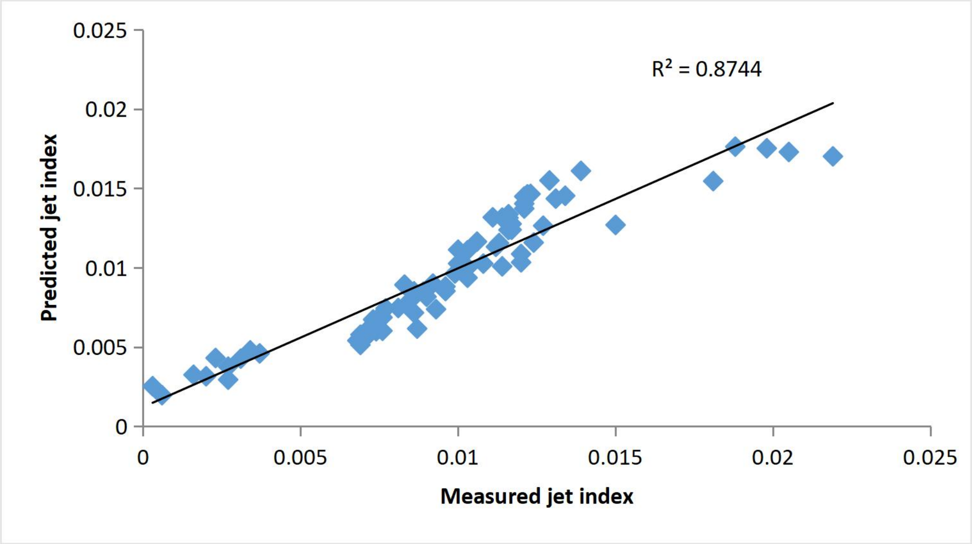


Fig. 3: Plot of model-predicted jet index against actual laboratory jet index

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IV. CONCLUSIONS

The jet index () and erodibility coefficient () values determined using a fabricated submerged impinging jet device indicate that the natural lateritic soil has low resistance to water erosion when compacted with the lowest BSL energy level used (BSL) while moderate resistance to erosivity was recorded for soil bio-treated with 2.4 × 108 cells/ml) - 0.75 M having peak and values of 0.012 and 0.3045cm3/N-s, respectively. The optimum and values of 0.0003 and 0.0034 cm3/N-s, respectively, were recorded for bio-treatment of soil with 2.4 × 109 cells/ml - 0.75 M when compacted using BSH energy. A predictive modelled equation developed for jet index (dependent variable) using multiple linear regression analysis with the following predictors; compaction energy, CE (kJ/m3), cementation solution concentration, Cs (M), Bacillus Thuringiensis suspension density, Bt (cfu/m), liquid limit, LL (%), plasticity index, PI (%), calcium carbonate content, CCC (%), UCS (kN/m2), hydraulic conductivity, (m/s), and urease activity, UA (mM) showed a strongest correlation between chosen predictive factors (independent variables) and the dependent variable.

It is therefore recommended that Lateritic soil bio-treated with Bacillusthuringiensis (Bt) (2.4 × 109cfu/ml) - cementation solution concentration (Cs) (0.75 M) using the mixing method and compacted with BSH energy be used to mitigate scour erosion of lateritic soil.

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