

PAPER 50 – EFFECT OF CURING AND TREATMENT METHOD ON ULTRASONIC PULSE VELOCITY OF COMPACTED LATERITIC SOIL TREATED WITH *BACILLUS THURINGIENSIS*

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ABSTRACT

The study used ultrasonic pulse velocity (UPV) to assess the integrity and apparent strength of compacted lateritic soil treated with *Bacillus thuringiensis* (Bt). The effect of treatment methods (mixing and injection methods) of cementation solution (C_s) applications and curing procedures (oven-cured at 30° C, wax-cured, and air-curing at 25 ± 2° C) on UPV was also investigated. Samples were treated with Bt suspension densities of 0, 1.5 × 10⁸, 6.0 × 10⁸, 12 × 10⁸, 18 × 10⁸ and 24 × 10⁸ cells/ml and varying concentrations of C_s of 0.25, 0.5, 0.75 and 1 M. Specimens were compacted using British Standard light, West African Standard, and British Standard heavy energies, extruded, and cured using the procedures listed before the UPV tests. Results showed that UPV values increased as the compaction energy, Bt suspension density, and C_s concentration increased. The mixing method recorded higher UPV values relative to the injection method of treatment regardless of the curing procedure used. Air-cured specimens recorded higher UPV values in comparison to oven-cured and wax-cured specimens. It is recommended that treatment with Bt (24 × 10⁸ cells/ml): C_s (0.75 M) by mixing method and air-curing at laboratory temperature can enhance the strength of lateritic soil for the embankment.

Keywords: *Bacillus thuringiensis*, Curing method, Microbial-induced calcite precipitation, lateritic soil, Ultrasonic pulse velocity.

1. INTRODUCTION

The heterogeneous nature of soil makes it a complex material for erecting civil engineering infrastructure. The determination of *in situ* index and other engineering characteristics of soil is commonly achieved using direct methods that are usually destructive. For example, field density tests are carried out by destructive core cutter or sand replacement methods. The amount of time taken for these tests to be conducted and in most cases putting a temporal stop to construction activities is of grave concern (Yesiller *et al.*, 2000). Consequently, the non-destructive test (NDT) methods offer a faster assessment of soil and other material properties (Shi *et al.*, 2007; Slavova *et al.*, 2010). Some of the commonly used NDT methods include electrical resistivity, nuclear density, cone penetration and ultrasonic pulse velocity (UPV) tests (Leong *et al.*, 2004). However, there are accuracy concerns and operational difficulties associated with some of these methods that limit their usage in real-life engineering practice (Vinay *et al.*, 2019).

The wider utilization of UPV as an NDT method in assessing the quality of construction materials such as concrete, soil, metals and asphalt is due to its simple and quick approach to material quality and strength assessment (Shi *et al.*, 2007). In geotechnical engineering, UPV has been utilised to predict the density, water content, and strength as well as other soil parameters such as Young's modulus (E), shear modulus (G) and Poisson's ratio (ν) (Nakagawa *et al.*, 1996; Vinay *et al.*, 2019).

Soil improvement via soil microorganisms has opened up a new and reportedly viable alternative soil enhancement method for geotechnical engineers for over a decade (van Paassen *et al.*, 2010; Matthew *et al.*, 2012; Liu *et al.*, 2021; Yohanna *et al.*, 2022; Etim *et al.*, 2022; Wang *et al.*, 2022). This is achieved through the isolation and culturing of soil microbes with the potential of degrading urea into its constituent ions (NH_4^+ and CO_3^{2-}) by urease enzymes produced during the bacterial metabolic activities through a process known as urea hydrolysis. When this happens in an environment rich in calcium, a biogeochemical reaction occurs resulting in calcite precipitation. The precipitated calcite can clog soil particles thereby enhancing their strength. Building on this knowledge, the geo-environmental engineers have devised ways of intentionally creating scenarios that bring about the precipitation of this important mineral in the soil in sufficient amounts to enhance its engineering properties using urease-positive bacteria through a process referred to as microbial-induced calcite precipitation (MICP) (Osinubi *et al.*, 2021). MICP method of soil improvement is more compatible with nature (environment)

relative to the traditional use of chemicals in soil improvement since the latter is associated with carbon emissions contributing to global climate change concerns (Karol, 2003; DeJong *et al.*, 2006; Osinubi *et al.*, 2021).

