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Original Research Article

# Performance Evaluation of Bagasse Ash and Cement Composite in Soil Stabilization of Highway Pavement Material

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**Abstract:** Expansive soils cause significant damage to infrastructure due to their swelling and shrinkage behavior with changing moisture content. This study evaluated the potential of Costus chartaceus mass ash (CCMA), an agricultural waste, in stabilizing expansive lateritic and clay soils from Nigeria for use as pavement subgrade material. Specimens of the problematic soils were mixed with varying proportions (2.5-10%) of CCMA and a fixed 5% cement content. The geotechnical properties of maximum dry density, optimum moisture content, consistency limits, California bearing ratio (CBR), unconfined compressive strength (UCS), and free swell index were determined via standardized tests. Results showed the maximum dry density generally decreased with higher CCMA contents due to ash particles occupying soil voids. However, inclusion of up to 2.5% CCMA increased density through beneficial pozzolanic reactions. Optimum moisture content rose with greater ash amounts owing to its hydrophilic nature. Consistency limits like liquid limit and plasticity index decreased significantly, while plastic limit increased, demonstrating modifications to clay mineralogy restricting water absorption. Both unsoaked and soaked CBR ratios augmented noticeably with rising CCMA up to 7.5%, reflecting strengthened inter-particle bonds. UCS strengths also steadily climbed to a peak at 7.5% CCMA, signifying physicochemical improvements. A judicious combination of 7.5% CCMA and 5% cement achieved optimal performance for controlling volume change and imparting bearing capacities to the problematic soils. This reflects balancing of pozzolanic gain versus dilution effects. The study validates use of CCMA-cement composite for rectifying consistency issues and upgrading strength characteristics of expansive soils. CCMA shows potential as an economical, eco-friendly stabilizer leveraging its high silica and pozzolanic properties compared to other agricultural wastes. Further work could explore CCMA blending with additional activators to maximize stabilization efficacy.

**Keywords:** Expansive Soils, Stabilization, Costus Chartaceus Mass Ash, Cement, Geotechnical Properties.

## 1. INTRODUCTION

Expansive soils are known to exhibit problematic swelling and shrinking behaviour under changing moisture conditions that can significantly damage civil infrastructure like roads and buildings (Nelson and Miller, 1992). These soils possess the ability to absorb water leading to expansion of their volume, while releasing water causes shrinkage. The swelling and shrinking properties depend on the soil's loading history, composition, and environmental factors, generating strains much larger than elastic deformations that classical theories cannot accurately predict (Al-Rawas *et al.*, 2005).

The swelling potential and shrinkage limit are key parameters used to classify the expansiveness of soils (Estabragh *et al.*, 2013). Clays like montmorillonite with high specific surface area and interlayer water content exhibit high expansiveness (Chen, 1975). According to Nelson and Miller (1992), the shrink/swell movements in expansive soils are influenced by clay mineralogy, initial density, degree of saturation, soil structure, stress state, climate, and vegetation. The monthly and seasonal moisture fluctuations in the ground cause cyclic shrink/swell behavior.

Expansive soils are widely prevalent across many regions including North and South America, Africa, Australia, Asia and cause billions in infrastructure damage annually (Jones Jr and Holtz, 1973; Dif and Bluemel, 1991). In the United States, over 20% of the land area contains problematic swelling soils, with even higher proportions in western states like Colorado and Texas where up to 80% of the areas have expansive subsoils (Jones Jr and Holtz, 1973). Regions in Canada, South Africa, Australia and India also report severe issues with swelling clays (Viswanadham and Phanikumar, 2009). In Nigeria, black cotton soils found in the central and eastern regions derived from sedimentary rocks pose major geotechnical challenges for civil engineering construction (Eze-Uzomaka, 2000; Nwaiwu and Olufemi, 2006; Agbede and Manasseh, 2011).

