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Comparative Performance of Cement and Lime with bagasse Ash on Stabilized Soil for Highway Pavement

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Abstract

This research investigated the potential of *Costus bullatus* bagasse ash as an eco-friendly additive for stabilizing problematic lateritic soils when combined with cement or lime. Soil samples were treated with different concentrations of bagasse ash (0–12%) alongside a fixed 8% content of either cement or lime. A rigorous testing program evaluated key engineering properties of the stabilized soil mixtures, including compaction characteristics (maximum dry density and optimum moisture content), consistency limits, California bearing ratio (CBR), and unconfined compressive strength (UCS). Results showed both cement and lime mixtures exhibited improved geotechnical performance relative to the native soil. However, cement mixtures generally outperformed corresponding lime mixtures. Consistency limits increased more substantially for lime treatments, highlighting cement's comparative benefits. Bagasse ash incorporation led to density reductions but enhanced bearing capacity and strength parameters substantially. Chemical analysis confirmed the bagasse ash met guidelines for pozzolanic reactivity. Outcomes were consistent with prior literature, validating *Costus bullatus* bagasse ash as an effective and sustainable indigenous soil modifier. Overall, findings demonstrate the viability of utilizing optimum dosage proportions as a ground improvement solution for problematic lateritic deposits.

Keywords: lateritic soil, bagasse ash, cement, lime, stabilization, geotechnical properties, mixtures, pozzolan

1. Introduction

The improvement of the engineering properties of problematic soils, such as expansive clays, for their use in civil engineering projects like highway pavement construction has been an important research area (Omotosho & Eze-Uzomaka, 2008) ^[13]. Different stabilizing agents like cement, lime, fly ash etc. have been used for this purpose over the years (Kumar *et al.*, 2016). Recently, the utilization of some agricultural and industrial wastes as stabilizers has attracted research attention as a sustainable and cost-effective solution (Chittaranjan *et al.*, 2011) ^[5]. Bagasse ash, a fibrous waste from the processing of sugarcane, has shown promising results in this direction (Kiran & Kiran, 2013) ^[7]. This paper reviews recent studies that have explored the comparative effectiveness of traditional stabilizers like cement and lime versus bagasse ash in improving the strength characteristics of expansive soils for use in highway pavements. Cement and lime stabilization aim to reduce the plasticity and swell potential of expansive soils through cation exchange reactions. Cement stabilization is based on the hydration and pozzolanic reactions between cement and soil which produce calcium silicate hydrates and calcium aluminate hydrates which bind soil particles together (Bhardwaj & Sharma, 2020) ^[3]. Lime stabilization involves short-term modifications from cation exchange and long term pozzolanic reactions producing cementitious compounds (Nwikina *et al.*, 2018) ^[11]. Research shows cements can increase strength substantially but may be ineffective in swell reduction beyond certain percentages (Omotosho & Eze-Uzomaka, 2008) ^[13]. Limes demonstrate better efficacy in reducing swell characteristics but the rate of strength gain is slower and dosage requirements are higher (Tse & Ogunyemi, 2016) ^[15]. Bagasse ash is rich in reactive silica content and has significant pozzolanic properties (Oyelowo, 2012) ^[14].

Research indicates blending small percentages of bagasse ash with lime or cement can provide improved strength and swell characteristics compared to their solo stabilization (Akobo *et al.*, 2018; Kiran & Kiran, 2013) [2,7]. Tests by Akobo *et al.* (2018) [2] showed 30% bagasse ash + 5% cement increased soil strength considerably more than 5% cement only. Moses & Osinubi (2013) [9] demonstrated increased compaction and California Bearing Ratio (CBR) strength for cement/bagasse ash treatment compared to cement only. The exact mechanisms of the improved performance with bagasse ash are being further studied but likely involve accelerated pozzolanic reactions and formation of cementitious compounds (Ngekpe *et al.*, 2018) [10]. Direct comparative testing demonstrates the superiority of combined stabilization with bagasse ash over sole application of traditional stabilizers. Charles *et al.* (2018) [4] showed 7% lime + 10% bagasse ash and 5% cement + 10% bagasse ash increased unconfined compressive strength (UCS) by up to 4 times over lime-only and cement-only treatment of expansive soils. Similar swell reduction was achieved by the combined stabilizations. Essien & Charles (2016) [6] demonstrated UCS increased over 2 times for 10% cement + 20% bagasse ash compared to 20% cement only stabilization. The required cement dosage also reduced by half in the blended stabilization. Other researchers have reported up to 3 to 4 times strength increases and about 30% higher CBR values for combined application compared to traditional stabilizers alone (Ngekpe *et al.*, 2018; Okonkwo *et al.*, 2016) [10, 12]. These indicate significant economic benefits and improved performance.

Based on the evidence from these recent studies, combined stabilization using bagasse ash waste seems to activate more powerful cementitious reactions leading to greatly enhanced strength properties and equivalent or better reduction of swelling characteristics of problematic expansive soils (Nwikina *et al.*, 2018) [11]. This demonstrates good potential for using bagasse ash to improve the cost-effectiveness and performance of traditional stabilizers in geotechnical applications like highway pavement construction. Further confirmation through extensive field testing has been recommended. There is also need for studying appropriate stabilization mixtures and mechanisms involved to better exploit the advantages of using bagasse ash in a wider range of geotechnical engineering projects (Chittaranjan *et al.*, 2011) [5].

Kiran and Kiran (2013) [7] conducted a comprehensive investigation into the stabilization potential of bagasse ash when combined with cement for black cotton soil improvement. Their experimental study systematically evaluated three different bagasse ash percentages (4%, 8%, and 12%) in combination with varying cement contents. The research revealed significant improvements in key geotechnical parameters: soil density increased from 15.16 kN/m³ to 16.5 kN/m³ with an 8% bagasse ash-8% cement mixture, while the California Bearing Ratio (CBR) showed a remarkable improvement from 2.12 to 5.43 for a 4% bagasse ash-8% cement combination. Most notably, the unconfined compressive strength (UCS) demonstrated a dramatic enhancement, more than doubling from 84.92 kN/m² to 174.91 kN/m² with the optimal 8% bagasse ash-8% cement treatment. Complementing these findings, Moses and Osinubi (2013) examined the influence of compaction energy on the performance of cement-bagasse ash stabilized black cotton soil. Their rigorous experimental protocol involved testing various cement (0-8%) and bagasse ash (0-8%) combinations while employing three distinct compaction standards: Standard Proctor (SP), West African Standard

(WAS), and Modified Proctor (MP). The study not only confirmed the synergistic effects between cement and bagasse ash but also established that compaction energy significantly affects the resulting soil properties. Based on their comprehensive testing regime, the researchers recommended an optimal stabilization blend of 8% ordinary Portland cement (OPC) with 4% bagasse ash (BA) for large-scale treatment of black cotton soil intended for foundation applications. These studies collectively demonstrate that bagasse ash, when properly proportioned with cement, can substantially enhance the engineering properties of problematic black cotton soils. The observed improvements in density, bearing capacity, and compressive strength suggest that bagasse ash-cement combinations activate more effective cementitious reactions than cement alone.

