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Comparative Analysis of the Geotechnical Performance of Lateritic Soil Stabilised with Bone Ash Versus Hydrated Lime

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ABSTRACT

This study presents a comparative analysis of lateritic soil stabilisation using bone ash and hydrated lime. Various geotechnical tests, including sieve analysis, moisture content determination, specific gravity, Atterberg limits, compaction, and California Bearing Ratio (CBR) tests, were conducted to evaluate the impact of both stabilisers on the soil's engineering properties. The lateritic soil, classified as silt with high plasticity, was found to benefit more significantly from hydrated lime treatment. Hydrated lime reduced the linear shrinkage, liquid limit, plastic limit, and plasticity index, improving the soil's workability and suitability for construction. Furthermore, the CBR values for both soaked and unsoaked samples increased with higher lime content, indicating enhanced soil strength.

In contrast, bone ash displayed mixed results. While it improved the CBR values for unsoaked samples, it decreased the values for soaked samples due to water absorption. Additionally, bone ash increased the soil's linear shrinkage, liquid limit, and plastic limit, suggesting limited effectiveness in reducing plasticity and shrinkage behavior.

Overall, the results demonstrate that hydrated lime is a more effective stabiliser than bone ash, particularly in improving strength, plasticity, and durability of lateritic soil for construction applications. Bone ash, though useful in certain conditions, does not provide the same level of stabilisation, making hydrated lime the preferred option in geotechnical soil stabilisation.

Keywords: Hydrated lime, Bone ash, Geotechnical properties, Plasticity index

1. Introduction

1.1 Background

Lateritic soil is widely used as a construction material, especially in tropical regions, due to its availability and cost-effectiveness. However, the soil's engineering properties, such as its high plasticity and susceptibility to moisture variations, limit its use in road construction without stabilisation. Stabilisation is the process of enhancing the physical and mechanical properties of soil to make it more suitable for construction applications. The traditional use of hydrated lime in soil stabilisation has proven effective in improving the load-bearing capacity and reducing the plasticity of lateritic soil. However, the rising cost of lime and environmental concerns associated with its production have led to an increased interest in alternative stabilisers such as bone ash.

Bone ash, a byproduct of calcined animal bones, primarily consists of calcium phosphate, making it a potential eco-friendly and cost-effective alternative to hydrated lime. In addition to its pozzolanic properties, bone ash provides an avenue for recycling agricultural waste, reducing environmental pollution, and minimizing the carbon footprint associated with conventional soil stabilisers. Despite these advantages, research comparing the geotechnical performance of bone ash and hydrated lime as stabilisers for lateritic soil remains limited.

This study seeks to address this gap by performing a comparative analysis of the geotechnical properties of lateritic soil stabilised with bone ash versus hydrated lime. The goal is to determine which stabiliser provides better improvement in soil characteristics such as strength, compaction, and load-bearing capacity. The findings will offer insights into the viability of bone ash as a sustainable alternative to hydrated lime for road pavement construction in tropical regions.

1.2 Problem Statement

With the rising cost of conventional stabilisers like lime and cement, there is a need to explore alternative materials such as bone ash. The comparative analysis of the performance of bone ash and lime as stabilisers for lateritic soil can help determine a sustainable solution for road construction in tropical regions.

1.3 Objectives

The primary objective of this study is to compare the geotechnical performance of lateritic soil stabilised with bone ash and hydrated lime. Specific objectives include:

- To evaluate the effect of bone ash and hydrated lime on the CBR of lateritic soil.
- To assess changes in the Atterberg limits of lateritic soil stabilised with bone ash and hydrated lime.
- To analyse the compaction characteristics of the stabilised soil.
- To compare the unconfined compressive strength of lateritic soil treated with bone ash and hydrated lime.

1.4 Significance of Study

This study provides a detailed comparison of bone ash and hydrated lime as stabilisers, contributing to the development of more sustainable and cost-effective stabilisation techniques for road construction. It highlights the potential environmental benefits of using bone ash and its effectiveness as an alternative to lime.