The study was focused on the investigation of the coupled effect of the curing method and treatment procedure on UPV of compacted biotreated lateritic soil using the MICP technique. The UPV non-destructive test method was used to determine the strength of the compacted soil for use as embankment construction material.

2. MATERIALS AND METHODS

2.1 Materials

Soil: The lateritic soil was collected at Abagana in Anambra State, Nigeria, at a location (6° 12' 15" N and 7° 0' 40" E on latitude and longitude, respectively). Disturbed samples were collected at 0.5 - 3 m depth.

Microorganism: *Bacillus thuringiensis* (*Bt*) was isolated from the soil and cultured using biochemical confirmatory test kits for identifying and characterising *Bt* in the laboratory and was used throughout the research.

Cementation solution: The study utilised equimolar calcium chloride, and urea 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 dm³ of de-ionized water for effective cementation solution suitable for MICP process (Stocks-Fisher *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 (NH₄Cl), urea (CO(NH₂)₂), sodium bicarbonate (NaHCO₃) and calcium chloride (CaCl₂).

2.2 Methods

Index properties: Soil basic properties such as natural moisture content, specific gravity, consistency limits, sieve analysis and soil classification were determined following British Standard (BS) 1377 (1990) procedures for testing natural soils and BS 1924 (1990) procedures for testing stabilised soils.

Preparation of sample: Lateritic soil was treated with *Bt* suspension densities of 0, 1.5 x 10⁸, 6.0 x 10⁸, 12 x 10⁸, 18 x 10⁸ and 24 x 10⁸ cells/ml (equivalent to 0, 0.5, 2.0, 4.0, 6.0 and 8.0 McFarland Standards (MFS), respectively) and varying concentration of cementation solutions (C_s) of 0.25, 0.5, 0.75 and 1 M using mixing and injection methods of bacterial/cementation solution application. In the mixing method, 50 % of *Bt* solution (relative to natural soil optimum moisture as recommended by Osinubi *et al.*, 2019) was pre-mixed with the soil sample and kept for 6 hours in sealed polythene bags to maintain the prevailing moisture and allow for bacterial attachment to soil particles thereafter, 50 % of C_s was added, properly mixed and compacted with British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) energy, respectively. In the injection method, $\frac{1}{3}$ soil pore volume (PV) of *Bt* solution (relative to natural soil optimum moisture as recommended by Rowshanbakht *et al.*, 2016) was mixed with soil and compacted (using BSL, WAS and BSH energies). The compacted soil was then saturated by injecting $\frac{2}{3}$ PV of C_s under gravity in three cycles. In both cases, the compacted soils were extruded, trimmed and subjected to the three curing procedures (oven-cured at 30^o C, wax-cured and direct exposure to room temperature) before carrying out the UPV test to assess the apparent strength.

2.3 Ultrasonic Pulse Velocity Measurement Procedure and Test Programme

In UPV measurement, two transducers (transmitter and receiver) are placed at both ends of the test samples with the aid of petroleum jelly (couplant) to eliminate the air gap between the test sample and the transducer surfaces to enhance the efficiency of the process as shown in Plate I. The transmitting transducer sends an ultrasonic wave signal through the test sample and this is detected at the other end by the receiving transducer over time. The UPV is therefore determined as the ratio of the travel distance (i.e., sample length, L) of the wave signal generated from the transmitting probe to the time, T when the signal is recorded at the receiving probe. This is represented mathematically in equation 1.

$$UPV = \frac{\text{Sample length, } L}{\text{Time, } T \text{ when the generated signal is recorded at the receiving probe}} \quad (1)$$

Where:

UPV = Ultrasonic pulse velocity (m/s)

The test programme involved the determination of UPV for the treated and additive-free compacted lateritic soil. The UPV test was performed on the wax-cured, oven-cured at 30° C and air-cured samples after 7 days.

3. RESULTS AND DISCUSSION

3.1 Index Properties

Based on the laboratory index properties determined, the natural soil was classified as SC or A – 2 – 6 (2) using USCS (ASTM D 2487-06) and AASHTO (1986) systems of soil classification, respectively. These properties are summarised in Table 2. The particle size distribution of the natural soil is shown in Figure 1.