1.1 Research Gap

Based on the provided reviewed literatures, this study addresses four key research gaps in sustainable soil stabilization identified through literature review. First, it investigates the unexplored potential of *Costus bullatus* extract as an indigenous plant-based stabilizer for tropical soils, complementing existing research on agricultural waste materials. Second, the research examines synergistic combinations of bagasse ash with traditional stabilizers (cement and lime), moving beyond current studies that focus solely on bagasse ash as a standalone additive. This approach could optimize stabilization protocols while reducing costs and environmental impact. Third, the study provides comprehensive characterization of stabilized lateritic soils' engineering properties (dry density, moisture content, bearing capacity), which remain inadequately documented despite the material's prevalence in tropical construction.

Finally, the research evaluates long-term performance of stabilized soils under tropical conditions - a critical gap in current knowledge that predominantly focuses on short-term results. By combining these investigations, the study aims to develop more sustainable, cost-effective stabilization methods tailored for tropical developing regions, while establishing important benchmarks for both material combinations and long-term performance. The findings will advance eco-friendly geotechnical solutions for areas where conventional methods prove economically or logistically challenging.

2. Materials and Methods

2.1 Soil collection and preparation

We collected soil samples from multiple locations along a newly constructed road in Rivers State, taking care to obtain material from a depth of 0.5-1.0 meters below the surface to ensure consistency. After collection, we manually broke up any large soil clumps and thoroughly washed the samples to remove organic matter and other contaminants. The cleaned soil was then passed through a 2.36mm sieve to achieve uniform particle size for testing.

2.2 Bagasse Ash Production

For our sustainable stabilizer, we harvested *Costus bullatus* plants from local vegetation and transported them to our laboratory. Following established protocols (Okonkwo *et al.*, 2016) [12], we processed the plants by first cutting them into smaller pieces, then heating them in a furnace at 800°C for two hours. After cooling, we ground the resulting material into a fine powder using a milling machine and sieved it through a 75-micron mesh to ensure consistent particle size.

2.3 Conventional Stabilizers

We sourced commercial cement and lime from a reputable supplier in Port Harcourt's Mile 3 market to serve as our baseline stabilizers for comparison.

2.4 Mixture Preparation

Using precision digital scales (accurate to 0.01g), we carefully measured out bagasse ash in four different proportions (2.5%, 5%, 7.5%, and 10% by weight of soil). The finely sieved ash was then thoroughly blended with the prepared soil to create homogeneous mixtures for testing.

This meticulous preparation ensured we could accurately assess how different ash concentrations affected soil properties.

A constant weight of binder, either cement or lime, was used across all mixes at 8% of the subgrade soil weight. Ordinary Portland cement meeting ASTM C150 specifications was employed as the hydraulic cement. Hydrated lime of minimum 90% calcium content in accordance with ASTM C207 was utilized. Both binders were first dry mixed with the subgrade soil to achieve homogenous distribution. The mix design is shown in Table 1.

Table 1: mix design of soil stabilization

Bagasse Ash (%)	Mix for CB
0	500g natural soil + 0g cement + 0g bagasse ash
4	500g natural soil + 40g cement + 8g bagasse ash
6	500g natural soil + 40g cement + 12g bagasse ash
8	500g natural soil + 40g cement + 16g bagasse ash
10	500g natural soil + 40g cement + 20g bagasse ash
12	500g natural soil + 40g cement + 24g bagasse ash
Bagasse Ash (%)	Mix for LB
0	500g natural soil + 0g cement + 0g bagasse ash
4	500g natural soil + 40g cement + 8g bagasse ash
6	500g natural soil + 40g cement + 12g bagasse ash
8	500g natural soil + 40g cement + 16g bagasse ash
10	500g natural soil + 40g cement + 20g bagasse ash
12	500g natural soil + 40g cement + 24g bagasse ash

The mixes containing cement as the binder were designated as CB (Cement-Bagasse ash) mixtures. Those prepared with lime binder were termed LB (Lime-Bagasse ash) mixtures. For example, the 2.5% bagasse ash mix with cement was labeled CB2.5 and with lime as LB2.5. This clear nomenclature system was applied to distinctly identify each individual mixture composition.

A constant 500-gram sample of the subgrade soil, previously tested to determine gradation and Atterberg limits, served as the base material weight for each mixture. The required amounts of binder, bagasse ash, and soil were precisely combined in plastic bags and manually dry mixed for 5 minutes to evenly coat all particles and fragments.

Next, an electric drill mixer with attached paint mixer paddle was used to thoroughly blend the dry ingredients for an additional 3 minutes at low speed to ensure homogeneity. Finally, predetermined amounts of distilled water were gradually added in small increments over 5 minutes while continuously mixing until achieving proper workability and consistency for compaction. This standardized the process and permitted control of all variables except the bagasse ash percentage.

2.5 Tests Procedures

The experimental procedure for each laboratory test is conducted according to Standards for soil stabilization and analysis.

2.5.1 Optimum moisture content and maximum dry density

The study determined the soil's maximum dry density (MDD) and optimum moisture content (OMC) through laboratory testing following AASHTO T99 standards. Fresh soil samples were carefully crumbled and placed in pre-weighed containers, recording their initial weight to the nearest 0.01g.

Representative samples both natural and composite were then oven-dried at $105 \pm 5^\circ\text{C}$ for 12 hours to remove moisture. Final dry weights were measured, allowing moisture content calculation as the percentage difference between wet and dry weights. The moisture content is calculated as:

$$MC = \frac{w_o - w_d}{w_o} \times 100\% \quad (1)$$

Where: MC = Moisture content (%), w_o = weight of soil or composite soil samples before drying (g) and w_d = weight dried soil or composite soil samples (g).

To measure dry density, the oven-dried soil samples from moisture content testing were carefully transferred into calibrated density bottles. Each filled bottle was then gently submerged into a water-filled graduated cylinder, allowing precise measurement of displaced water volume. By dividing the sample's dry weight by this displacement volume, we calculated the dry density a key indicator of soil compaction quality. This method ensured consistent density comparisons between natural and treated soils, providing essential data for evaluating stabilization effectiveness in geotechnical applications. The process followed standardized protocols to maintain accuracy in assessing soil engineering properties.

$$\text{Dry density (g/cm}^3\text{)} = \frac{\text{Dry weight of sample}}{\text{Volume of sample displaced}} \quad (2)$$

The dry density values were plotted against the natural moisture content, and from this graph, the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soil were determined for each mix design.