2. Literature Review

Lateritic soil is widely used in construction, especially in tropical and subtropical regions, due to its natural abundance and suitability for road and building foundations. However, lateritic soil, typically high in clay content, tends to exhibit undesirable characteristics, such as high plasticity and poor load-bearing capacity, which makes it prone to cracking, shrinking, and swelling under varying moisture conditions (Akinmade, 2016). This has driven the need for stabilisation to improve its engineering properties for more effective use in road pavements.

Soil stabilisation is a process that enhances the engineering properties of soil to make it more suitable for construction purposes. Stabilisation techniques include mechanical, physical, and chemical methods:

Mechanical stabilisation involves the compaction and densification of soil to improve its load-bearing capacity (Joel & Edeh, 2014).

Physical stabilisation includes the addition of materials, such as fibers or geotextiles, to reinforce the soil (Cokca, 2001).

Chemical stabilisation, the focus of this study, involves the addition of binders like lime, cement, or other pozzolanic materials to alter the chemical and physical properties of the soil, enhancing its strength, reducing plasticity, and improving durability (Charman, 2010).

In road construction, chemical stabilisation is frequently used to modify the subgrade soil, increasing its ability to withstand traffic loads and reducing the risk of failure. Common stabilisers include lime, cement, and industrial/agricultural byproducts such as fly ash and rice husk ash (Makusa, 2012).

Bone ash, a byproduct of animal bones, consists primarily of calcium phosphate and calcium oxide. Its composition and chemical characteristics make it a potential alternative stabiliser for soil. Previous studies have investigated the use of bone ash as a stabiliser for lateritic soil, demonstrating improvements in compressive strength, shear strength, and California Bearing Ratio (CBR) (Oluremi, 2012). Moreover, bone ash offers an environmentally friendly solution, reducing the waste burden from abattoirs and contributing to sustainable construction practices (Osinubi & Ijimdiya, 2015).

Studies have shown that bone ash has pozzolanic properties, allowing it to react with soil constituents, forming cementitious compounds that enhance the soil's strength and reduce its plasticity (Otoko, 2014). The use of bone ash also addresses environmental issues, such as pollution caused by the improper disposal of animal bones (Gbadamosi & Okunlola, 2019).

Hydrated lime (calcium hydroxide) is a well-established chemical stabiliser known for its ability to improve soil workability, reduce plasticity, and increase compressive strength. When mixed with soil, lime reacts with clay minerals, initiating a pozzolanic reaction that results in the formation of calcium silicate hydrates and calcium aluminate hydrates. These compounds contribute to the long-term strength gain and durability of the stabilised soil (Okagbue, 2007). Hydrated lime has been widely used in road construction to stabilise subgrade soils, particularly those with high plasticity and poor load-bearing capacity. It improves the soil's structural integrity, reduces its moisture susceptibility, and enhances its resistance to environmental conditions (Bell, 1996).

Optimizing the proportions of stabilisers is crucial to achieving the desired improvement in soil properties. Various methods, such as the Design of Experiments (DOE), response surface methodology (RSM), and factorial designs, have been used to identify the optimal mix of materials (Montgomery, 2013). These methods help determine the ideal combination of stabilisers (such as bone ash and hydrated lime) that yield maximum benefits in terms of strength, durability, and workability of the soil (Rao et al., 2012).

Optimizing stabiliser proportions is particularly important in road construction, where factors like cost, material availability, and environmental impact need to be balanced with performance. This research aims to find the optimal proportions of bone ash and hydrated lime to stabilise lateritic soil for road construction, ensuring that the mix delivers enhanced geotechnical properties and sustainability benefits while comparing it with hydrated lime.

3. Materials and Methods

3.1 Materials

Lateritic Soil

The lateritic soil used in this study will be sourced from a site within a tropical region. The soil will be air-dried, pulverized, and sieved through a 4.75 mm sieve to remove large particles and debris.

Figure 1: Material sample of Laterite, crushed bone ash and hydrated lime

Bone Ash

Bone ash will be produced from calcined animal bones obtained from local abattoirs. The bones will be thoroughly cleaned, air-dried, and heated in a kiln at temperatures between 600°C and 900°C. After calcination, the bones will be ground into fine ash, passing through a 75 µm sieve.

