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IMPROVEMENT IN COMPACTION CHARACTERISTICS OF LATERITIC GRAVEL SOILS STABILIZED WITH LOCUST BEAN POD EXTRACT

Vordoagu, J. J.[1] and Adams, C. A.[2]
[1] Department of Civil Engineering Faculty of Engineering, Sunyani Technical University, Sunyani, Ghana.
[1&2] Regional Transport Research Education Centre, Kumasi (TRECK), College of Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Ghana.
[1]joshua.vordoagu@stu.edu.gh
[2]caadams.coe@knust.edu.gh

ABSTRACT

Purpose: The compaction properties of chemically stabilised weak or marginal sub-grade soils were investigated using locust bean pod extract (LBPE) derived from soaked locust bean pods (LBP).

Design/Methodology/Approach: An experimental approach was employed. The extract was created by pounding and soaking the locust bean pods for varying durations, ranging from 1 day to 28 days. Soil samples for the research were collected from three different sources: Agyei Ano South and behind the AVIC laboratory of Sunyani Technical University, both located in the Sunyani East Municipality and Fiapre in the Sunyani West Municipality. The tests were conducted at the geotechnical engineering laboratory (AVIC lab) of Sunyani Technical University (STU) in the Bono Region of Ghana. Chemical and elemental analyses were carried out.

Findings*:* The experimental findings indicate that the locust bean pod extract generally raises the Maximum Dry Density (MDD) and reduces the Optimum Moisture Content (OMC). In comparison, the control specimen recorded 1.97g/cm^3 and 13.10% for MDD and OMC, respectively. The soil's dry density increases with the extract's rising concentration. Concentrations of 50g/l and 100g/l of extract notably increased the MDD of the stabilised soil compared to the control.

Research Limitation: Soil samples were collected from three locations, so the findings cannot be generalised.

Practical Implication: This research can enhance eco-friendly soil stabilisation methods, consequently reducing carbon footprints.

Social Implication: This study will assist road construction industry policymakers in finding sustainable ways of improving the compaction characteristics of lateritic gravel soils using a biopolymer such as a locust bean pod extract.

Originality/ Value: This study is grounded in cost reduction and sustainability in road construction, specifically in resource use and earth movement reduction.

Keywords*: Chemical stabilisation. compaction. gravel. lateritic. soil.*

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INTRODUCTION

Road transportation forms the principal mode of transport in many countries. In road pavement construction, the soil is the primary construction material. In many cases, suitable material is not found within the road corridor, thus presenting a challenge in the amount of work to be done in earth movement along the road corridor. Excavating and hauling suitable material to the site and unsuitable material from the site require earthmoving equipment and transport using trucks. The operation of this equipment releases carbon dioxide into the atmosphere, causing an increase in carbon footprints, the greenhouse effect and global warming, thereby causing environmental pollution and increased safety risks (Arioli et al., 2020; Woodcock et al., 2007).

Furthermore, the movement of haulage trucks on existing roads to transport material could result in further and rapid deterioration of existing pavement layers, thereby placing additional strain on already scant national resources. Haulage of suitable material not found within the road corridor could present cost overruns for the project and increase the project duration. For many farm-to-market roads with less traffic, stringent material specifications for road pavement construction may not be necessary; therefore, slightly improving the unsuitable material could make it sound. This issue compels one to improve the soil properties along the road corridor to meet material specifications to reduce road pavement construction costs (Vordoagu & Adams, 2024).

Given these problems, suitable and sustainable ways must be found to improve these mostly marginal materials that fail to meet the requirements of base and sub-base material specifications. This will reduce the cost of hauling materials over a long distance and, by extension, the cost of road construction projects in the country, as well as carbon footprints and their attendant global warming issues. Using Locust Bean Pod Extract (LBPE), obtained by soaking the locust bean pods in water, could provide a cost-effective solution for stabilising marginal soils to meet standard specifications for use as subbase and base material, especially for less trafficked rural roads.

This study explores the potential impact of using locust bean pod extract (LBPE) to stabilise marginal lateritic gravel soils, focusing on gravel materials' compaction characteristics (optimum moisture content, OMC and maximum dry density, MDD) for road construction.

LITERATURE REVIEW

With the rise in industrial and agricultural activities, there has been a significant increase in industrial and agricultural wastes, which often harm the environment. Globally, there has been a recent increase in research efforts focused on finding ways to recycle these wastes for reuse in order to maintain a hygienic and safe environment (Adama & Jimoh, 2012)The construction, transportation, and environmental industries are well-positioned to recycle these substantial waste

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materials (Basha et al., 2003). These waste materials can be used primarily as pozzolana or chemical additives in soil stabilisation.

The Locust Bean Tree, Pods and Extract

The African locust bean tree's fruit is the source of the locust bean pod. The tree is a perennial leguminous tree crop commonly grown in the tropics and savannah countries such as Ghana, Nigeria, Uganda and Senegal (Campbell-Platt, 1980; HOPKINS, 1983). In Ghana, it is commonly found in the northern regions and other parts of the country, such as Techiman, Kintampo and some parts of the Eastern region, especially Afram Plains. After harvesting, the fruits are opened, and the yellowish pulp containing seeds is subsequently removed to obtain the pods, which account for 39% of the fruit's weight (Adama & Jimoh, 2012). The production of Locust Bean Pod Extract (LBPE) requires the husk or pods (as shown in Figure 1) and water as the primary material resources.

Figure 1: Locust bean pods

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Chemical composition of aqueous extract of Locust Beam Pod (LBPE)

Abagale et al. (2013), in a study on the chemical analysis of the aqueous extract of *Parkia biglobosa*, used both ethanol and water as solvents for the extraction process. Water was, however, found to be the best solvent for the extraction process. Again, according to Abagale et al. (2013)The locust bean pods contain tannins and polyphenols, flavonoids, alkaloids and saponins, anthraquinones, and glycosides. However, steroids and terpenes may not be present.

The LBPE is a suitable binder or pozzolana containing all the significant oxides in ordinary Portland cement (Auta et al., 2015). Essentially, the extract contains 49.99% silicon dioxide (SiO2), 3.294% Calcium oxide (CaO), 18.966% Aluminium oxide (Al_2O_3) and 6.342% Iron (III) oxide (Fe_2O_3) (Auta et al., 2015). The bulk density of the LBPE can be 1840 ± 10.4 kg/m^3 (Oyelaran et al., 2015).

Previous Experimental Works on the Uses of Locust Bean Pod Ash (LBPA) and Locust Bean Pod Extract (LBPE)

Many studies have been conducted on using LBPA as a pozzolanic material in concrete and as a chemical stabiliser of weak soils. Many of these studies reported improved results when LBPA is used as a pozzolanic material.

Adama & Jimoh (2012) investigated the effect of Locust bean pod ash (LBPA) on the strength properties of weak soils. They obtained the LBPA from incinerated locust bean pod waste. They also classified the LBPA as a class C group of the ASTM pozzolanic material because the sum of SiO_2, Al_2O_3 and Fe_2O_3 percentage content was greater than 50% but less than 70%. They added the LBPA to the weak soil in increments of 2% by weight, still 12%, and cured the samples in moist conditions for a week prior to conducting the tests on the samples. It was observed that the presence of LBPA in the test samples increased California Bearing Ratio (CBR) values up to 50%, with the optimum rate of LBPA stabilisation realised to be 8%. The unconfined compression strength tests carried out also show improved stabilised soil over the non-stabilized soil. For the two soils used in the experiment, in the non-stabilized state, strains of 0.049 were observed at the failure stage, while the stress of 41.149 and 155.9 caused soil failures. For the stabilised soils, however, strains observed at failure were 0.059 and 0.030, corresponding to failure stresses of 217.934 and 702.475, respectively. Thus, the stabilised soils exhibit very high failure stresses.

The effect of locust bean pod ash on compaction characteristics of weak subgrade soils was also examined by Adama et al. (2013). Materials from old borrow pits along Minna – Kataeregi – Bida road in northern Nigeria, which fail to meet specifications for use as subbase material, were used in this study. The LBPA used was also classified as class C pozzolana according to ASTM C618 after chemical analysis was conducted on the sample. Typical major components include 39.01%

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silicon dioxide (SiO_2), 15.71% Calcium oxide (CaO), 13.05% Aluminium oxide (Al_2O_3) and 11.51% Iron (III) oxide (Fe_2O_3). Compaction results indicate a general trend of increase in OMC with increasing LBPA content, whilst a general decrease in MDD with increasing LBPA content exists. The authors suggest that an increase in OMC indicates additional moisture held within the soil structure due to the presence of pozzolanic action of LBPA. According to Adama et al. (2013), additional water aids ionic exchange within the soil to form calcium silicate cement, a reaction that is not soluble in water. The silicate gel coats and binds the clay lumps; well-crystallised and interlocked calcium silicate hydrates are formed in time. This assertion seemed to confirm the reason for the high failure stress attained by the LBPA-stabilized soils compared to non-stabilized soils from earlier studies (Adama & Jimoh, 2012; Rahman, 1987; Zhang et al., 1996). The decrease in MDD, according to Adama et al. (2013), signals the possible effect of the LBPA on the specific gravity and particle size of the soil. Lower MDD infers that less compaction effort is needed to attain the required MDD, implying lower costs to achieve the same MDD. These results are compared favourably with other authors' use of pozzolanic materials and cement for soil stabilisation (Basha et al., 2003; Muntohar & Hantoro, 2000).