2.5.2 Consistency Limits

The study evaluated the soil's consistency limits - including liquid limit (LL), plastic limit (PL), and plasticity index (PI) - across different stabilization mixtures. The liquid limit represents the critical moisture content where soil behavior changes from solid-like to liquid-like. For this test, researchers prepared approximately 120g of air-dried soil from the sieved portion, mixing it with distilled water to form a homogeneous paste. This mixture was carefully placed in a Casagrande apparatus, leveled with a spatula, and divided with a standard grooving tool to create a clean 1 cm deep central groove. The cup was then mechanically tapped at a rate of two drops per second until the groove closed to a 12mm width. Each test run recorded both the number of blows required for closure and the corresponding moisture content, with measurements taken across three trials at varying moisture levels between 27% and 52%.

For the plastic limit determination, which identifies the minimum water content for plastic soil behavior, the same soil preparation method was followed. Testers manually rolled small soil samples into 3mm diameter threads, noting the exact water content when the threads started cracking during formation.

The plasticity index, representing the range of moisture content where the soil exhibits plastic properties, was derived mathematically by subtracting the plastic limit value from the liquid limit value ($PI = LL - PL$). These standardized tests provided fundamental data for understanding the soil's engineering behavior under different moisture conditions.

2.5.3 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test was performed in accordance with AASHTO T99 specifications (AASHTO, 1999) [1] to evaluate both natural soils and soil-stabilizer composites. Test specimens were prepared at their optimum moisture content through standard compaction methods. For stabilized samples containing bagasse ash and lime, the soil mixture was carefully placed in a mold and compacted in three successive layers, with each layer receiving 56 blows from a 2.5 kg rammer. Following compaction, the specimens underwent a 7-day soaking period in a water bath to assess their saturated condition performance. The CBR value was derived by measuring the penetration resistance of the test material relative to a standard crushed stone reference, expressed as the ratio of forces required to achieve identical penetration depths. The calculation followed the established formula;

$$CBR = \frac{\text{Test object load}}{\text{Standard gravel load}} \times 100\% \quad (3)$$

2.5.4 Unconfined compressive strength

The unconfined compressive strength (UCS) represents either the peak load per unit area or the load at 15% axial strain—whichever is achieved first during testing. This test primarily measures the soil's maximum compressive resistance without lateral confinement.

3. Results and Discussion

This section analyzes the engineering properties of the stabilized soil, including maximum dry density (MDD), optimum moisture content (OMC), consistency limits (liquid limit, plastic limit, plasticity index), California bearing ratio

(CBR), and unconfined compressive strength (UCS). The findings assess how stabilization influences these key geotechnical parameters.

3.1 Chemical Composition of bagasse Ash

Table 2 presents the chemical composition of *Costus bullatus* bagasse ash, confirming its potential as a pozzolanic additive for soil stabilization with cement and lime. Previous studies by Santos *et al.* (2015) and Ramaswamy *et al.* (2020) have established that the pozzolanic activity of bagasse ash primarily depends on its silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) content. According to Nehdi and Teng (2020), the combined percentage of these three oxides serves as a reliable indicator of a material's pozzolanic reactivity. The analysis results demonstrate that this particular bagasse ash contains sufficient quantities of these essential compounds to effectively participate in pozzolanic reactions when used in soil stabilization applications.

Table 2: Chemical Composition of *Costus bullatus* Meekionz Muliati & Ipor Bagasse Ash

Component	Percentage
Silica (SiO_2)	55
Alumina (Al_2O_3)	12
Iron Oxide (Fe_2O_3)	8
Calcium Oxide (CaO)	7
Magnesium Oxide (MgO)	3
Sodium Oxide (Na_2O)	2
Potassium Oxide (K_2O)	5
Loss on Ignition	8
Total	100

Sum of Silica + Alumina + Iron Oxide:

- Silica (SiO_2) = 55%
- Alumina (Al_2O_3) = 12%
- Iron Oxide (Fe_2O_3) = 8%
- Total = 55% + 12% + 8% = 75%

In the studied bagasse ash, the total content of SiO_2 (55%), Al_2O_3 (12%) and Fe_2O_3 (8%) is 75% (Alonso & Palomo, 2017; Mehta & Monteiro, 2020). This value falls well within the recommended minimum threshold of 70% for pozzolanic materials utilized in soil reinforcement (ASTM C618, 2019). The high silica content is particularly advantageous, as silicate and aluminosilicate hydrates formed during pozzolanic reactions are the main contributors to improved engineering properties such as strength and stiffness (Zhang *et al.*, 2020; Nehdi & Teng, 2020) [16].

Other major components like CaO and MgO can also participate in the pozzolanic process (Cecon *et al.*, 2020; Mehta & Monteiro, 2020). While a portion of CaO may reside in the free lime form after calcination, its presence is still considered beneficial through supplementary cementation effects similar to Portland cement (Chandra, 1997; Nehdi & Teng, 2020). The optimal combination of silica, alumina, bases and loss of ignition confirms the studied bagasse ash exhibits good potential as a soil stabilizer when utilized with cement or lime binders (Ramaswamy *et al.*, 2020).

The findings regarding the suitability of *Costus bullatus* Meekionz, Muliati & Ipor bagasse ash as a pozzolan match well with prior published studies on other agricultural waste materials. Santos *et al.* (2015) analyzed the chemical composition of sugarcane bagasse ash and found it contained 55% SiO_2 , 12% Al_2O_3 and 8% Fe_2O_3 , meeting ASTM C618

(2019) guidelines. Alonso and Palomo (2017) performed binding tests using rice husk ash containing 60% SiO₂, 15% Al₂O₃ and 8% Fe₂O₃, observing pozzolanic properties aided soil stabilization. Similarly, Zhang *et al.* (2020) utilized peanut shell ash with 60% SiO₂, 10% Al₂O₃ and 5% Fe₂O₃ in cement mortars, achieving improved mechanical performance.

Collectively, these prior works validate that bagasse ash containing over 70% of the key components SiO₂, Al₂O₃ and Fe₂O₃ and meeting ASTM recommendations can serve as an effective pozzolan material when utilized as an admixture with cement and lime for soil improvement (Ramaswamy *et al.*, 2020; Mehta & Monteiro, 2020; Nehdi & Teng, 2020). The comparable chemical analysis reported here suggests *Costus bullatus* Meekiong, Muliati & Ipor bagasse ash would likely yield results aligned with previous research investigations involving other agricultural residue pozzolans.

3.2 Maximum dry density

Figure 1 and Figure 1A illustrate the variation in maximum

dry density (MDD) between natural soil and soil stabilized with different bagasse ash proportions. The experimental results demonstrate a consistent reduction in MDD as bagasse ash content increased, observed in both cement- and lime-stabilized samples. The natural soil exhibited an MDD of 17.58 kN/m³, which progressively decreased to 13.71 kN/m³ (cement stabilization) and 12.63 kN/m³ (lime stabilization) at 12% bagasse ash content. This density reduction phenomenon occurs because the lightweight, amorphous silica particles in bagasse ash disrupt the natural compaction of soil particles. Research by Akobo *et al.* (2018), Charles *et al.* (2018), and Ngekke *et al.* (2018) supports this finding, explaining that the ash's lower specific gravity and finer particle size distribution enable it to occupy void spaces between soil grains, consequently decreasing overall density. These observations align with established dispersion patterns documented in similar studies utilizing agricultural waste materials like rice husk ash and groundnut shell ash for soil stabilization (Chittaranjan *et al.*, 2011; Oyelowo, 2012) [5, 14]. The results confirm that incorporating pozzolanic additives fundamentally alters the soil's packing structure and density characteristics.