Hydrated Lime

Commercially available hydrated lime will be used for the stabilisation process. The lime will be weighed and prepared according to the desired proportions for the study.

3.2 Sample Preparation

Lateritic soil, commonly found in abundance in Nigeria, is widely used in geotechnical engineering applications due to its accessibility and suitability for construction. The lateritic soil sample for this research was collected from a depth of 1 to 1.5 meters below the ground surface in Galadimawa, Abuja, Nigeria. The soil samples were air-dried at room temperature and then ground to fine particles, ensuring that they passed through an 80 µm sieve. For stabilisation purposes, bone ash, produced from calcined cattle bones, was used in combination with hydrated lime. Both the bone ash and hydrated lime were sieved through a No. 40 mesh before use to ensure uniform particle sizes for the stabilisation process.

3.3 Preliminary Laboratory Tests

To effectively classify and understand the behavior of the natural lateritic soil, a series of geotechnical tests were performed on the untreated soil to determine its fundamental properties. The preliminary tests conducted included sieve analysis, moisture content determination, specific gravity, and Atterberg limits tests. After these baseline tests, the stabilised soil samples (with varying percentages of bone ash and lime) were subjected to further testing, including the California Bearing Ratio (CBR) and Atterberg limits tests, to assess the improvements in soil properties.

3.3.1 Sieve Analysis

Sieve analysis was conducted to determine the particle size distribution of the lateritic soil. This test provides valuable data regarding the soil's suitability for construction applications, such as road and airfield construction. For this study, a measured mass of the soil sample was placed on the top of a stack of sieves with progressively smaller aperture sizes, down to a base sieve that captured the finest particles. The sieves were mechanically shaken for a set period, and the material retained on each sieve was weighed. The results were used to plot a particle size distribution curve, helping to classify the soil based on its gradation.

3.3.2 Water/Moisture Content Test

The moisture content test was performed to determine the percentage of water present in the lateritic soil relative to its oven-dry mass. This test is crucial, as moisture content affects several soil properties, including permeability, compaction, and particle size behavior. The moisture content was determined following ASTM D2216 – "Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock." The test procedure involved weighing a moisture can, filling it with wet soil, drying the soil in an oven at 105°C overnight, and re-weighing the can. The moisture content was calculated by comparing the mass of the wet and dry soil.

3.3.3 Specific Gravity Test

The specific gravity of the soil was determined using a density bottle method, which measures the ratio of the weight of a given volume of soil to the weight of an equal volume of water at a standard temperature. This test, conducted in line with ASTM D854, helps in understanding the soil's density and its behavior under load. The dried soil sample was transferred into a pre-weighed density bottle, soaked in distilled water for several hours to remove air bubbles, and weighed again. The process involved vacuuming to eliminate trapped air, and the specific gravity was calculated based on the measured weights.

3.3.4 Atterberg Limits Test

Atterberg limits were tested to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the fine-grained lateritic soil. These limits are indicative of the soil's plasticity and its water content behavior during compaction and strength tests. The liquid limit was measured by determining the moisture content at which the soil changes from a plastic to a liquid state, while the plastic limit represents the point where the soil can no longer be deformed without cracking. The plasticity index (PI), calculated as the difference between the LL and PL, provides a measure of the soil's plasticity. The test was carried out following ASTM D4318.

3.3.5 Experimental Design

Various geotechnical tests, including compaction and California Bearing Ratio (CBR) tests, were conducted to determine the engineering properties of the stabilised lateritic soil. These tests evaluated the effectiveness of bone ash and hydrated lime as stabilisers, individually and in combination.

3.3.6 Compaction Test

The compaction test was performed to determine the moisture-density relationship of the stabilised lateritic soil and to identify the optimal moisture content (OMC) at which the soil achieves its maximum dry density (MDD). The test was conducted in accordance with ASTM D698. Air-dried soil samples passing through a No. 4 sieve were compacted at varying moisture contents using a Proctor compaction mold. Each soil sample was compacted in three layers, with each layer subjected to 25 blows from a 2.6 kg hammer. The moisture content was incrementally adjusted, and the dry density was calculated for each test. The relationship between dry density and moisture content was plotted to generate a compaction curve, from which the MDD and OMC were determined.