Aguwa and Okafor (2012) investigated the use of locust bean pod extract as a binder for building lateritic blocks. From the particle size distribution, the lateritic material used could be classified as well-graded gravel, with about 14% passing through the 75μm sieve size. Lateritic blocks were moulded by ramming with a 2.5 kg hammer falling from a height of 300 mm with only water for mixing as the control and with only locust bean pod extract at varying concentrations (0.04 kg/l, 0.06 kg/l, 0.08 kg/l and 0.10 kg/l) as the test specimens. Both the blocks moulded with the extract and the control were cured under atmospheric conditions and tested after 7, 14, 21 and 28 days. Compressive strength tests on the blocks reveal that the test specimens produce higher compressive strength values than the control. Generally, the higher the concentration of the extract, the higher the compressive strength of the block. The highest extract concentration of 0.10 kg/l produced the highest compressive strength, 78.57% of the control.

Further studies were conducted by Aguwa et al. (2016) on the Effectiveness of Locust Bean Pod Solution (LBPS) in the Production of Sandcrete Blocks for Buildings. In this study, various extract concentrations were prepared by soaking various weights of the husks in water for 24 hours. The various concentrations of the extracts were used to prepare sandcrete blocks. In addition, a known concentration of 50 g/l was used to prepare sandcrete blocks in which the weight of cement was reduced by 0, 5, 10, 15, 20, 25, 30, 35 and 40%, respectively. The blocks were cured and tested at 7, 14, 21 and 28 days. The effect of the duration of soaking was also investigated by soaking the same 50 g/l weight of husk for 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 days, respectively and using the extracts to mould concrete blocks, which were crushed for compressive strength after 28 days of curing. The results indicated that the compressive strength of sandcrete blocks increases with

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increasing extract concentration and that the extracts can be used to reduce the cement content by as much as 25% without adversely affecting the compressive strength of the sandcrete blocks. It was also deduced that soaking the pods for more than 24 hours is not necessary because the compressive strength of blocks tends to decrease with LBPE extraction periods greater than 24 hours.

Osinubi et al. (2016) also assessed the strength characteristics of tropical black clay treated with locust bean waste ash. Index property and other tests on the natural soil indicate the soil is A-7-6 by AASHTO classification and highly plastic clay (CH) by the Unified Soil Classification System (USCS), hence unsuitable for use as a road construction material. X-ray fluorescence (XRF) analysis on the LBPA used in the study indicates a class F pozzolanic material according to ASTM C 618 (1994) with 55.38% silicon dioxide (SiO_2) content, 1.08% Calcium oxide (CaO) content, 14.93% Aluminium oxide (Al_2O_3) content whilst Iron (III) oxide (Fe_2O_3) content was 0.278%. Results from tests conducted on the stabilised soil show improved soil properties. Generally, MDD decreases with increasing LBPA content, whilst OMC increases with increasing LBPA content. Regardless of the various compaction efforts used and the curing period, strength and durability properties increased with higher LBPA content. CBR values also increase with increasing LBPA content, with the lower compaction effort recording a 175% CBR value increment, the medium compaction effort giving a 100% CBR value increase whilst the highest compaction effort gives a 50% CBR value increment. The study showed tropical black clay can be beneficially treated with LBPA with optimum treatment values between 10% and 12.5 %.

MATERIALS AND METHODS

An experimental approach was employed to investigate the effects of the LBPE stabilisation on the compaction characteristics of lateritic gravel. A two-fold experiment was conducted in this research. The first experiment was set up to determine the optimum soaking duration of the extract that gives the optimum values for compaction characteristics. In the first experimental setup, the concentration of the extract was kept constant while the soaking durations for the extract were varied. Only Agyei–Ano South material was used in this experimental setup. The second experimental setup was carried out to determine the optimum concentration of extract that gives the best results. In the second experimental set-up, three different soil materials from different locations were used: Agyei – Ano South, Avic Lab of STU and Fiapre.

Materials

Soil Sample

Soil samples (figure 2) used in this research were collected from Agyei-Ano South and Avic lab (Sunyani Technical University Campus) within the Sunyani East Municipality and Fiapre in the

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Sunyani West Municipality, all of the Bono Region of Ghana. The soil samples were collected and air-dried before the tests were carried out.

(a) *(b)* *(c)*

Figure 2: Soil samples used in the experiment: (a) – Agyei Ano South, (b) – Avic Lab, and (c) – Fiapre CUC

Locust Bean Pod

The Locust Bean Pods used for the initial experimental setup were sourced from Tongo in the Upper East Region of Ghana. These pods are typically leftover as a byproduct from fruit processing. Similarly, the pods for the second experimental setup were obtained from Bolgatanga in the Upper East region of Ghana and dried before extraction.

Methods

First experimental Setup – Varying Soaking Durations of Extraction

As previously mentioned, the first experiment aimed to determine the optimal soaking duration of the extract that would yield the MDD and OMC. Only soil from Agyei Ano South was used in this experiment. A measured quantity of the crushed locust bean pod was thoroughly macerated in water for varying days. The procedure involved compaction tests on the gravel material with water as the control. The test specimens were prepared by completely substituting water with the LBPE in the compaction test. Various durations of soaking of the locust bean pod extracts were employed in the research process to identify the duration of LBPE that would yield optimal values for compaction characteristics.

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Extraction Procedures for LBPE

The locust bean pods were first pounded into a mixture of powder and broken-down pods using a wooden mortar and pestle. The wooden mortar and pestle were used to pound the locust bean pod to finer particle sizes to ensure effective extraction.

Five hundred and fifty (550) grams of pounded LBP were weighed and soaked in 5.5 litres of tap water free from contaminants for one day. Abagale et al. (2013) identified water as the best solvent for the extraction. The solution was sieved using a 0.075mm sieve size to obtain the one-day duration extract. This process was repeated for the various durations of soaking to obtain the 2-day, 3-day, 4-day, 5-day, 7-day, 14-day, 21-day, and 28-day duration extracts, respectively.

Particle Size Determination of the Control Specimen

Wet sieving was conducted on the natural soil by adding three (3) litres of water containing dissolved sodium hexametaphosphate, a dispersing agent, to the soil specimen. The specimen was stirred for one (1) hour before washing to separate the fine particles in the soil thoroughly. Each litre of water contained two (2) grams of sodium hexametaphosphate. Subsequently, the soil specimen was oven-dried for twenty-four (24) hours before being used for the sieve analysis. The sieve sizes were arranged in ascending order, with the lowest sieve size beneath and the highest at the top. The soil was poured into the top sieve, and a lid was placed on it. The set of sieves was shaken for ten (10) minutes using a mechanical shaker. Afterwards, the sieves were separated, and the mass of the soil retained on each sieve was determined for further analysis. This test was performed following BS 1377 1990 Part 2 (British Standards Institution, 1990). Sieve analysis was carried out for all three (3) soils in the setup 1.

The hydrometer test was also conducted on the fine particles, specifically the soil finer than the 75µm sieve size to the pan, for all three (3) soils in setup 1. Fifty (50) grams of the soil passing through the 75µm sieve size was used for the test. To the soil specimen, 100ml of sodium hexametaphosphate solution was added. The soil specimen was then stirred for four (4) hours before being added to the 1000ml measuring cylinder. Distilled water was added to reach the 1000ml graduation, and the hydrometer readings were taken at predetermined time intervals. This test was conducted per BS 1377 1990 Part 2 (British Standards Institution, 1990).

Determination of the Consistency Limits of the Control Specimen

Sample Preparation

The test specimen was prepared per BS 1377 1990 Part 1 (British Standards Institution, 1990). A 200-gram weight of the test specimen passing through the 0.425mm sieve was obtained and placed on the Perspex plate. Distilled water was used to fully mix the material and create a thick, uniform paste, which was then stored in an airtight container for 24 hours before conducting the test. After

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24 hours, the specimen was remixed and used to determine the liquid and plastic limits. This process was carried out for all three (3) soil samples.

Liquid Limit and Plastic Limit Determinations

To prepare the specimen for liquid limit determination, a small quantity of distilled water was introduced to the sample, and the specimen was fully remixed for at least 10 minutes using two spatulas. The test was conducted per BS 1377 1990 Part 2 (British Standards Institution, 1990)The cone penetrometer used was designed according to the Chinese standard. The liquid limit was determined at a cone penetration of 17mm, while the plastic limit was determined at a cone penetration of 2mm.

Determination of the Compaction Characteristics (MDD & OMC)

The test specimen was prepared following BS 1377 1990 Part 1 (British Standards Institution, 1990). The soil was quartered and passed through the 20.00mm sieve size. The soil sample's mass and the compaction mould's mass without the collar were determined using a weighing balance, and the masses were recorded. Each compaction operation was done throughout the testing using a mass of 2600g of the soil sample.