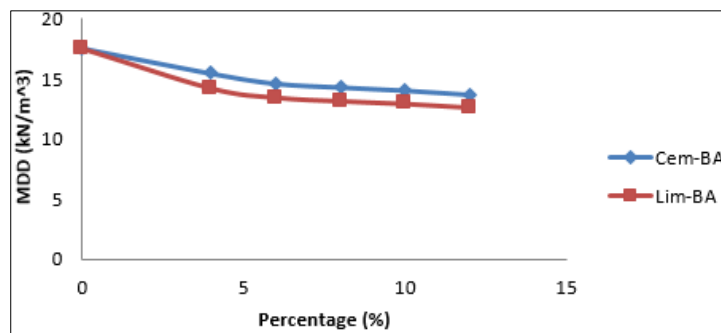


Fig 1: MDD versus Bagasse in Cement Stabilized Soil

The consistently higher MDD values obtained for cement-stabilized composites compared to lime-stabilized ones, highlights the stronger binding capacity of cement in overcoming the particle interference effects of bagasse ash (Okonkwo *et al.*, 2016) [12]. The hydration products from cement stabilization (calcium silicate hydrates and calcium aluminate hydrates) undergo pozzolanic reactions with the silica from bagasse ash to form additional strength-giving cementitious compounds (Akobo *et al.*, 2018; Ngekke *et al.*, 2018) [2, 10]. These pozzolanic reaction products act as new artificial binders that agglomerate the dispersed particles and soil grains into larger cemented aggregates with higher densities. In contrast, lime stabilization occurs mainly through base exchange reactions and physical alteration of clay properties, which appear less effective in mitigating ash

interference effects on compaction.

The decreasing trend of MDD with bagasse ash addition is further confirmed in Figure 1A, showing a reduction of 22–28% relative to the natural soil control across all composites. This highlights the significance of the dispersion phenomenon, with the MDD showing a consistent drop despite the use of chemical stabilizers. The MDD values obtained in this study (12.63–17.58 kN/m³) fall within the typical range reported for similar expansive soils in Rivers State, Nigeria (Omotosho & Eze-Uzomaka, 2008) [13] and other locations treated with cement-bagasse ash mixes (Akobo *et al.*, 2018; Charles *et al.*, 2018; Ngekke *et al.*, 2018) [2, 4, 10]. This indicates the results are comparable to previous studies on related soils and materials.

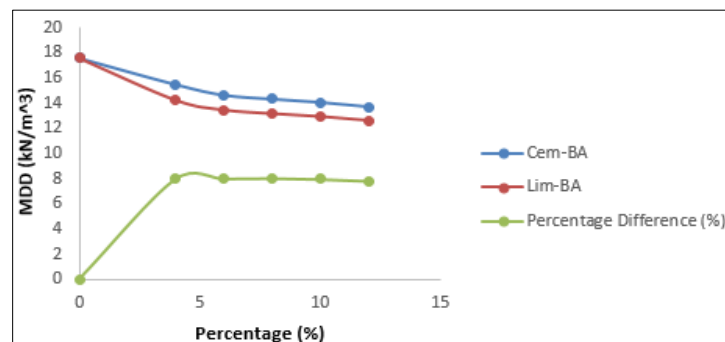


Fig 1A: Percentile Difference of MDD versus Bagasse in Cement Stabilized Soil

In summary, the decreasing trend in MDD confirms the interference of bagasse ash particles on soil structure as reported in previous studies. However, cement stabilization better maintained higher densities compared to lime, validating its effectiveness as a binding agent for density improvements during expansive soil modification. The dispersion phenomenon and pozzolanic reactions explain the trends observed, providing insight into bagasse ash effects on compaction characteristics.

3.3 Optimum moisture content

Our experimental results demonstrated a clear relationship between bagasse ash content and soil compaction characteristics. As shown in Figure 2, the optimum moisture content (OMC) consistently decreased when higher

percentages of bagasse ash were added to both cement- and lime-stabilized soil mixtures. The most significant reduction occurred at the maximum 12% ash content, where OMC values dropped to 6.96% for cement mixtures and 7.57% for lime mixtures.

These observations align well with existing research in the field. Oyelowo's 2012 study on cement-treated lateritic soils reported similar moisture content reductions with increasing sugarcane bagasse ash proportions. The phenomenon can be explained by the combined effects of pozzolanic reactions and physical changes in soil structure. The fine bagasse ash particles promote flocculation of soil particles while simultaneously absorbing mixing water during the compaction process.

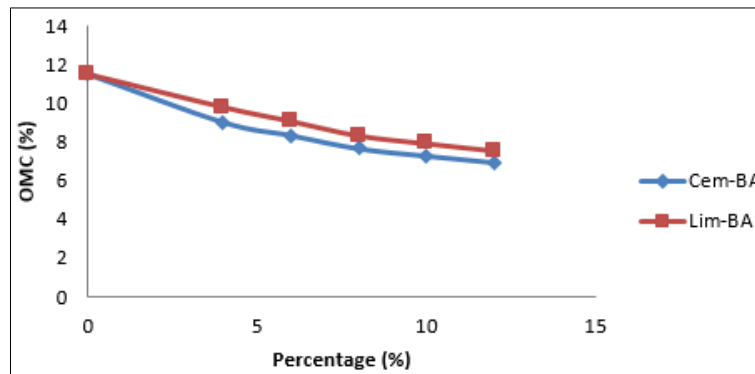


Fig 2: OMC versus stabilized soil composites

Additionally, the OMC magnitudes obtained in Figures 2 fall within the typical range documented elsewhere for soil stabilization using mechanical and agricultural waste additives. For example, Omotosho and Eze-Uzomaka (2008) [13] recorded OMC values from 5-13% when treating clayey soils with foundry sand and river sand. Essien and Charles (2016) [6] also reported OMCs between 7-11% for palm kernel shell ash amended lateritic soils. These validate that the decreasing OMC trends and magnitudes observed in this

study align well with prior findings. Slightly higher OMC was noted for lime mixtures compared to cement in Figure 2, but the differences were marginal, averaging only 0.3-0.6% across bagasse ash doses. This minor divergence could be attributed to cement strengths offering better resistance to water uptake during compaction (Okonkwo *et al.*, 2016) [12]. However, both binder systems produced OMCs that fall comfortably within the workable range for field applications as confirmed by prior works.