3.3.7 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test, as per ASTM D1883, was used to assess the load-bearing capacity of the stabilised soil. This test measures the resistance of the soil to penetration by a standard plunger, with the results expressed as a percentage of the resistance of a standard material (crushed aggregate). The test was performed on both unsoaked and soaked samples to evaluate the effects of water on the soil's strength. The soil samples were compacted in a CBR mold at their respective OMCs, and a surcharge weight was applied. The penetration of the plunger was recorded at various depths

(0.5 mm to 12.5 mm), and the CBR value was calculated for 2.5 mm and 5 mm penetrations. The moisture content of the samples was determined post-testing.

Figure 2: CBR testing machine

4.0 Result and Discussion

4.1 Structure and Composition of Samples

The lateritic soil sample utilized in this study is reddish-brown in colour and was sourced from Galadimawa, Airport Road, Abuja, Nigeria. To provide a comprehensive understanding of the materials used, the chemical compositions of the hydrated lime, bone ash, and natural lateritic soil samples are detailed in Tables 1, 2, and 3, respectively.

Table 1: Chemical Composition of Hydrated Lime Used for the Study

Constituents	**Percentages (%)**
$Ca(OH)_2$	95.0
Substances not precipitated by Ammonium oxalate	2.5
Sulfate (SO_4)	0.4
Heavy metals (as Pb)	0.005
Chloride (Cl)	0.04
Iron (Fe)	0.1
Loss on ignition	1.955

Table 2: Chemical Composition of Bone Ash Used for the Study

Constituents (Oxides)	**Percentages (%)**
Calcium Oxide (CaO)	52.2020
Phosphorus Oxide (P_2O_5)	48.0770
Magnesium Oxide (MgO)	2.0770
Sodium Oxide (Na_2O)	1.3290
Aluminium Oxide (Al_2O_3)	0.6130
Chloride (Cl)	0.3400

Constituents (Oxides)	**Percentages (%)**
Sulfur (S)	0.2124
Potassium Oxide (K_2O)	0.0907
Iron Oxide (Fe_2O_3)	0.0303
Zinc Oxide (ZnO)	0.0069
Nickel Oxide (Ni_2O)	0.0003
Manganese Oxide (MnO)	0.0002

Table 3: Chemical Composition of Natural Lateritic Soil Samples Used for the Study

Constituents (Oxides)	**Percentages (%)**
Silicon Oxide (SiO_2)	68.1210
Aluminium Oxide (Al_2O_3)	19.5280
Iron Oxide (Fe_2O_3)	5.8743
Sodium Oxide (Na_2O)	0.3680
Magnesium Oxide (MgO)	1.2590
Potassium Oxide (K_2O)	1.8219
Calcium Oxide (CaO)	0.1109
Zinc Oxide (ZnO)	0.0045
Sulfur (S)	0.1134
Manganese Oxide (MnO)	0.0906
Phosphorus Oxide (P_2O_5)	0.3837
Nickel Oxide (Ni_2O)	0.0014

4.2 Characterization of Bone Ash

Fourier Transform Infrared Spectroscopy (FTIR) was used to characterize the bone ash, revealing that the mineral is a poorly crystalline, carbonate-containing apatite. The FTIR spectrum displayed typical bands for hydroxyapatite, including the $\nu_3PO_4^{3-}$ (1200-900 cm^{-1}) band, which appeared as a broad band with a discrete shoulder. The $\nu_1PO_4^{3-}$ (980-940 cm^{-1}) band overlapped with the $\nu_3PO_4^{3-}$, while the $\nu_4PO_4^{3-}$ (650-500 cm^{-1}) was partially resolved into two broad peaks, indicating low crystallinity.