The soil was thoroughly mixed with different percentages of lubricant for compaction, starting from 3%, 6%, 9%, 12%, and 15% for both the control (where water is the lubricant) and the test specimens (where LBPE is the lubricant). After attaching the collar, the sample was compacted into the previously measured 948.25 cm^3 volume mould in five (5) layers of almost similar mass. Each layer was subjected to 27 blows, uniformly distributed from a 450mm-high, 4.5 kg rammer. After removing the collar, the compacted sample was levelled using a straight edge at the top of the mould.

The mass of the compacted soil was then ascertained by weighing the mould containing the levelled sample. The sample was then extruded from the mould, and small samples were retrieved from the removed sample for moisture content determination. These samples were dried for 24 hours in an oven regulated at 105^{o}C, and their moisture content was determined. This procedure was repeated until a minimum of five compactions were carried out, with two (2) sets of samples taken to determine each sample's moisture content. The test procedure was conducted according to BS 1377 1990 Part 4 (British Standards Institution, 1990).

Second Experimental Setup – Varying Concentrations of LBPE

The second experimental setup was carried out to determine the optimum concentration of extract that gives the best results. Three different soil materials were used: Agyei–Ano South, Avic Lab, and Fiapre.

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Extraction Procedures for LBPE

The locust bean pods were ground to facilitate efficient extraction. Based on a study by Vordoagu & Adams (2024), LBPEs of various concentrations (10g/l, 20g/l, 50g/l and 100g/l) were produced after soaking for an optimal duration of 3 days. The resulting solution was filtered using a 0.1mm sieve size to obtain the LBPE for each concentration.

Determination of the Compaction Characteristics (MDD & OMC)

The test specimen was prepared per BS 1377:1990 Part 1 (British Standards Institution, 1990). However, the soil was sieved over the 2.00mm aperture sieve, and the finer material was used. This was to enable the actual observation of the effect of the extract on the finer materials. The compaction mould's mass without the collar was determined and recorded using a weighing balance. Each compaction process involves using 2300g of the soil sample throughout the tests. The soil mass was thoroughly mixed with varying percentages of lubricant for compaction, starting from 3%, 6%, 9%, 12%, and 15% for both the control (where water is the lubricant) and the test specimens (where LBPE is the lubricant). The same procedure was followed in the first experimental setup. The test procedure was conducted per BS 1377:1990 Part 4 (British Standards Institution, 1990).

Chemical Analysis of LBPE

The prepared LBPE samples were submitted for chemical and elemental analysis. X-ray fluorescence (XRF) and Fourier Transform Infrared Spectroscopy (FTIR) were used to identify the oxides and elements in the extract and its functional groups.

RESULTS AND DISCUSSION

Results from Chemical Analysis of LBPE

The FTIR results are presented in Figure 3. The observed peak at 3326.19cm^{-1} aligns with the 3400 – 3200 band for OH stretching tannins and catechol tannins (Fernández & Agosin, 2007; Murugananthan et al., 2005; Ricci et al., 2015; Zhu et al., 2004). The peak at 2115.40cm^{-1} corresponds to H – O – H bending free water as well as CH_3 and CH_2 stretching, representing the alkyne group (Pantoja-Castro & González-Rodríguez, 2011; Pardeshi et al., 2013; Ping et al., 2012; Ricci et al., 2015). Additionally, the peak at 1634.61cm^{-1} corresponds to the C=C stretching of the alkene group (Chen et al., 2010; Jensen et al., 2008; Ricci et al., 2015). These results indicate the presence of tannins in the extract, which have the potential to undergo a series of chelation reactions to form complexes (Slabbert, 1992).

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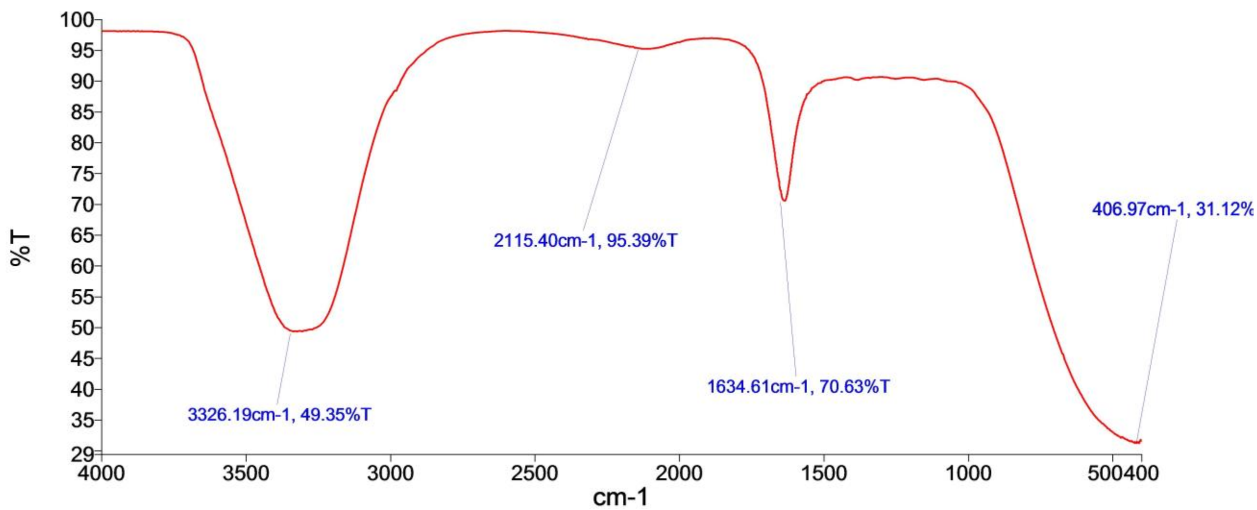

Figure 3: FTIR Spectrum Graph of LBPE

The results of the x-ray fluorescence analysis shown in Table 1 determined the major chemical constituents of LBPE. The principal oxides identified, in descending order of percentage by weight in the sample, were Magnesium, Potassium, Lead, Calcium, Silicon, and Aluminium. These elements were also identified in the elemental analysis in the same order, measured in parts per million (ppm). Any other elements and oxides present in amounts less than 0.006% by weight for oxides and less than 60 ppm are considered trace elements and are not included in the report.

Table 1: Major Oxides and Elements of LBPE from XRF Analysis

OXIDES		**ELEMENTS**	
Unit	wt.%	Unit	ppm
MgO	0.5336	Mg	3218
Al2O3	0.0697	Al	369
SiO2	0.0888	Si	415
P2O5	0.1638	P	715
K2O5	0.1590	K	786
K2O	0.0947	Ca	890
CaO	0.1245		

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Results for Set-up 1

Particle Distribution Curve (PDC) of Control Specimens

Figure 4 presents the results of both the grading test and hydrometer test as particle distribution curves. The grading characteristics are also presented in Table 2 below.

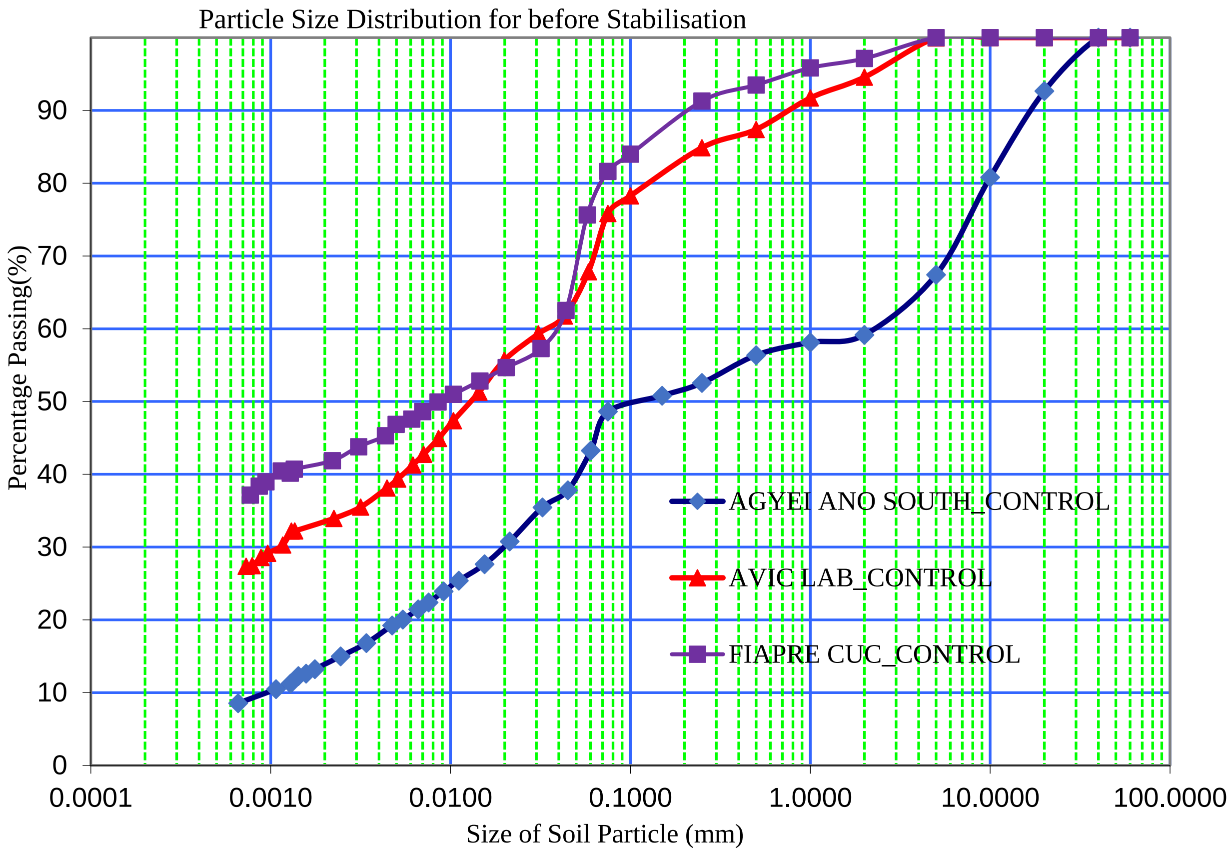

Figure 4: Gradation Curve for the Control Soils

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Table 2: Grading Characteristics of the Control Sample