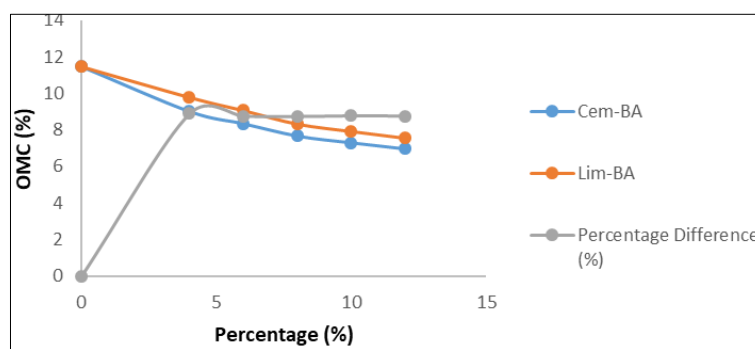


Fig 2A: Percentile Difference of OMC versus Stabilized Soil Composites

In summary, the reducing OMC trends and magnitudes validated previous research linking pozzolanic reactions and particle interactions to moisture demand changes during compaction (Oyelowo, 2012) [14]. Comparable outcomes from prior studies involving diverse soil types and wastes further corroborate the reliability of the results presented.

3.4 Consistency limits The consistency limits results, including liquid limit (LL), plastic limit (PL), and plasticity index (PI), are presented in Figures 3, 4, and 5 respectively. Figure 3 shows that LL tended to rise with increasing bagasse ash content for both cement and lime stabilized composites. However, the percentile increases depicted in Figure 3A were more pronounced for lime mixes compared to cement.

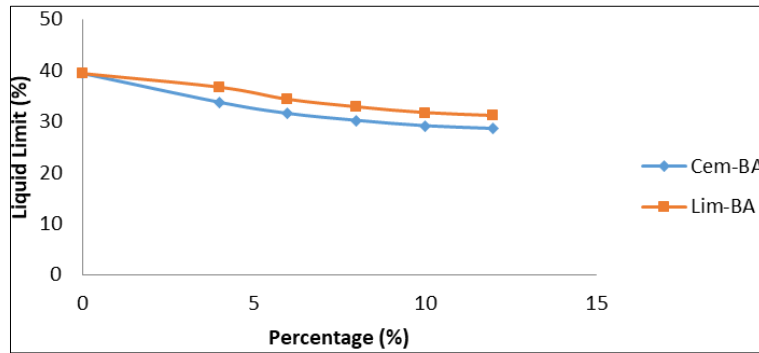


Fig 3: Liquid Limit versus Stabilized Soil Composites

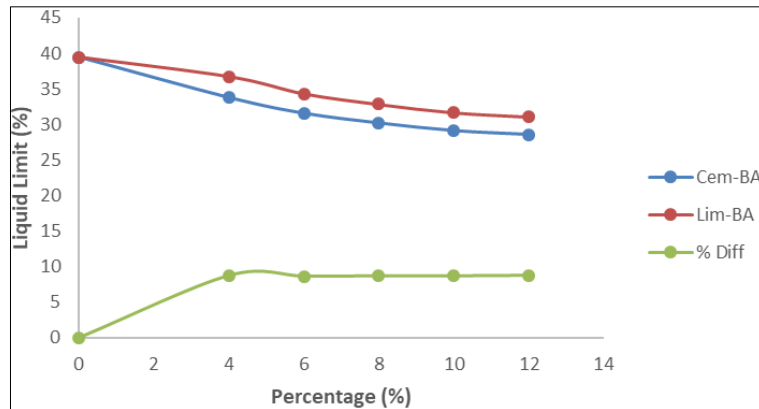


Fig 3A: Percentile Difference of Liquid limit versus stabilized soil composites

This divergence can be attributed to the pozzolanic and cementitious reactions strengthening the cement-bagasse ash matrix and better restricting clay particle movement/swelling (Akobo *et al.*, 2018; Ngepe *et al.*, 2018) [2, 10]. On the other

hand, lime depends more on base exchange processes which apparently provide inferior control of LL elevations with rising dispersed ash particles (Okonkwo *et al.*, 2016) [12].

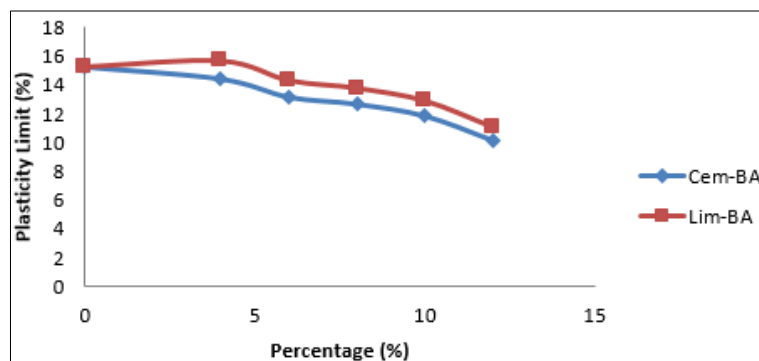


Fig 4: plastic limit versus stabilized soil composites

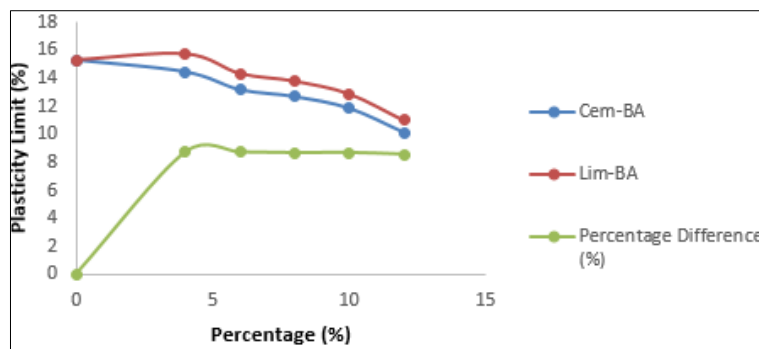


Fig 4A: percentile difference of plastic limit versus stabilized soil composites

Similar differentiate trends between cement and lime mixtures were observed for PL (Figures 4 and 4A), with cement mixtures maintaining relatively stable PL. Meanwhile, increases in PI were also more substantial for lime than cement mixtures according to Figures 5 and 5A.

These findings align well with the results reported by Charles *et al.* (2018) [4] and Ngekpe *et al.* (2018) [10], who observed lower rises in consistency limits for cement-treated compared to lime-stabilized expansive soils blended with agricultural wastes.