To mitigate the detrimental effects of expansive soils on foundations, pavements, and other civil structures, various ground improvement techniques are employed (Nelson and Miller, 1992; Petry and Little, 2002). Physical compaction densifies the soil matrix, reducing the swell potential. Chemical stabilization alters the clay mineralogy using additives like lime, cement, fly ash etc. that reduces plasticity and shrink/swell capacity (Eze-Uzomaka, 2000; Brooks, 2009). Moisture control through drainage, barriers and vegetative covers helps maintain a consistent moisture content in the soil. Reinforcement using geosynthetics provides tensile inclusion to counter swell pressures. Deep foundations extending below the active zone transfer foundation loads to underlying non-expansive strata (Nelson and Miller, 1992; Al-Rawas *et al*., 2005).

Apart from the conventional techniques, use of agricultural and industrial waste materials as economical and eco-friendly stabilizers for improving expansive soils has gained significant research attention in recent years (Osinubi *et al*., 2015; Ahmaruzzaman, 2010). The high silica content of many waste ashes induces pozzolanic reactions with lime that alter the clay mineral structure (Chusilp *et al*., 2009). Rice husk ash, sawdust ash, bagasse ash, bamboo leaf ash and other similar waste materials have shown promising results for stabilization of expansive soils (Brooks, 2009; Osinubi *et al*., 2009; Charles *et al*., 2018).

This study evaluates the potential of an agricultural waste, Costus chartaceus mass ash (CCMA), in combination with cement/lime for stabilizing an expansive residual lateritic soil typical of south-eastern Nigeria. The effects on compaction characteristics, consistency limits, California Bearing Ratio (CBR), unconfined compressive strength (UCS) and swelling potential are analyzed to assess suitability for road subgrade application. Costaceae/AFAM is a tropical plant of the ginger family native to West Africa that produces high biomass yields. The morphology, mineralogy, elemental composition and pozzolanic reactivity of CCMA indicate advantages over other waste ashes that have been studied for soil stabilization (Chusilp *et al*., 2009).

## 2. MATERIALS AND METHODS

### 2.1 Materials

The key materials utilized in this experimental study are described in the following subsections. Appropriate standards were followed for sourcing, preparation and testing of the materials based on recommended procedures in previous studies on stabilization of expansive soils (Brooks, 2009; Sabat, 2012; Ngekpe *et al*., 2018).

#### 2.1.1 Soil

The soil samples used for investigation were collected from a road construction site in Port Harcourt, Rivers State of Nigeria, at a depth of 1 m below the ground level. Disturbed soil samples were extracted for laboratory testing while undisturbed samples were collected by driving steel sampling tubes into the ground. As per ASTM D420, the samples were preserved in airtight containers to retain the natural moisture content and avoid changes in soil properties prior to testing (ASTM International, 2010).

The collected soils were characterized by visual-manual procedures and laboratory tests as per ASTM D2488 (ASTM International, 2017). Based on the Unified Soil Classification System (USCS), the soil was classified as an inorganic clay of high plasticity (CH). The clay fraction consisted predominantly of kaolinite and montmorillonite minerals based on X-ray diffraction analysis. Montmorillonite has expansive properties due to its high specific surface area and affinity for absorbing water (Estabragh *et al*., 2013).

#### 2.1.2 Costus Chartaceus Mass

Costus chartaceus mass (CCMA) was collected as raw biomass from the tropical rainforests of south-eastern Nigeria. CCMA is a species of tropical ginger belonging to the Costaceae family. The stalks were dried, crushed into smaller pieces using a hammer mill and then burnt slowly in a muffle furnace at 650°C for 6 hours. Brooks (2009) recommended calcination temperatures of 500-800°C to achieve good pozzolanic activation in agricultural ashes.

The burnt ash was ground to a fine powder using a Los Angeles abrasion grinding machine and sieved through a 75 µm sieve as per ASTM C618 (ASTM International, 2019). The specific gravity of the fine CCMA powder was 2.12

based on pycnometer tests as per ASTM D854 (ASTM International, 2014). Prior studies have analyzed the physical characteristics, mineralogical composition, particle size distribution and morphological properties of CCMA ash for assessing its suitability as a pozzolanic admixture (Chusilp *et al*., 2009; Agbede and Joel, 2011).