Grading Characteristic	**Agyei Ano South**	**Avic lab (STU)**	**Fiapre CUC**
D_{10} (mm)	0.001	-	-
D_{30} (mm)	0.02	0.0011	-
D_{60} (mm)	2.1	0.032	0.04
C_u	2100	-	-
C_c	0.19	-	-
% passing 75 µm	48.6	75.9	81.6
% passing 0.425 mm	56.0	86.5	93.0
% passing 2.0 mm	59.2	94.6	97.1
% passing 4.75 mm	66.5	99.5	99.5
Effective Size (mm)	0.001	-	-

Consistency Limits of Control Specimens

The consistency limits of the control specimens were ascertained and displayed in Table 3.

Table 3: Consistency limits of Control specimens

Control Specimen	**Liquid Limit (%)**	**Plastic Limit (%)**	**Plasticity Index (%)**
Agyei Ano South	38.25	22.44	15.81
Avic Lab (STU)	48.56	30.97	17.59
Fiapre	49.54	32.90	16.64

Compaction Characteristics – Agyei Ano South

Figures 5 and 6 present the dry density and moisture contents results for both the control and the test specimens.

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African Journal of Applied Research
Vol. 10, No. 2 (2024), pp. 537-568
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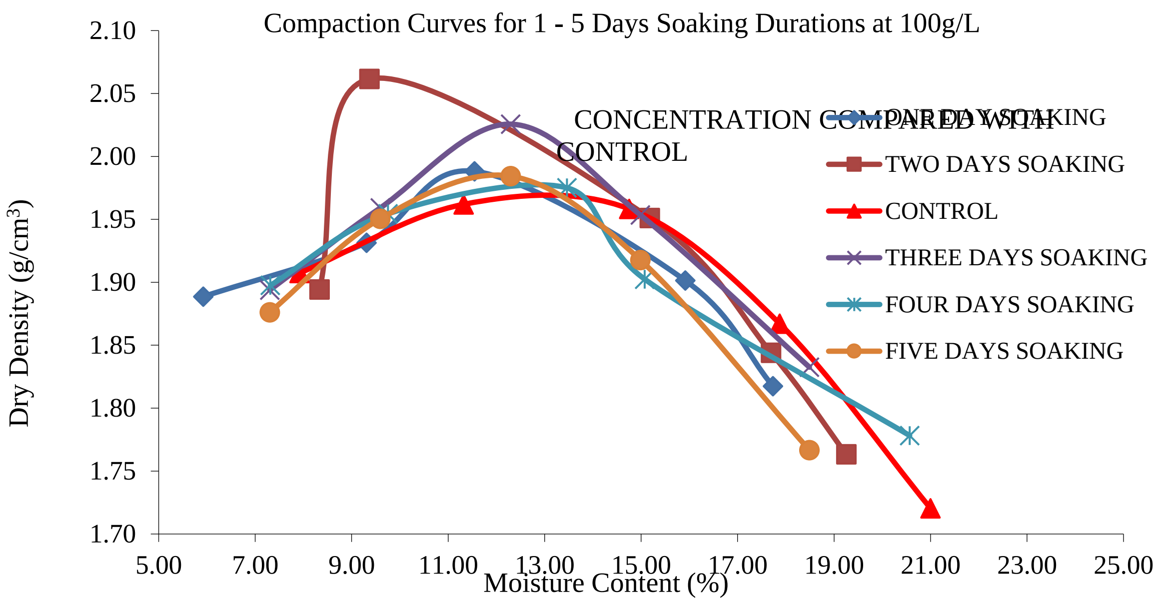

Figure 5: Compaction curves for 1 – 5 Days LBPE Soaking Duration

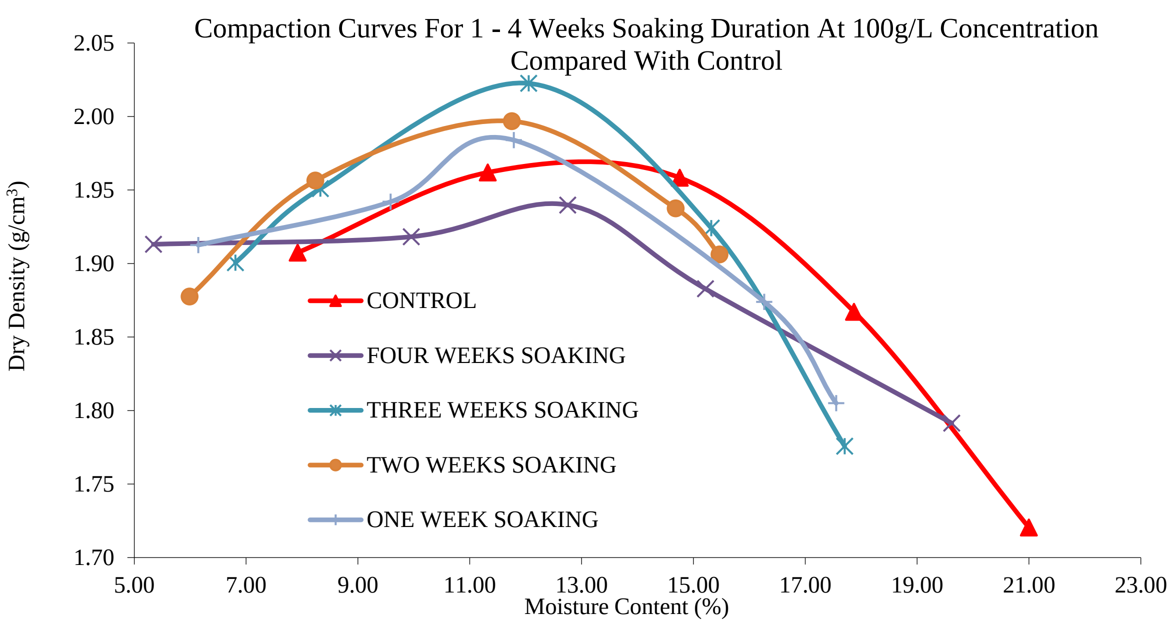

Figure 6: Compaction curves for 1 – 4 Weeks LBPE Soaking Duration

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Vol. 10, No. 2 (2024), pp. 537-568
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Published: December 2024

Table 4 also presents the control and test specimens' optimum moisture contents and maximum dry densities.

Table 4: MDD and OMC Values – Control and Stabilized Materials

SOAKING DURATION	MDD (g/cm^3)	OMC (%)
Control	1.97	13.10
1 Day	1.99	11.50
2 Days	2.06	9.50
3 Days	2.03	12.30
4 Days	1.98	13.00
5 Days	1.97	13.00
1 Week	1.98	11.50
2 Weeks	2.00	11.80
3 Weeks	2.02	12.00
4 Weeks	1.94	12.50

Results from Set-up 2

Compaction Characteristics

Figures 7, 8, and 9 present the dry density and moisture content results for the control and the test specimens.

Compaction Characteristics – Agyei Ano South

Figure 7 illustrates the compaction characteristics of the soil sample from Agyei Ano South, including both the control and the soil stabilized with various concentrations of LBPE.