The clear bands of the $\nu_3CO_3^{2-}$ (1600-1350 cm^{-1}) confirmed the presence of carbonate (CO_3^{2-}), and overlapping peaks of the ν_1OH^- and ν_2OH^- (3572 cm^{-1}) were observed. However, the νLOH^- (630 cm^{-1}) peak was absent from the spectra. Additionally, the presence of isothiocyanate (2000 cm^{-1}) was detected in the FTIR results.

These findings provide a detailed insight into the mineralogical composition and crystallinity of the bone ash used in this study.

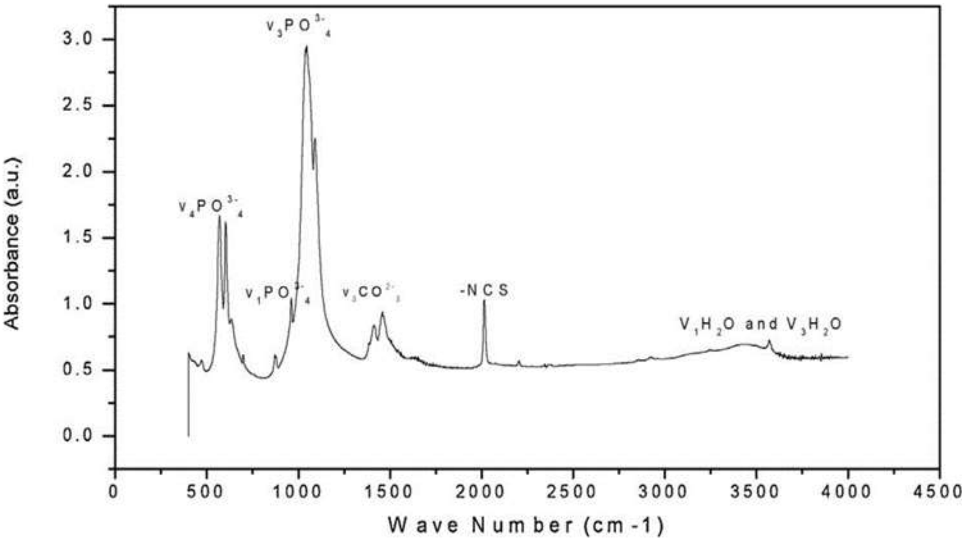
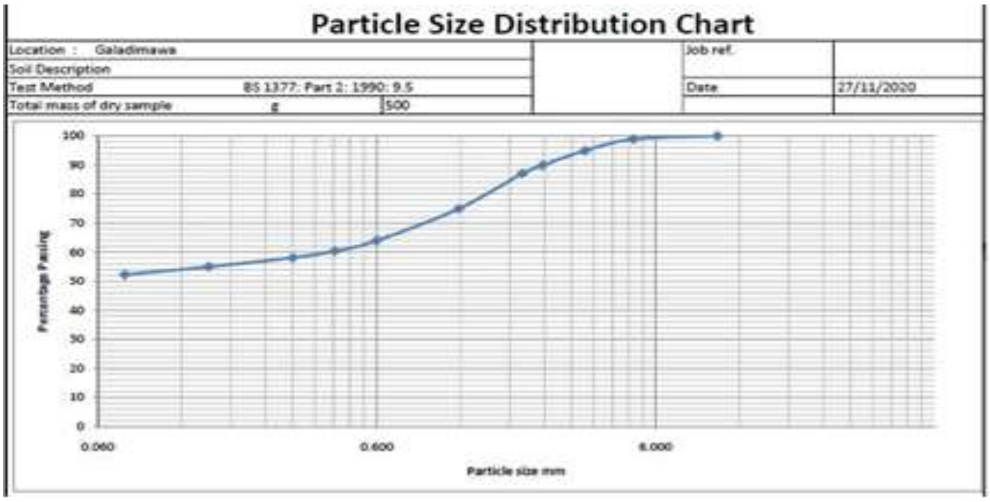


Figure 4: FTIR Spectra of CBA used for the Study

4.3 Sieve Analysis Results

The results of the sieve analysis, as depicted in Figure 5, provide the particle size distribution and classification of the lateritic soil sample used in this study. The analysis followed the guidelines of British Standards (BS 1377: Part 2: 1990: 4.3). Soils are typically classified based on the predominant particle size into categories such as gravel, sand, silt, or clay. According to the particle size distribution curve shown in Figure 5, the lateritic soil sample is classified as silt.