#### 2.1.3 Cement

Limestone cement Grade 42.5 conforming to ASTM C150 (ASTM International, 2018) was procured from a local manufacturer in Port Harcourt, Nigeria for use as the main stabilizing agent. The cement had a specific gravity of 3.15 and a Blaine fineness value of 3840 cm2/g based on laboratory testing as per ASTM C204 (ASTM International, 2016). Commercial OPC was opted as previous studies have demonstrated its effectiveness for stabilization of expansive soils using between 2-10% cement content (Sabat, 2012; Charles *et al*., 2018).

### 2.2 Methods

A range of laboratory tests were conducted on untreated and stabilized soil specimens to evaluate the effects of CCMA-cement additive on the geotechnical properties. The test methods adopted are briefly described below:

#### 2.2.1 Compaction Tests

Standard Proctor compaction tests were performed as per ASTM D698 (ASTM International, 2012) to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the untreated and stabilized soils. The samples were compacted in a 100 mm mold using a 2.5 kg rammer dropping from 300 mm height.

#### 2.2.2 Atterberg Limits

The liquid limit (LL) and plastic limit (PL) of the raw and stabilized soils were determined using the Casagrande percussion cup apparatus and thread rolling method respectively as per ASTM D4318 (ASTM International, 2010). The plasticity index (PI) was calculated as the difference between LL and PL.

#### 2.2.3 California Bearing Ratio

California bearing ratio (CBR) tests were conducted on unsoaked and 4-day-soaked samples based on ASTM D1883 (ASTM International, 2016). A 152 mm diameter plunger was penetrated at 1.25 mm/min on specimens compacted to optimum moisture content at energies per ASTM D698.

#### 2.2.4 Unconfined Compressive Strength

The unconfined compressive strength (UCS) was measured on 38 mm diameter and 76 mm high specimens as per ASTM D2166 (ASTM International, 2016). The samples compacted to MDD and OMC were extruded from compaction molds and cured for 7 days prior to testing at an axial strain rate of 1% per minute.

#### 2.2.5 Free Swell Index

The free swell index was determined as per ASTM D4546 (ASTM International, 2014). 10 g air-dried soil passing 425 µm sieve was poured into a 100 ml graduated cylinder and the volume noted. Distilled water was added up to 100 ml mark and the soil allowed to settle overnight. The swelling volume was calculated as the ratio of final volume to initial volume.

The test methods were selected based on their standard usage for characterizing Strength-deformation properties like MDD, OMC, UCS, CBR; volume change potential through LL, PI, free swell index; and clay mineralogy based on compaction-permeability-strength relationships of fine-grained soils (Nelson and Miller, 1992; Das and Sobhan, 2013; Ngekpe *et al*., 2018; Charles *et al*., 2018). Duplicate specimens were tested in all cases to ensure reliability of the results.

## 3. RESULTS AND DISCUSSION

The maximum dry density, optimum moisture content, consistency limits, California bearing ratio and unconfined compressive strength of stabilized soils have been analyzed.

### 3.1 Maximum Dry Density

The maximum dry density (MDD) results for the stabilized lateritic and clay soils with 5% cement and 2.5-10% Costus chartaceus mass ash are shown in Table 1. The MDD values generally decreased with increasing bagasse ash content for both soil types. As shown in Figure 1, the MDD of the lateritic soil ranged from 2.07 g/cm3 to 1.68 g/cm3, while the MDD of the clay soil ranged from 1.81 g/cm3 to 1.56 g/cm3 with varying bagasse ash proportions.

The initial increase in MDD up to 2.5% bagasse ash could be attributed to pozzolanic reactions between the ash and cement that improved particle packing and reduced void ratios in the soil matrix (Chusilp *et al*., 2009; Ngekpe *et al*., 2018). Similar increases in MDD with low doses of bagasse ash have been reported in prior studies stabilizing clayey soils

(Akobo *et al*., 2018; Okonkwo *et al*., 2016). However, the MDD started decreasing with further rise in bagasse ash content above 2.5% due to the ash particles occupying voids between soil grains and displacing the soil (Charles *et al*., 2018).