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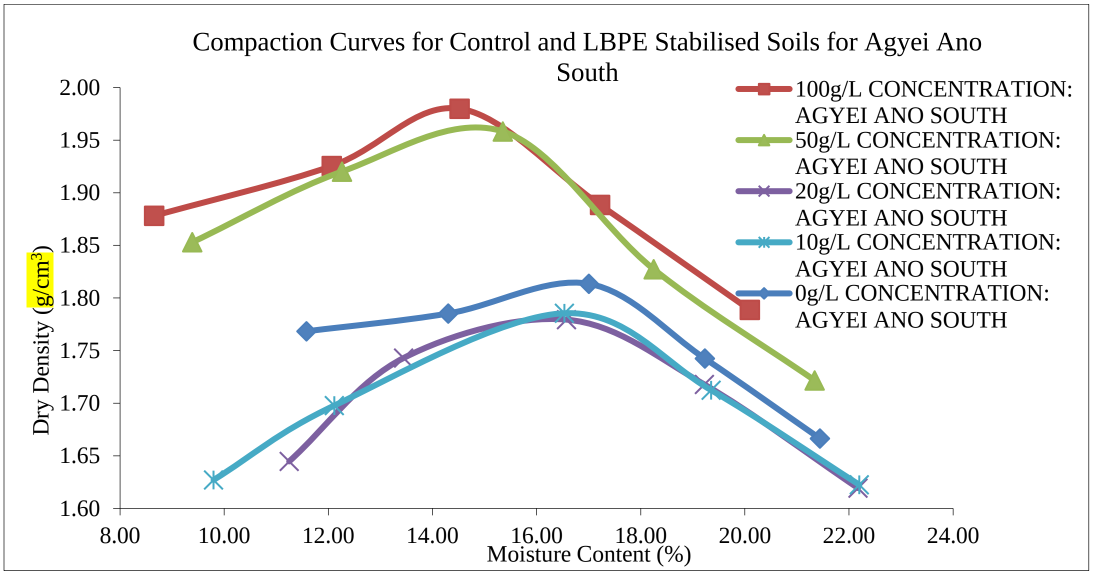

Figure 7: Compaction curves for various LBPE concentrations and the control – Agyei Ano South sample

Compaction Characteristics – Avic Lab (STU)

Figure 8 presents the compaction characteristics of the Avic Lab (STU) soil sample for both the control and the soil stabilised with various concentrations of LBPE.

ISSN: 2408-7920

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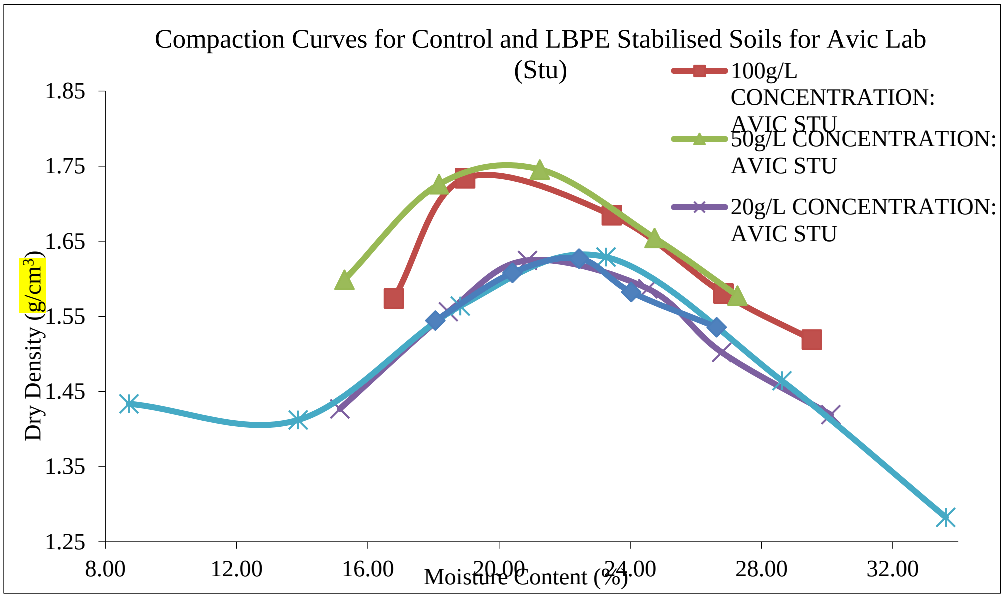

Figure 8: Compaction curves for various LBPE concentrations and the control – AVIC lab (STU) sample

Compaction Characteristics – Fiapre CUC

Figure 9 presents the compaction characteristics of the soil sample from Fiapre CUC, both the control and the soil stabilised with various concentrations of LBPE.

African Journal of Applied Research
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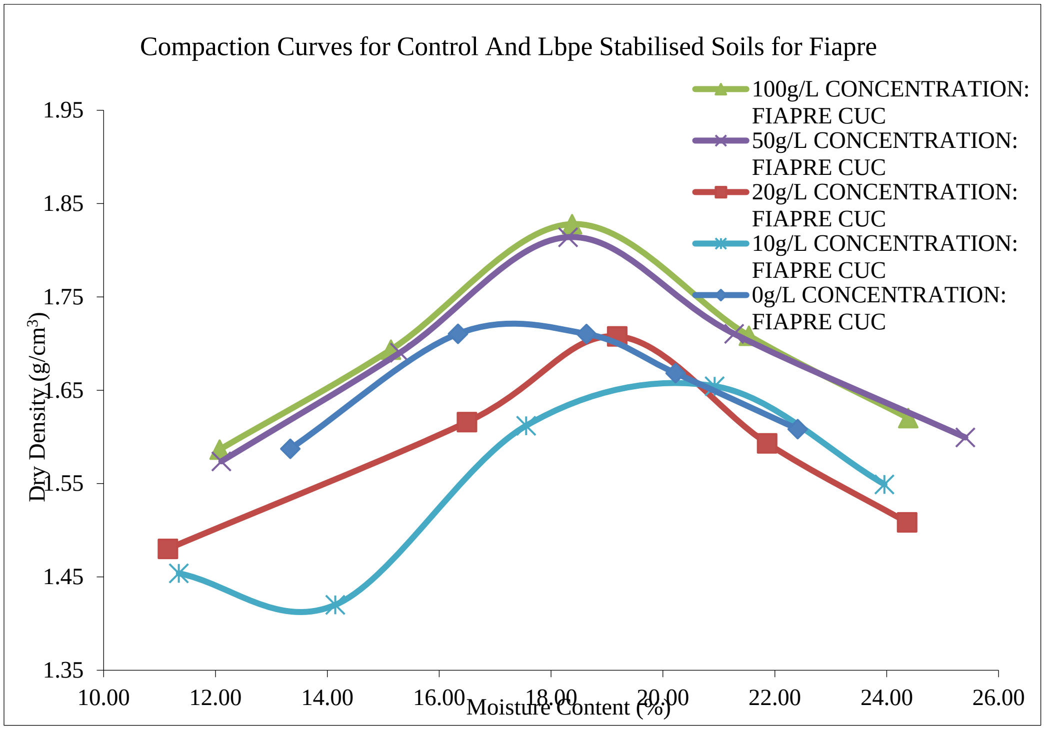

Figure 9: Compaction curves for various LBPE concentrations and the control – Fiapre CUC sample

Discussion

Soil Classification of Control Specimens

Based on the index property tests on the control soils, the Agyei Ano South soil was classified as clayey gravel with sand or gravel-sand-clay mixtures using the USCS D. ASTM (1985), with the group symbol GC. According to the AASHTO System of Classification AASHTO M145-91 (2012), the soil was classified as Silt-Clay material with the group symbol A-6(5). The Avic soil was classified as poorly graded low plasticity clayey Silt with some sand, with the group symbol ML, according to the USCS (D. ASTM, 1985). According to the AASHTO Classification System AASHTO M145-91 (2012), it was classified as Silt-Clay material with the group symbol A-7-5(15). The Fiapre soil was classified as poorly graded low plasticity silty Clay with sand, with the group symbol CL, according to the USCS (D. ASTM, 1985). According to the AASHTO Classification System AASHTO M145-91 (2012), it was classified as Silt-Clay material with the group symbol A-7-5(16).

Variation of Compaction Characteristics – Results from Set-up 1

African Journal of Applied Research
Vol. 10, No. 2 (2024), pp. 537-568
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The variation of the maximum dry density for the various soaking durations was analysed and graphically illustrated in Figure 10. Notably, LBPE from the various soaking durations gave higher MDD than the control except for the 4-week soaking duration. This means that increased densification is achieved at the same compaction effort. For the same material and compaction effort, an increase in densification should only be possible with increased compaction effort or using a lubricating material, which could assist in the rearrangement of the soil particles under the same compaction effort. This indicates that the LBPE, which contains tannins, is a better lubricant than water since higher dry densities were achieved with the LBPE. Another possible explanation could be that the LBPE, as a chemical stabiliser (a biopolymer containing tannins), can react with the soil and create new compounds. This claim was corroborated by Slabbert (1992), Chen et al. (2010) and Du et al. (2022).

The analysis and illustration of the variation of OMC for the various soaking durations can be found in Figure 11. The extract's soaking durations gave lower OMC than the control OMC. This further reinforces the claims that the LBPE, as a chemical stabiliser, possesses better lubrication ability than water or that the LBPE can react with the soil to form new compounds. These results also compare favourably with Du et al. (2021), who concluded that oak tannins with sodium hydroxide are a superplasticiser for earthen materials.

Thus, LBPE enables compaction at the dry side of control OMC, resulting in higher MDD at the same compaction effort. Optimum performance was obtained for the 2-day duration of soaking with 9.50% for OMC and 2.06g/cm^3 for MDD. This is a 4.57% increment of MDD over the control. This differs slightly from the 3-day duration of soaking obtained by the authors in an earlier study on the effects of LBPE on consistency limits of marginal lateritic gravel soils (Vordoagu & Adams, 2024).