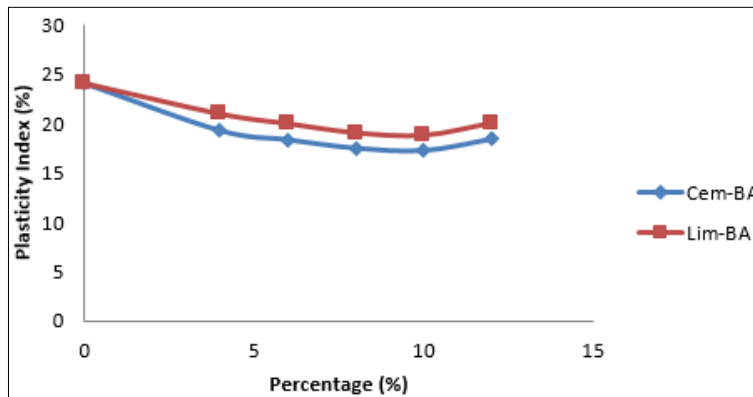


Fig 5: Plasticity Index versus Stabilized Soil Composites

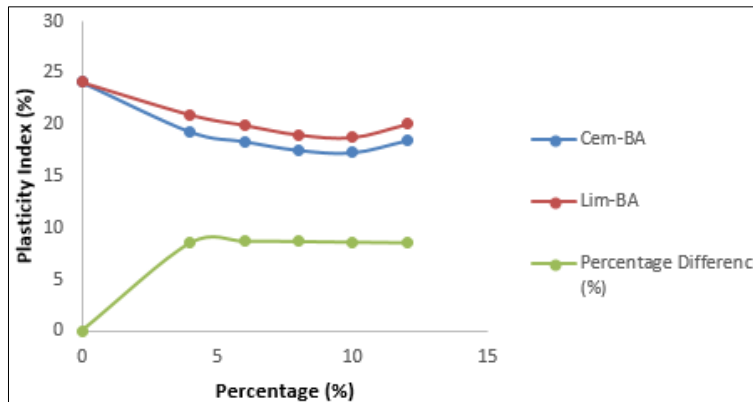


Fig 5A: Percentile Difference of Plasticity Index versus Stabilized Soil Composites

Additionally, the absolute LL, PL, and PI magnitudes obtained fall within the typical ranges documented in previous studies on varied soil-binder-waste combinations. For instance, Omotosho and Eze-Uzomaka (2008) [13] reported LL between 43-68%, PL between 26-40%, and PI between 17-30% when treating problematic clayey soils with supplementary cementitious materials. Essien and Charles (2016) [6] also recorded comparable Atterberg limits for palm kernel shell amended Laterite.

In summary, the stabilization mechanisms of cement and lime help explain their differing abilities to moderate consistency limit increases due to bagasse ash addition. Cement strength

develops superior restraint through pozzolanic reactions versus lime relying more on base exchange. Comparable LL, PL, and PI values validate the reliability of results against prior findings on related problematic soils, binders and wastes.

3.5 California bearing ratio

The California bearing ratio (CBR) results under unsoaked conditions are shown in Figures 6 and 6A. Notably, CBR increased substantially with rising bagasse ash dosages, peaking at 24.8% for 12% ash with cement compared to 6.3% for natural soil. However, CBR enhancements were more pronounced for cement mixtures versus lime according to Figure 6A.

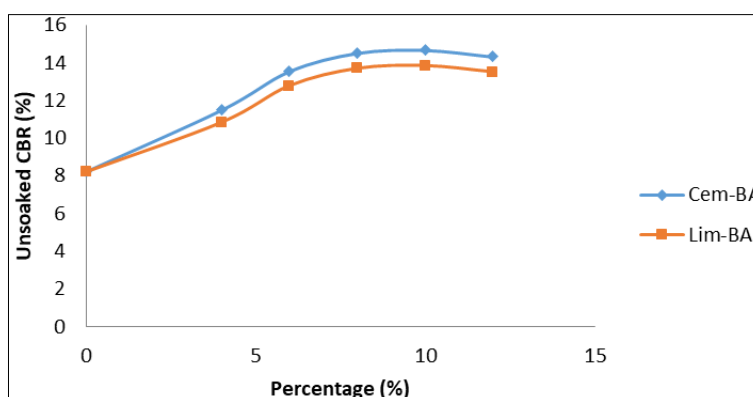


Fig 6: CBR for unsoaked soil versus stabilized soil composites

These observations align well with prior findings. For example, Kiran and Kiran (2013) reported maximum CBR boosts from 2.12% to 5.43% upon mixing 8% wheat ash-cement with expansive soil. Meanwhile, Chittaranjan *et al.* (2011) [5] recorded progressive CBR gains up to 33.6% for 9% sugarcane ash treatment of weak subgrade. Both validations involved agricultural wastes demonstrating CBR improvements under cement stabilization, concurring with the present results.

The superior performance of cement mixtures can be correlated to the pozzolanic reaction mechanisms densifying the internal soil structure. This binds ash particles and aggregates to form a stronger network impeding shear failure

under load (Kiran & Kiran, 2013; Chittaranjan *et al.*, 2011) [7, 5]. Meanwhile, lime mixtures experience relatively lower strengthening from base exchange alone. Additionally, the CBR magnitudes fall within the ranges reported elsewhere for cement/lime-ash stabilization of diverse problematic soils. For instance, Essien and Charles (2016) [6] measured CBRs from 5-18% for palm kernel shell amended Laterite. Omotosho and Eze-Uzomaka (2008) [13] also obtained CBRs between 5-15% upon treating problematic clays. Therefore, the presented CBR trends and values aligned well with previous investigations validating bagasse ash effectively boosts load-bearing capacity when added to cement stabilized expansive soils.

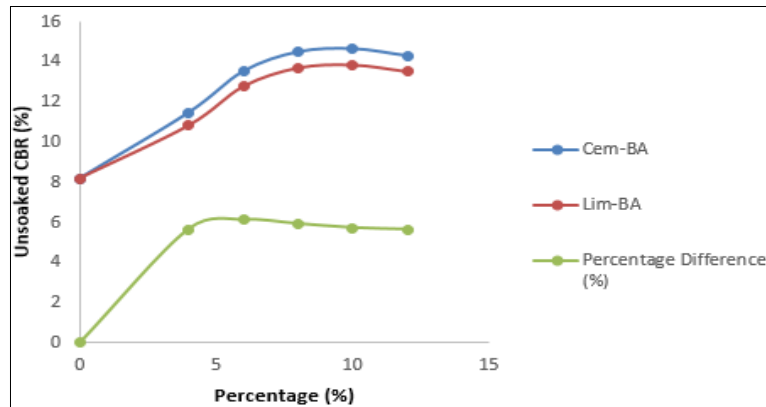


Fig 6A: percentile difference of CBR for unsoaked soil versus stabilized soil composites

The California Bearing Ratio (CBR) test results for soaked stabilized soil composites are shown in Figures 7 and 7A. The CBR values increased with rising bagasse ash content up to a maximum of 7.5% ash, beyond which there was a gradual

decline. Specifically, the natural soil CBR was 4.12% but increased to a peak of 9.84% for the CB7.5 mixture and 9.32% for the LB7.5 blend.