**Table 1: Effect of bagasse ash and cement composite on soil MDD**

| Bagasse Ash (%) | MDD ($g/cm^3$) | |
|---|---|---|
| | Laterite soil | Clay soil |
| 0 | 1.96 | 1.73 |
| 2.5 | 2.07 | 1.81 |
| 5 | 1.85 | 1.65 |
| 7.5 | 1.81 | 1.60 |
| 10 | 1.68 | 1.56 |

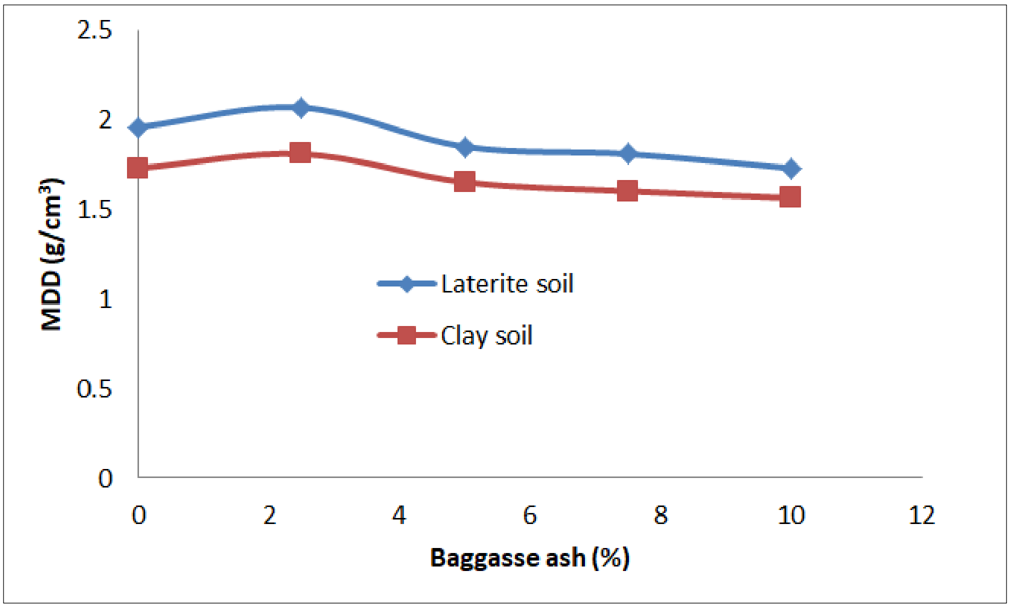


**Figure 1: MDD of soil stabilized with bagasse ash and cement composite**

The densities achieved in the present study are comparable to the ranges documented elsewhere for cement-stabilized lateritic soils. For example, MDD values between 1.7-2.1 g/cm3 were recorded by Sabat (2012) using 5-10% cement. Amu (2011) also measured maximum dry densities of 1.8-2.0 g/cm3 for lateritic samples stabilized with 5-10% sugarcane ash and 2-5% cement. It is noteworthy that the lateritic soil exhibited consistently higher MDD than the clayey soil, as its coarser texture enabled better particle rearrangement during compaction (Akobo *et al*., 2018).

In summary, the results demonstrate that substitution of bagasse ash up to a threshold of 2.5% in combination with cement is effective for improving the compaction characteristics by enhancing maximum dry density of the problematic expansive soils. However, ash contents exceeding this limit were deleterious and compromised the density benefits of stabilization.

### 3.2 Optimum Moisture Content

The OMC test results for the stabilized lateritic and clay soils containing 5% cement and varying proportions of bagasse ash from 2.5-10% are presented in Table 2. As shown in the figure, the OMC values ranged from 9.36-11.12% for the lateritic soil and 13.26-15.18% for the clay soil. In general, an increasing trend in OMC was observed with higher bagasse ash contents for both soil types. However, an initial decrease in OMC was noted at the lower ash inclusion of 2.5% before commencing an upward change.