The variation in the moisture content samples taken could explain this variation. The presumption here is that in taking samples for the moisture content determination of the 2-day LBPE test specimen, rock minerals were picked instead of clay minerals in moisture content determination for the 3-day LBPE test specimen. The MDD and OMC for the 3-day soaking duration were 2.03g/cm^3 and 12.30% respectively. The MDD and OMC for the 21-day soaking duration were 2.02g/cm^3 and 12.00% respectively. The 3-day duration of soaking and 21-day duration of soaking gave 3.05% and 2.54% increments in MDD over the control, respectively. The control specimen recorded 1.97g/cm^3 and 13.10% for MDD and OMC, respectively.

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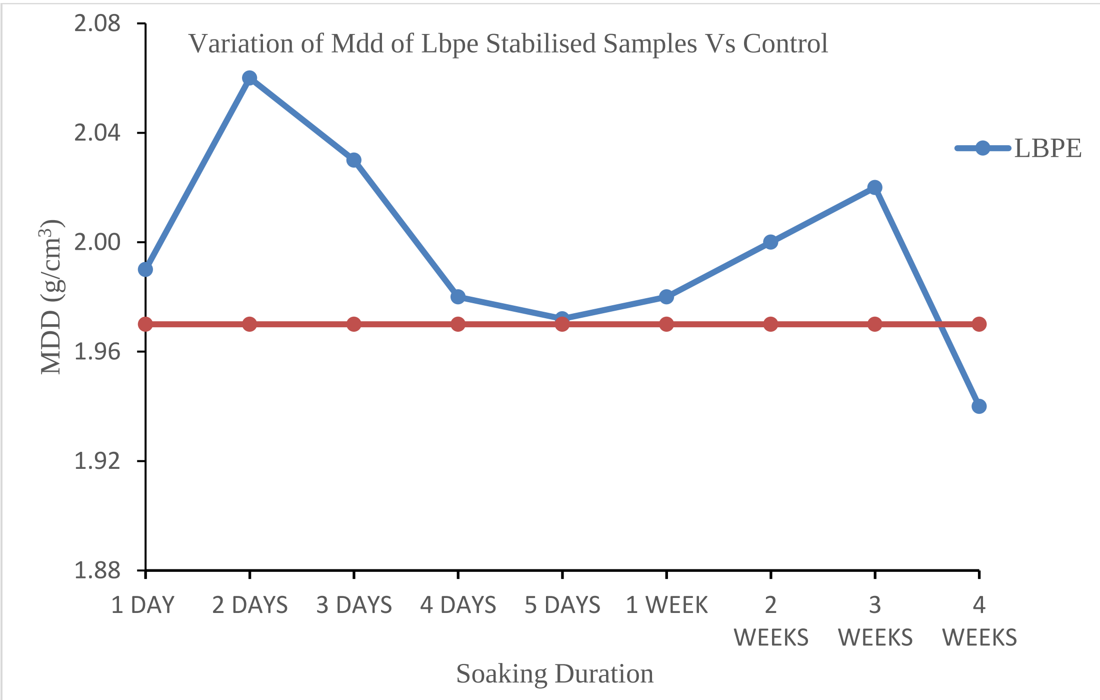

Figure 10: Variation of MDD of LBPE Stabilized Samples with Soaking Duration Compared with Control Sample

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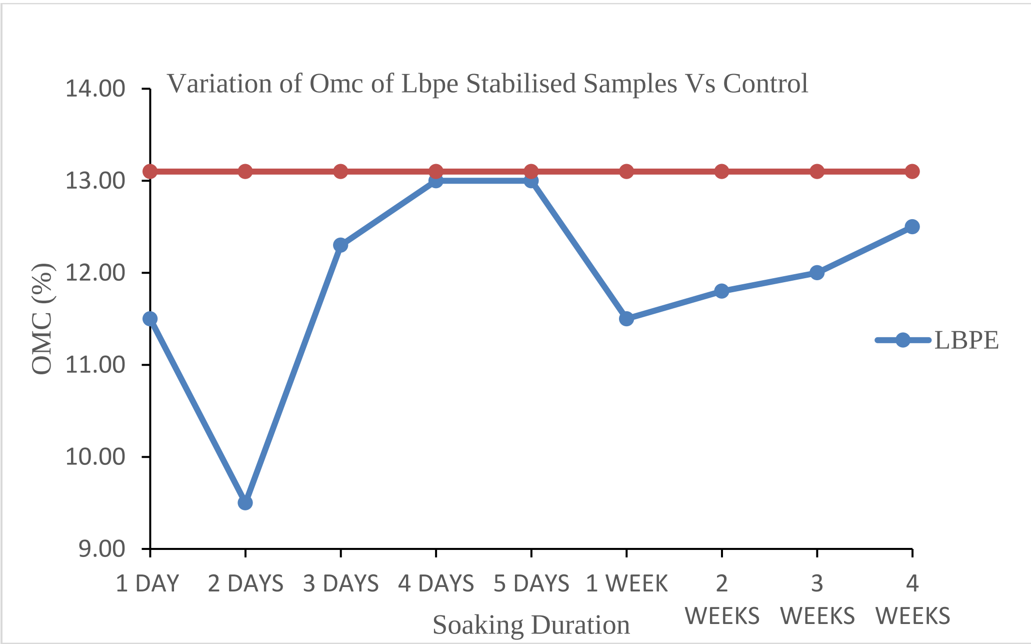

Figure 11: Variation of OMC of LBPE Stabilized Samples with Soaking Duration Compared With Control Sample

The results indicate an improvement in the compaction characteristics of lateritic gravel soils treated with locust bean pod extract. Results from the FTIR analysis show that the LBPE contains tannins and flavonoids and could, therefore, be regarded as a bio-based polymer. This was corroborated by Abagale et al. (2013), (Okewale & Adedokun, 2022) and (Vordoagu & Adams, 2024). This could account for the density increases seen in the results indicated above. As noted in the results, soaking for four weeks gave lower values than the controls. These could be attributed to fermentation and the breakdown of tannins and volatile components in the extracts during the long extraction process. Some bacteria could reduce the tannin and other phenolic compounds' content during fermentation. (Shang et al., 2019), (Šalić & Šamec, 2022) and (Tian et al., 2023)Thus, the reduction in tannin content due to fermentation could result from lower MDD values at longer (4 weeks) of the extraction process.

Variation of Compaction Characteristics – Results from Set-up 2

Figures 12 to 17 illustrate the variations of MDD and OMC for various concentrations for all three samples. Notably, for all three samples, lower concentrations of LBPE (10g/l and 20g/l) resulted

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in a lower MDD than the control. On the other hand, higher concentrations of LBPE (50g/l and 100g/l) led to higher MDD than the control. This could mean that at lower concentrations of LBPE, the tannin concentration was insufficient to cause dispersion and rearrangement of fine particles during compaction to ensure high densities (Du et al., 2021). There is a sharp increase in MDD for soils stabilised with a 50g/l concentration of LBPE for all three soils. The increase in MDD from 50g/l concentration to 100g/l is shallow, and even in the instance of AVIC lab soil, the 100g/l concentration even recorded a lower value than that of the 100g/l concentration. This could mean that the optimum increase in density is attained at a concentration of 50g/l. Thus, from these results, the optimum concentration of LBPE for soil stabilisation was 50g/l.

Table 5: MDD (g/cm^3) and OMC (%) of Stabilised Soil for Various LBPE Concentrations

Concentration	**AGYEI ANO SOUTH**		**AVIC LAB (STU)**		**FIAPRE CUC SOIL**	
	MDD	OMC	MDD	OMC	MDD	OMC
0g/l (Control)	1.818	16.25	1.628	22.25	1.721	17.5
10g/l	1.788	16	1.632	22.5	1.665	19.75
20g/l	1.783	16	1.633	22	1.71	19
50g/l	1.967	14.5	1.752	20	1.814	18.5
100g/l	1.981	14.25	1.751	20.25	1.828	18.4

Generally, increasing LBPE concentration results in a decreasing OMC. Also, the OMC of the control compaction is generally more significant than the OMC of the stabilised soil. This shows that higher density is achieved at lower moisture contents, a testament to the superplasticiser action of tannin-containing LBPE. These results align with the works of Pizzi (2008) and Du et al. (2021)