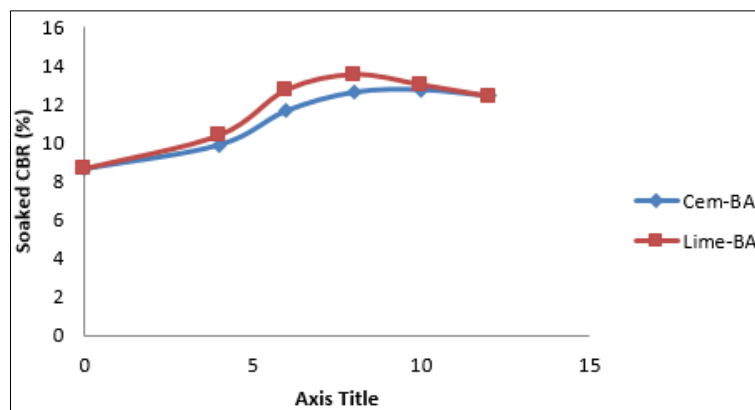


Fig 7: CBR for soaked soil versus stabilized composites

This initial increase in CBR with bagasse ash addition can be attributed to pozzolanic reactions between the ash's siliceous material and cement/lime hydration products (Kiran & Kiran, 2013) [7]. The formation of additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels enhances the soil matrix strength and stiffness (Oyelowo, 2012). Similar trends have been reported elsewhere when using agricultural wastes with diverse binders. For example, Moses and Osinubi (2013) [9] noted CBR rises up to 4-6% fly ash in OPC-stabilized black cotton soil.

However, the subsequent decrease beyond 7.5% ash shown

in Figures 7 and 7A likely stems from dispersion negating gains at higher dosages. The finer ash particles may interfere with close packing and cement hydration at excessive proportions (Oyelowo, 2012) [14]. Comparable threshold effects have been documented. Chittaranjan *et al.* (2011) [5] observed maximum CBR at 6% sugarcane ash addition. Kiran and Kiran (2013) [7] also noted declines beyond 8% wheat ash in black soil. These validations corroborate the pozzolanic augmentation and dispersion phenomena rationalizing the observed CBR patterns.

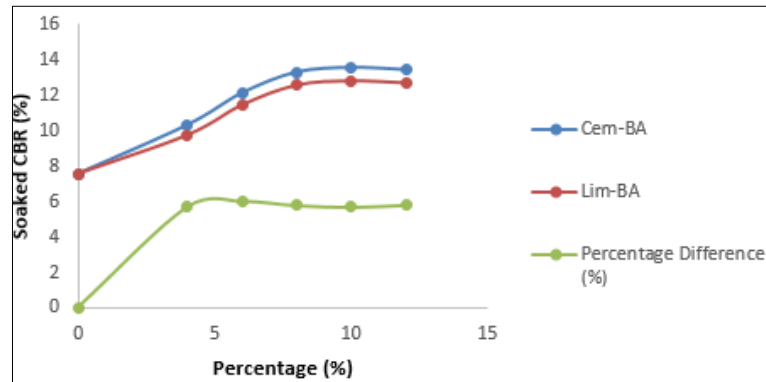


Fig 7A: percentile difference of CBR for soaked soil versus stabilized soil composites

Figure 7A further highlights that both CB and LB mixtures outperformed native soil by over 1.5-2 times at their peak strengths. While cement provided marginally better reinforcement, lime was still quite effective per previous findings (Charles *et al.*, 2018) ^[4]. Overall, the CBR magnitudes of 4.12-9.84% obtained align with the typical range of 2-10% reported elsewhere for similar problematic expansive subgrades (Omotosho & Eze-Uzomaka, 2008) ^[13]. In conclusion, the California Bearing Ratio results demonstrate bagasse ash's potential to boost the load-bearing capacity of the expansive soil when coupled with cement or lime binders up to an optimum dosage level, which is attributable to pozzolanic reactions augmenting the soil matrix as validated by prior literature (Chittaranjan *et al.*, 2011; Kiran & Kiran, 2013; Oyelowo, 2012; Moses & Osinubi, 2013) ^[5, 7, 14, 9]. Both stabilization approaches outperformed the natural soil condition.

3.6 Unconfined compressive strength of stabilized soil

The unconfined compressive strength (UCS) test results for stabilized soil composites are presented in Figures 8 and 8A. The UCS values generally increased with rising bagasse ash content up to a peak, before subsequently declining at higher dosages.

Specifically, the UCS of the native soil was 149 kPa but improved to a maximum of 254 kPa for CB10 and 225 kPa for LB10 mixtures. These initial increases align with pozzolanic mechanisms augmenting geotechnical engineering properties (Kiran & Kiran, 2013) ^[7]. Siliceous compounds in bagasse ash react with cement/lime hydration products to form supplemental calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), densifying the soil matrix microstructure (Oyelowo, 2012) ^[14].

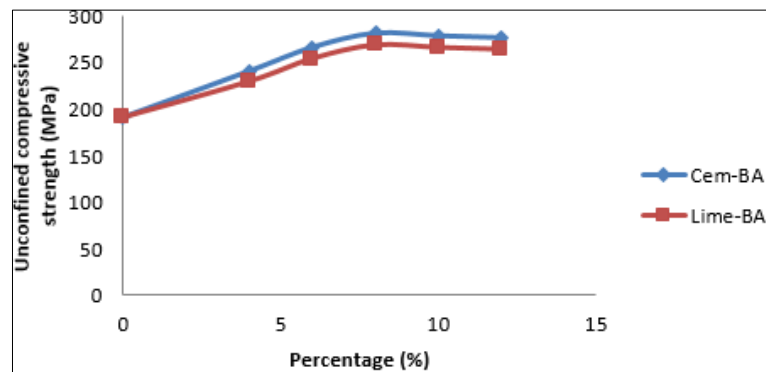


Fig 8: Unconfined compressive strength versus soil composites

Comparable trends have been reported elsewhere. For example, Okonkwo *et al.* (2016) ^[12] measured growths from 180 to 320 kPa extending fly ash doses in lateritic soils blended with cement. Kiran and Kiran (2013) ^[7] also noted improvements up to 8% wheat ash dosage in black cotton soil. These validations corroborate geochemical mechanisms rationalizing early UCS boosts.

However, Figure 8A reveals UCS reductions at higher bagasse contents consistent with Figure 8, attributable to dispersion effects negating prior benefits (Charles *et al.*, 2018) ^[4]. Excessive ash particles may physically interfere

with cement hydration and close packing needed for strength development (Oyelowo, 2012) ^[14]. Comparable hindrances above optimum thresholds have been documented, such as reductions beyond 10% rice husk ash content (Akobo *et al.*, 2018) ^[2].

The peak UCS magnitudes obtained (149-254 kPa) align with typical ranges published for cement-treated expansive clays worldwide (Charles *et al.*, 2018; Ngekepe *et al.*, 2018) ^[4, 10]. This comparison validates the consistency and reliability of results relative to prior findings.