Table 2. Physical properties of the natural lateritic soil

Property	Quantity
Natural moisture content (%)	19.6
Specific gravity	2.67
Percentage passing No. 200 sieve	33.2
Liquid limit (%)	36.0
Plastic limit (%)	17.1
Plasticity index (%)	18.9
Linear shrinkage (%)	7.7
USCS	SC
AASHTO classification	A – 2 – 6 (2)
Gravel fraction (%)	0.1
Sand fraction (%)	66.7
Silt fraction (%)	18.0
Clay fraction (%)	15.2
Dominant clay mineral	Kaolinite
Colour	Reddish-brown

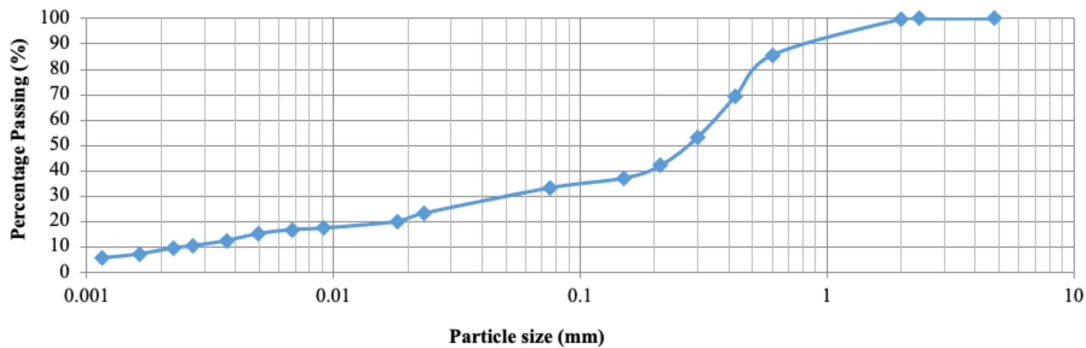


Figure 1. Particle size distribution curve of the natural lateritic soil

3.2 Effect of Curing Procedure and Bacillus Thuringiensis Density in Solution on UPV

The variation of UPV with the varying *Bacillus thuringiensis* densities in solution for the three curing procedures considered is shown in Figure 2. The UPV values increased as Bt population density in the mixture increased. The increasing trend was found to be similar when the compacted soils were subjected to different curing procedures (Figures 2a, b and c). The UPV values of 588, 618 and 634 m/s recorded for soil compacted with BSL energy and treated with C_s (0.25 M) after 7 days curing period increased to peak values of 634, 661 and 786 m/s for soil treated with Bt. (12×10^8 cells/ml) and C_s (0.25 M) for specimens wax-cured, oven-cured and air-cured, respectively. Similarly, UPV values of 603, 636 and 858 m/s were recorded for specimens treated with C_s value of 0.75 M after 7 days of curing increased to peak values of 814, 1142 and 1219 m/s for specimens wax-cured, oven-cured and air-cured at room temperature, respectively. It was observed that UPV values increased as the C_s concentration increased. The increase in UPV values recorded could probably be attributed to the biogeochemical reaction involving Bt and the C_s in the soil mixture leading to the deposition of calcite in the matrix. The precipitated calcite filled voids and bridged particle contact points in the compacted soil (Osinubi *et al.*, 2021;

Wang *et al.*, 2022) thereby enhancing the transmission of the pulse velocity signal and subsequently increasing UPV values (Shi *et al.*, 2007; Slavova *et al.*, 2010).