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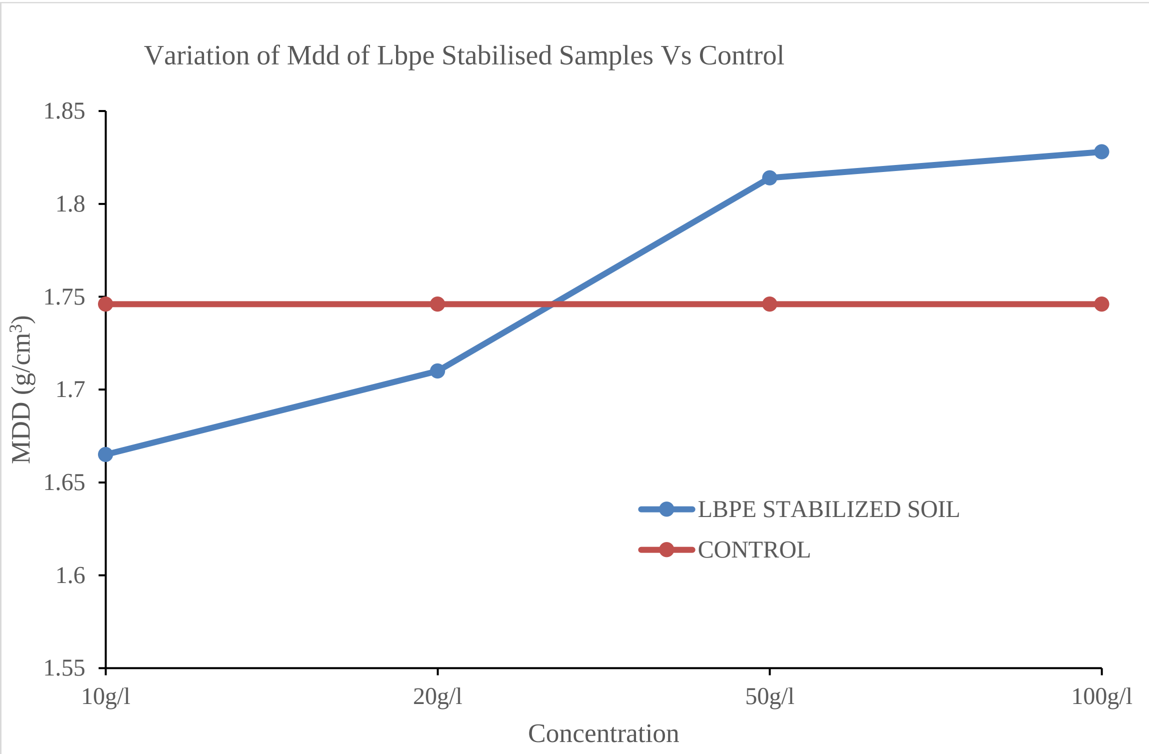

Figure 12: Variation of MDD for various LBPE concentrations and the control – Agyei Ano South sample

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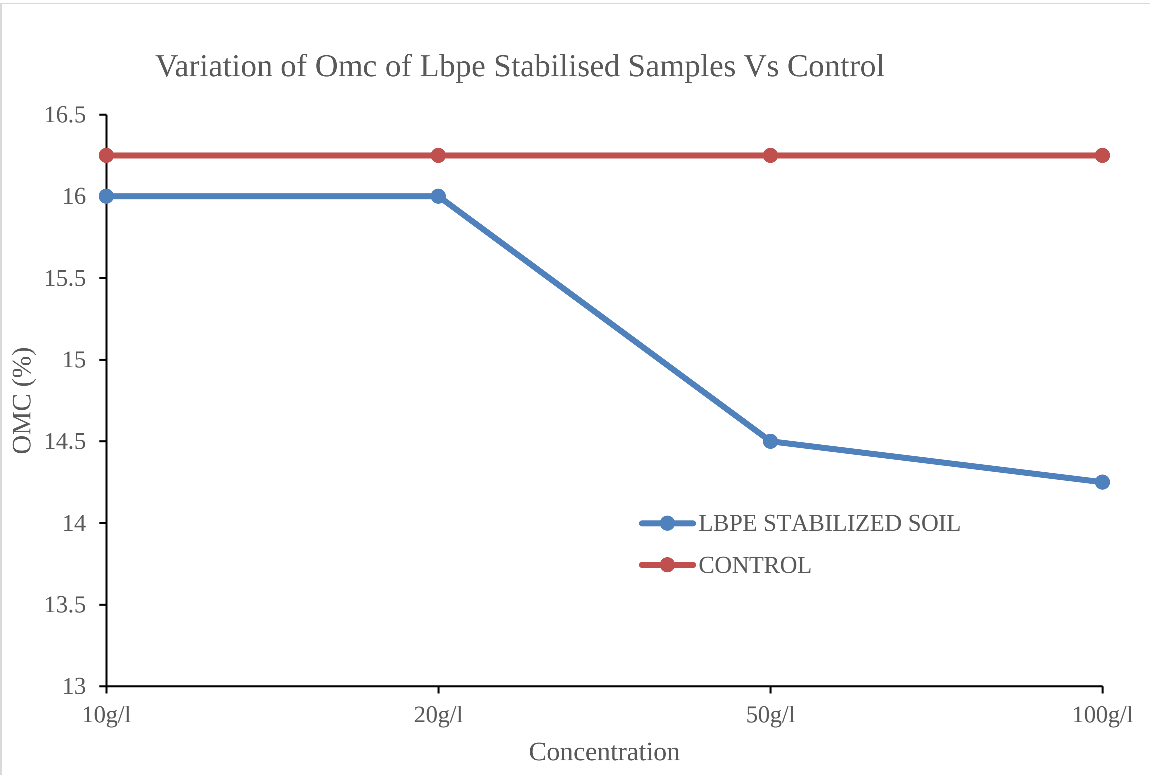

Figure 13: Variation of OMC for various LBPE concentrations and the control – Agyei Ano South sample

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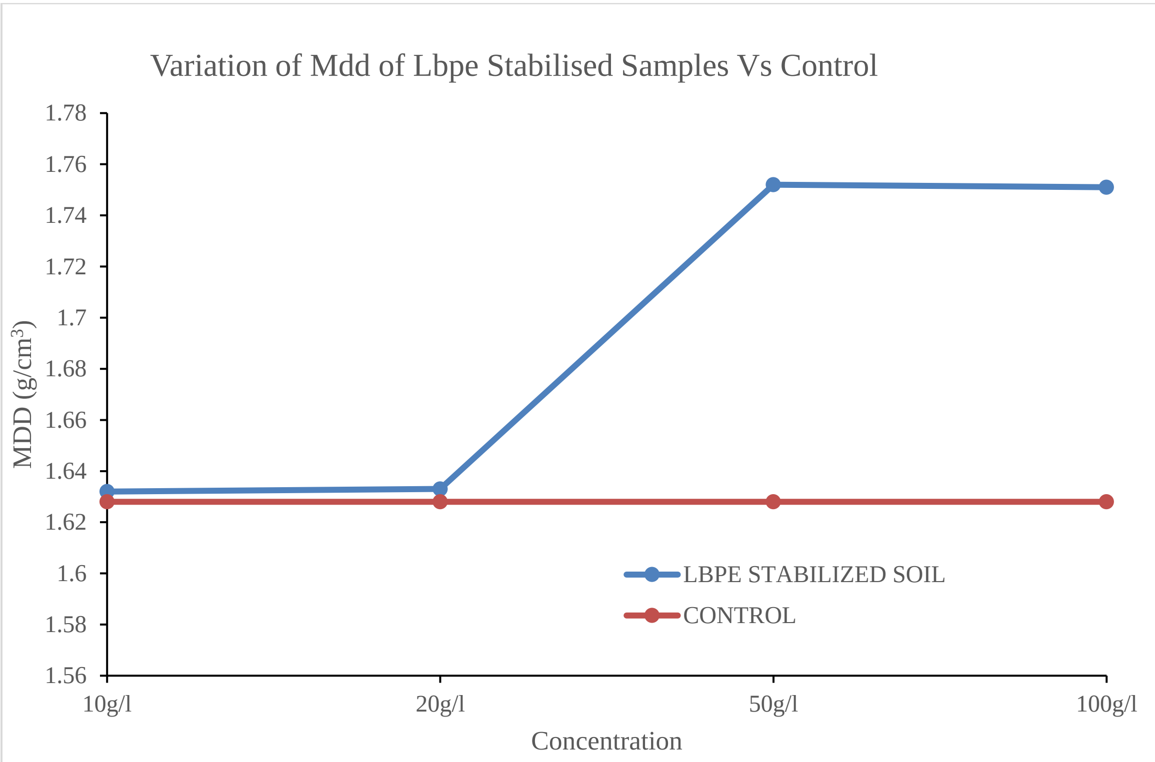

Figure 14: Variation of MDD for various LBPE concentrations and the control – AVIC lab (STU) sample