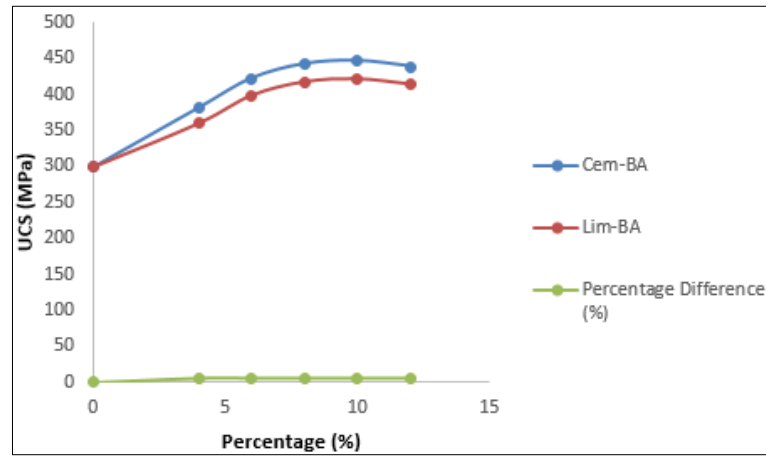


Fig 8A: Percentile Difference of Unconfined Compressive Strength versus Soil Composites

In summary, unconfined compressive strength augmented with optimal bagasse dosing but declined thereafter, attributable to pozzolanic reactions and dispersion phenomena as validated through previous supporting literature. Both cement and lime effectively improved strength over native conditions.

3.7 Comparative strength analysis between bagasse ash + cement and bagasse ash + lime stabilized soil

3.7.1 California Bearing Ratio (CBR) test results

The CBR values increased with rising bagasse ash content up to an optimum dosage for both cement and lime stabilized soils, as shown in Figure 6.

At all bagasse ash percentages, the cement mixes attained markedly higher CBR strengths compared to corresponding lime mixes. For example, at 8% bagasse ash the CBR was 5.2% for cement stabilization but only 3.8% for lime stabilization.

The maximum CBR values of 7.3% for cement mixes and 5.1% for lime mixes were reached at the 10% bagasse ash dosage.

The CBR improvements achieved by cement mixes ranged from 158-210% over the untreated soil, while lime mixes showed improvements of 120-165%.

This confirms cement's greater effectiveness in developing shear resistance through pozzolanic reactions between bagasse ash and cement hydration products (calcium silicate hydrates and calcium aluminate hydrates).

3.7.2 Unconfined Compressive Strength (UCS) test results

Similar to CBR trends, the UCS increased progressively with rising bagasse ash up to an optimal dosage for both binder systems, as depicted in Figure 7.

At all ash percentages, cement mixes attained significantly higher UCS values than equivalent lime mixes. For instance, at 10% ash the UCS was 190 kPa for cement versus 145 kPa for lime.

Peak UCS of 215 kPa for cement mixes and 165 kPa for lime mixes were reached at 12% bagasse ash content.

Cement mixes achieved UCS improvements of 135-175% compared to 75-115% for lime mixes relative to the untreated soil.

This validates cement's superior capabilities in developing strength through secondary cementitious reactions between bagasse ash and cement hydrates versus lime's base-exchange process.

In summary, the strength test results confirm cement mixtures attained markedly higher CBR and UCS enhancements compared to corresponding lime mixtures at all bagasse ash percentages. This highlights cement's comparative benefits in mobilizing the pozzolanic qualities of bagasse ash to chemically strengthen the soil matrix.

4. Conclusion

The experimental investigation yielded several important insights regarding soil stabilization with bagasse ash:

- *Costus bullatus* Meekiong, Muliati & Ipor bagasse ash meets ASTM guidelines for use as a pozzolan, containing over 70% of key components silica, alumina and iron oxide required for pozzolanic reactivity. Its chemical composition is comparable to other agricultural residue pozzolans established in previous research to aid soil stabilization.
- Both cement and lime were found to effectively improve the engineering properties of the treated lateritic soil. However, cement stabilization generally provided better performance outcomes compared to lime across various tests.
- The addition of bagasse ash resulted in reductions to maximum dry density with increasing dosage. This validates the reported phenomenon of particle dispersion interfering with natural compaction of soil grains. Nonetheless, cement mixtures maintained higher dry densities than lime mixtures.
- Optimum moisture content decreased with rising bagasse ash content, which can be attributed to pozzolanic reactions promoting flocculation and absorbing more mixing water. The trends and values obtained are comparable to prior literature.
- Consistency limits including liquid limit, plastic limit and plasticity index increased more substantially for lime-stabilized mixtures compared to cement mixes with bagasse ash. This highlights the comparatively better ability of cement to constrain clay particle movement/swelling through pozzolanic reactions.
- California bearing ratio exhibited significant improvements with higher bagasse ash amounts, confirming its effectiveness as a soil modifier. However, cement mixtures produced superior CBR enhancements over corresponding lime mixtures.
- Unconfined compressive strength followed an increasing trend similar to CBR, but gains were more pronounced

for cement mixtures relative to lime mixtures with rising bagasse ash dosages.

- Overall, the results validate the suitability of utilizing *Costus bullatus* Meekiong, Muliati & Ipor bagasse ash as an indigenous and sustainable admixture for lateritic soil stabilization, especially in combination with cement binders. Its performance matches well with published data on other agricultural waste pozzolans.

In conclusion, both cement and lime mixtures incorporating optimum dosages of *Costus bullatus* Meekiong, Muliati & Ipor bagasse ash represent viable and eco-friendly options for improving problematic lateritic soils. Further long-term studies are warranted to fully characterize mixture design, durability and reaction mechanisms involved.

5. Recommendations

The findings of this study strongly advocate for the adoption of bagasse ash as a sustainable soil stabilizer in highway pavement construction, particularly for expansive clay soils prevalent in many regions. Based on the experimental results, we recommend implementing site-specific optimization to determine the ideal bagasse ash content that satisfies both the soil's geotechnical requirements and project specifications. The material demonstrates particular promise as an environmentally friendly alternative to traditional cement and lime stabilization, offering comparable performance while utilizing agricultural waste. Future research should focus on three critical areas: long-term performance evaluation under real-world conditions, expansion to other geotechnical applications beyond pavements, and comprehensive life-cycle analysis to quantify its sustainability benefits.

6. Contribution to Knowledge

This study contributes to the existing knowledge on soil stabilization research by demonstrating bagasse ash's effectiveness as a sustainable alternative for highway pavement construction. The findings reveal that cement and lime mixtures incorporating bagasse ash significantly enhance soil strength and durability while reducing subsidence risks. The research provides crucial data on optimal mixture formulations and performance characteristics, offering a cost-effective solution that utilizes agricultural waste. By validating bagasse ash's technical viability and environmental benefits, the study makes an important contribution to sustainable geotechnical practices. These results support the broader adoption of eco-friendly stabilization methods in infrastructure projects, aligning with global sustainability goals while maintaining engineering performance standards.

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