Particle Size Distribution Chart

Location : Galadimawa		Job ref.	
Soil Description			
Test Method	BS 1377: Part 2: 1990: 9.5	Date	27/11/2020
Total mass of dry sample g	500		

Figure 5: Particle size distribution of Lateritic soil sample

4.4 Water/Moisture Content Test Results

The natural moisture content of the lateritic soil sample was found to be 13.23%, indicating that the soil possesses a high natural water-retention capacity.

4.5 Specific Gravity Test Results

The specific gravity of the lateritic soil sample was determined to be 2.8208, suggesting a significant clay mineral content. Typically, clay minerals exhibit a higher specific gravity than sandy soils, which aligns with the characteristics observed in the sample.

4.6 Atterberg Limits Test Results

The Atterberg limits of the lateritic soil were assessed following the British Standards (BS 1377: Part 2: 1990: 4.3). The results, as plotted on a plasticity chart (Figure 6), indicate that the soil is classified as silt with high plasticity, which corresponds to a higher clay content. The plasticity index (PI) values further support this classification.

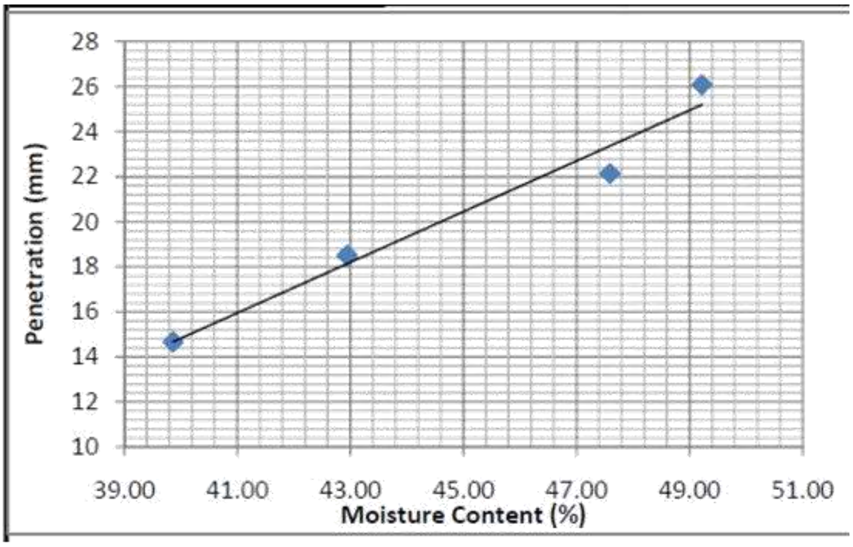


Figure 6: Atterberg Limits (Cone penetration) test results for Lateritic soil sample

4.7 Compaction Test Results

Figure 7 presents the relationship between dry density and moisture content from the compaction test. The optimum moisture content (OMC) was determined to be 11.40%, while the maximum dry density (MDD) was 1.83 kg/m³.

The California Bearing Ratio (CBR) test results, as shown in Table 5, reveal the influence of varying lime and bone ash contents. For samples soaked in water, an increase in the percentage of bone ash (CBA) led to a decrease in CBR values, likely due to water absorption during soaking. Conversely, for unsoaked samples, an increase in CBA content improved the CBR values. Additionally, increasing the percentage of hydrated lime resulted in higher CBR values for both soaked and unsoaked samples.