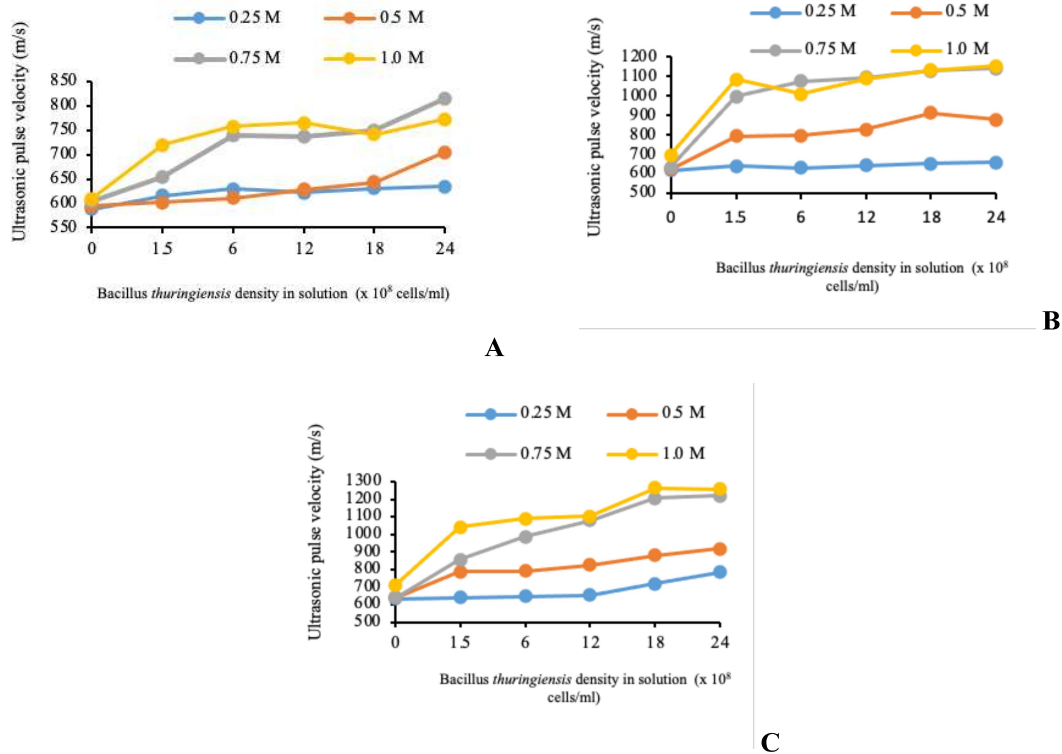


Figure 2: Variation of ultrasonic pulse velocity of compacted soil (BSL energy) with varying *Bacillus thuringiensis* density in solution for the three curing procedures: (A) 7 days wax-cured (B) 7 days oven-cured at 30° C (C) 7 days air-cured at ambient temperature.

A similar trend as discussed above was observed when the compacted soil was treated with 0.5 M and 1 M C_s with varying Bt density in solution. Also, the above results revealed that compacted soil specimens treated and air-cured at ambient temperature yielded higher UPV values. Least UPV values were recorded for wax-cured specimens while intermediate values were recorded for specimens oven-cured at 30° C. The increase in UPV values signifies an improvement in the strength of the bio-treated soil.

3.3 Effect of Treatment Method on UPV

The variation of UPV value of lateritic soil compacted using BSL energy with *Bacillus thuringiensis* suspension density for the treatment methods considered after 7 days of curing is shown in Figure 3. The UPV values increased as bacterial population density in the mixture increased irrespective of the treatment method (i.e., mixing and injection methods) used. However, the mixing method of C_s application during experimentation recorded higher UPV values. The mixing method presented a situation in which there were more bacterial interactions with the C_s thus leading to more calcite formed in the soil matrix. On the other hand, the injection method produced results that depicted limited bacterial interaction with the C_s since the movement of the organism within the soil matrix was dependent on the compacted soil pore throat and the ability of the Bt in the mixture to flow through the pore spaces (Rowshanbakht *et al.*, 2016; Etim *et al.*, 2022). The compacted soil pore throat did not offer a great chance for effective movement of the organism. According to Rebata-Landa (2007), the MICP process performs optimally for soil with grain size in the range of 50 and 400 μm . Therefore, bacterial activity is not usually effective in fine-grained soil. Thus, the observed variation in the UPV values in the injection method could be linked to this effect. Similar trends were also observed when higher compaction energy (i.e., WAS and BSH) was deployed.