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Vol. 10, No. 2 (2024), pp. 537-568
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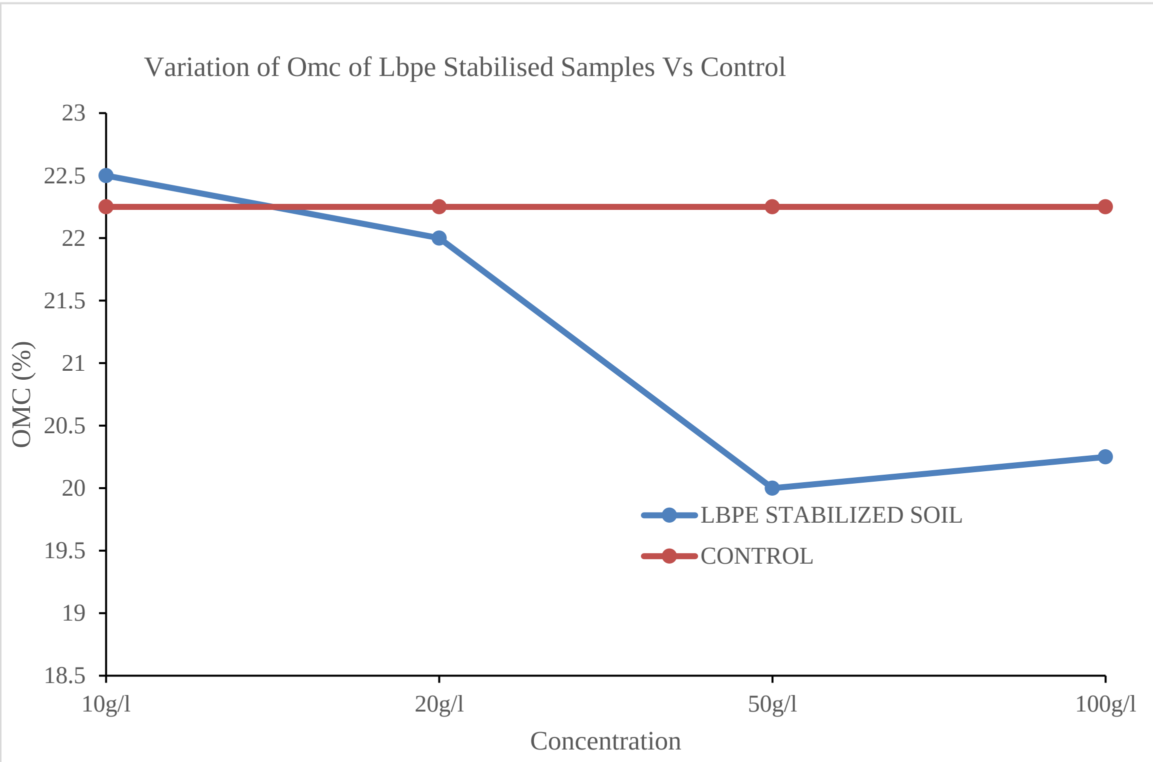

Figure 15: Variation of OMC for various LBPE concentrations and the control – AVIC lab (STU) sample

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Vol. 10, No. 2 (2024), pp. 537-568
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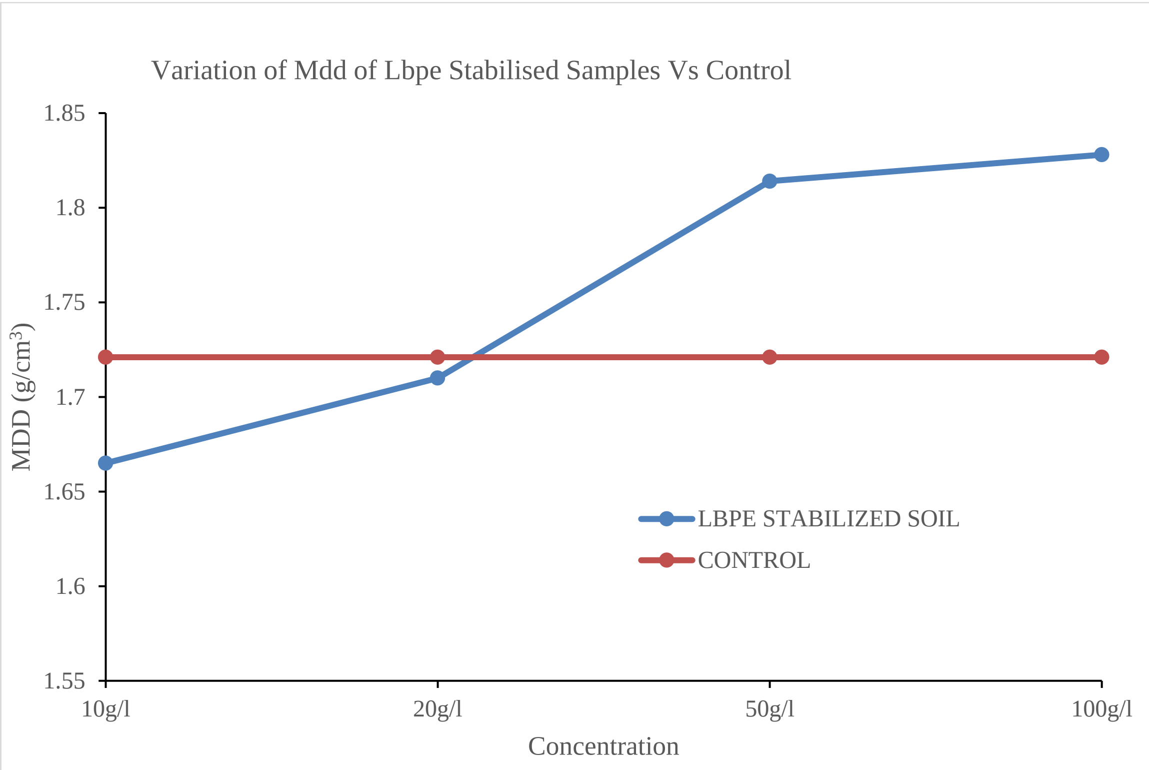

Figure 16: Variation of MDD for various LBPE concentrations and the control – Fiapre CUC sample

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Vol. 10, No. 2 (2024), pp. 537-568
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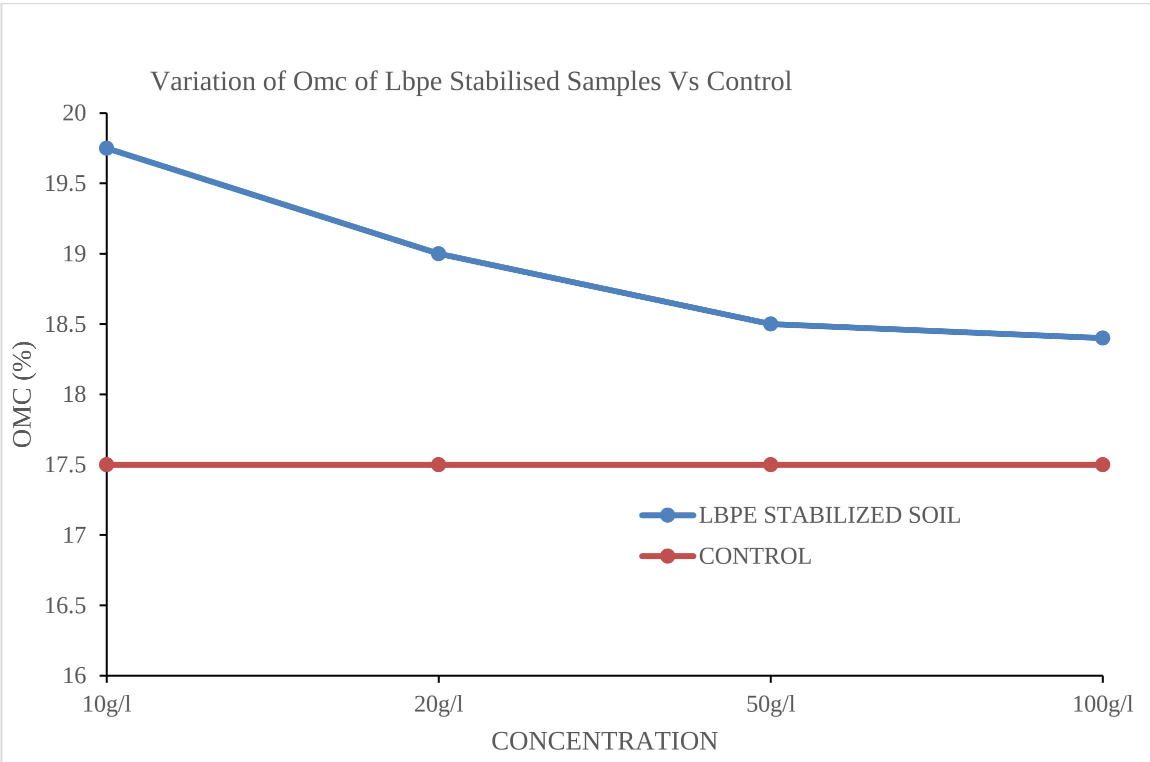

Figure 17: Variation of OMC for various LBPE concentrations and the control – Fiapre CUC Sample

CONCLUSION

The findings from the experiments demonstrate that LBPE typically raises the Maximum Dry Density (MDD) and lowers the Optimum Moisture Content (OMC). These results suggest an enhancement in the compaction properties of lateritic gravel soils treated with locust bean pod extract. The optimal concentration of LBPE for stabilisation of all three soils in this study was 50g/l. This represents 8.20%, 7.62% and 5.40% increases in MDD over the control for Agyei Ano South, Avic lab and Fiapre soils, respectively. Regarding the OMC, the 50g/l concentration translates into 10.77% and 10.11% decreases over the control for Agyei Ano South and Avic lab soils, respectively. The OMC for the Fiapre soil recorded an increase of 5.71% over the control. The optimal soaking duration for increased densification was two days. The best performance was obtained for the 2-day duration of soaking, which gave 9.50% for OMC and 2.06g/cm^3 for MDD,

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representing a 4.57% increment of MDD over the control. LBPE could, therefore, be used as a soil stabiliser.

Recommendations

Further studies should be carried out where the concentrations of LBPE between 20g/l and about 200g/l are varied to confirm the optimum concentration observed in this study and investigate the behaviour after a concentration of 100g/l LBPE. Further studies are also recommended to evaluate the strength, durability, and erodibility characteristics of LBPE-stabilized materials.

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