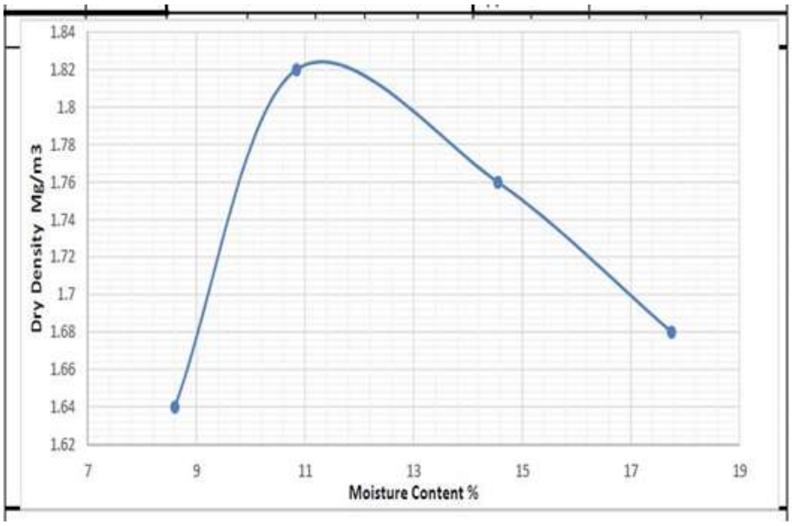


Figure 7: Compaction test result for the lateritic soil sample

Table 4: Engineering Properties of natural lateritic soil sample

Liquid limit, LL (%)	44.8
Plastic limit, PL (%)	24.92
Plasticity index, PI (%)	19.88
Linear Shrinkage (%)	14.44
Natural moisture content (%)	13.23
Plasticity Chart Classification	Silt with high plasticity

OMC (%)	11.4
MDD (kg/m^3)	1.83
CBR (unsoaked) %	38.03
Specific gravity(kg)	2.8208

4.8 Effect of Lime and Bone Ash on Atterberg Limits of the Stabilised Soil

Table 6 summarizes the effect of lime and bone ash on the Atterberg limits of the stabilised soil. The addition of hydrated lime reduced the linear shrinkage, liquid limit, plastic limit, and plasticity index, thus improving the soil’s suitability for construction applications. On the other hand, the inclusion of bone ash caused an increase in the linear shrinkage, liquid limit, and plastic limit of the soil sample.

Table 5: CBR Values for lime and bone ash stabilised lateritic soil

	Percentages	**Soaked**	**Unsoaked**
Control	0%	5.53	38.03
	2%	31.4	8.7
Hydrated lime	4%	37	9.15
	6%	38.15	14.5
	5%	12.2	30.45
CBA	10%	9.62	51.82
	15%	9.47	73.41

5.0 Conclusion

This study conducted a comparative analysis of the stabilisation of lateritic soil using bone ash and hydrated lime, assessing their effects on the soil’s engineering properties through various geotechnical tests, including sieve analysis, moisture content determination, specific gravity, Atterberg limits, compaction, and California Bearing Ratio (CBR) tests.

The sieve analysis classified the lateritic soil as silt with high plasticity, as confirmed by the Atterberg limits, indicating significant clay content. Both stabilisers had distinct impacts on the soil. Hydrated lime demonstrated superior stabilisation performance, significantly reducing the linear shrinkage, liquid limit, plastic limit, and plasticity index. This reduction in plasticity improved the soil's workability and suitability for construction applications. The compaction test revealed an optimum moisture content (OMC) of 11.40% and a maximum dry density (MDD) of 1.83 kg/m^3, both of which were positively influenced by lime stabilisation. Furthermore, the CBR values for both soaked and unsoaked samples increased with higher percentages of hydrated lime, indicating a substantial improvement in soil strength.

In contrast, bone ash showed mixed results. Although it increased the CBR values for unsoaked samples, it reduced them for soaked samples, likely due to water absorption during soaking. Additionally, bone ash led to an increase in the linear shrinkage, liquid limit, and plastic limit, indicating that while it can enhance unsoaked strength, it does not improve plasticity or shrinkage behavior to the same extent as hydrated lime.

Overall, the comparative analysis indicates that hydrated lime is a more effective stabiliser for improving the geotechnical properties of lateritic soil, particularly in terms of strength and plasticity reduction. Bone ash, while showing some potential in unsoaked conditions, is less effective and may not be as suitable for construction purposes, especially in conditions where water retention and shrinkage behaviour are critical concerns. Therefore, hydrated lime is the preferred choice for soil stabilisation in geotechnical applications where durability, strength, and reduced plasticity are essential.

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