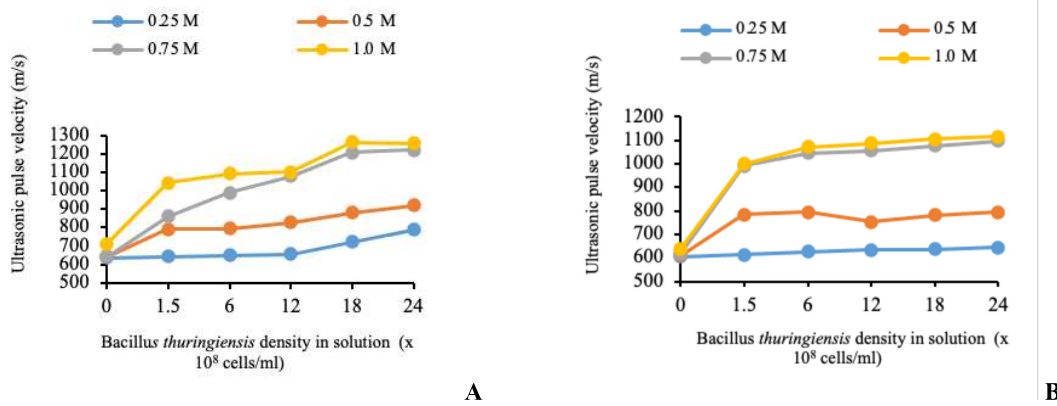


Figure 3: Variation of ultrasonic pulse velocity of compacted soil (BSL energy) with varying *Bacillus thuringiensis* density in solution for the treatment method: (A) 50 % Bt: 50 % Cs (mixing method) 7 days air-cured at ambient temperature (B) 1/3 PV (injection method) 7 days air-cured at ambient temperature.

3.4 Effect of Compaction Energy and Cementation Solution Concentrations on UPV

Variations of UPV of lateritic soil – C_s – *Bacillus thuringiensis* mixtures with compaction energy are shown in Figures 4 - 6. The UPV values increased as the compaction energy and C_s concentration increased. The trends of increase in the UPV values are similar irrespective of the curing procedure adopted. Although, maximum UPV values were obtained when treated specimens were cured by direct exposure to ambient conditions.

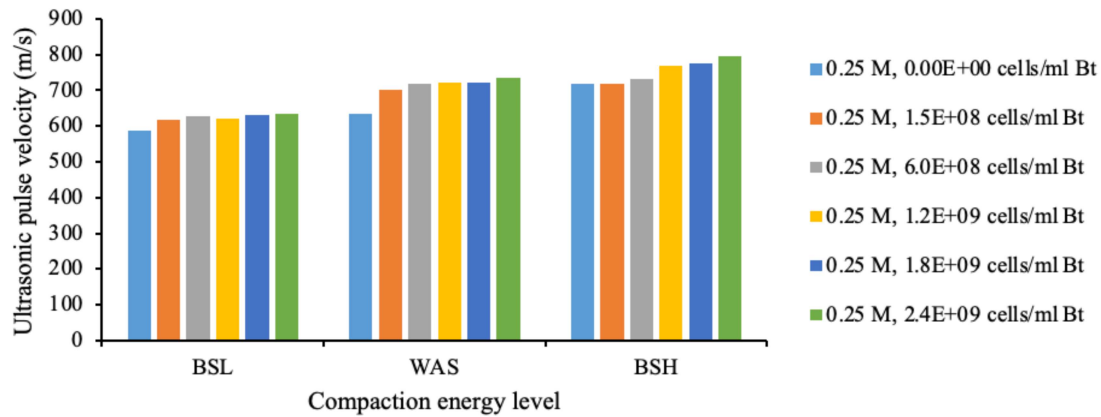


Figure 4. Variation of ultrasonic pulse velocity of lateritic soil – 0.25 M C_s – *Bacillus thuringiensis* mixtures with compaction energy (wax-cured).

The increase in UPV values with increment in C_s concentration may be attributed to greater quantities of urea and calcium chloride in the mixture at higher concentrations leading to increased urease activity that favoured the production of calcite in the soil matrix (Yohanna *et al.*, 2022). The produced mineral (calcite) bound the particles together thereby improving the UPV values.

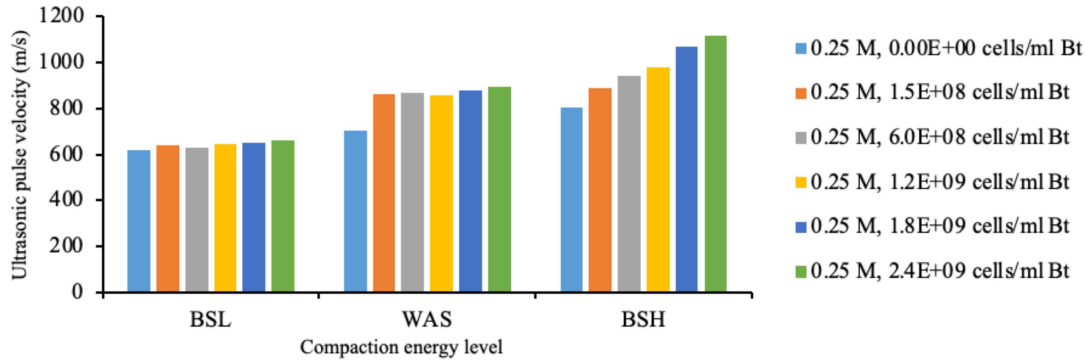


Figure 5: Variation of ultrasonic pulse velocity of lateritic soil – 0.25 M C_s – *Bacillus thuringiensis* mixtures with compaction energy (oven-cured).

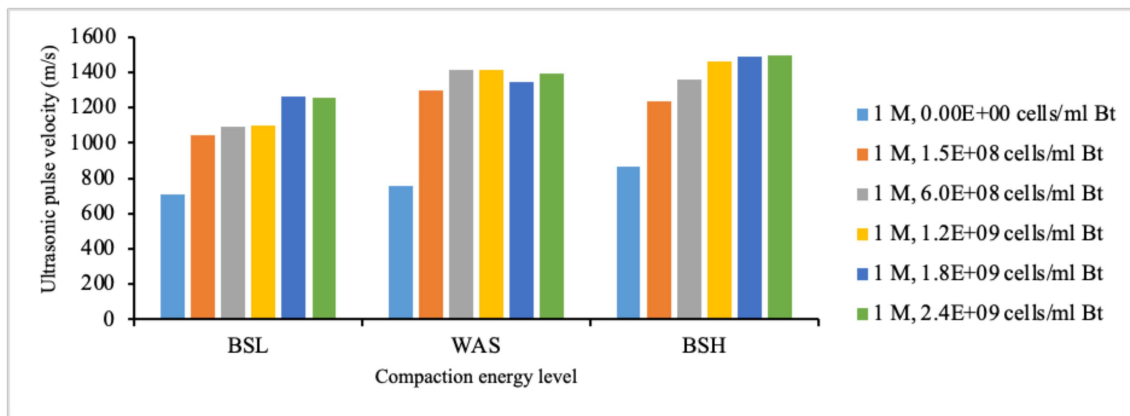


Figure 6: Variation of ultrasonic pulse velocity of lateritic soil – 1 M C_s – *Bacillus thuringiensis* mixtures with compaction energy (Air-cured at ambient temperature).

4. CONCLUSION

The study assessed the effect of curing and treatment procedures on UPV of MICP-treated compacted lateritic soil classified as A – 2 – 6 (2) and SC using the AASHTO and USCS systems, respectively. The results showed that:

- The UPV values increased as Bt population density in the mixture increased. The UPV values of 588, 618 and 634 m/s recorded for compacted soil (BSL energy) treated with C_s (0.25 M) after 7 days of curing increased to peak values of 634, 661 and 786 m/s when treated with 12×10^8 cells/ml at 0.25 M for wax-cured, oven cured and air-cured samples respectively.
- The mixing method of C_s application recorded higher UPV values in comparison with the injection method irrespective of the curing procedure used.
- Specimens cured at ambient temperature recorded higher UPV values in comparison to oven-cured and wax-cured specimens.
- The UPV values increased as the compaction energy and C_s concentrations increased.

RECOMMENDATION

It is recommended that lateritic soil treated with Bt (24×10^8 cells/ml): 0.75 M C_s (0.75 M) mix ratio prepared using the mixing method and compacted with BSH energy when air-cured at ambient temperature can be used for embankment construction.

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