**Table 2: Effect of bagasse ash and cement composite on OMC of the soils**

| Bagasse ash (%) | OMC (%) | |
|---|---|---|
| | Laterite soil | Clay soil |
| 0 | 11.59 | 15.44 |
| 2.5 | 9.36 | 13.26 |
| 5 | 10.75 | 14.83 |
| 7.5 | 11.12 | 15.18 |
| 10 | 10.03 | 13.64 |

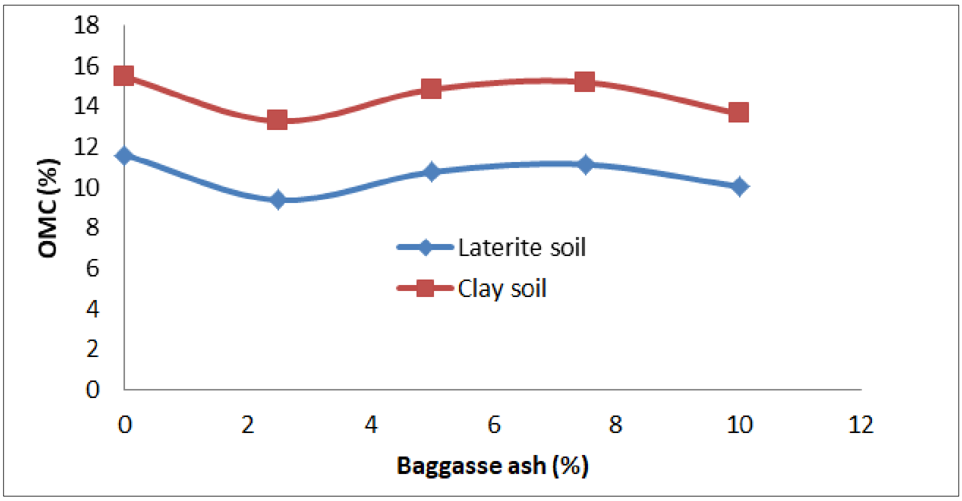


**Figure 2: OMC of soil stabilized with bagasse ash and cement composite**

The ascending OMC pattern agrees with findings of prior studies examining cement-ash blends for soil stabilization. Charles *et al*., (2018) and Ngekpe *et al*., (2018) also reported augmenting OMC with rising bagasse ash ratios in cement-treated lateritic materials. This could be attributed to the hydrophilic nature of ash particles attracting more water during compaction (Okonkwo *et al*., 2016). The ash's porous and amorphous structure enables greater imbibition and retention of mixing water within the soil voids (Sabat, 2012).

Interestingly, the current study observed a transient dip in OMC at the 2.5% ash-cement mix proportion. A similar initial reduction followed by recovery has been documented by Akobo *et al*., (2018) for cement-bagasse ash stabilized tropical soils. They attributed this to early pozzolanic reactions between cement and low ash dosages densifying the soil fabric and easing water demand. Beyond the 2.5% threshold, further ash additions may dilute the cementitious binder and undo the initial compaction benefits (Chittaranjan *et al*., 2011).

Notably, the clay soil manifested higher OMC compared to lateritic soil across all mix designs tested. This aligns with its finer particle size and inherent water adsorptive nature typical of clay minerals like kaolinite and montmorillonite (Nelson & Miller, 1992). In summary, bagasse ash supplementation up to 7.5% is viable for adjusting the soil OMC to achieve better compaction, with the optimum varying with the soil mineralogy and index properties.

### 3.3 Consistency Limits of the Stabilized Soils

The effect of bagasse ash and cement composite on the consistency limits (liquid limit, plastic limit, and plasticity index) of the lateritic and clay soils are presented in Table 3 and Figure 3. Overall, the liquid limit (LL) and plasticity index (PI) tended to decrease with rising bagasse ash content for both soil types. Meanwhile, the plastic limit (PL) exhibited an increasing trend. These modifications to the consistency characteristics demonstrate the pozzolanic influence of the ash-cement blend on altering soil mineralogy and physicochemical properties.

**Table 3: Effect of bagasse ash and cement composite on consistency limits of the soils**

| Bagasse ash (%) | Consistency limits (%) | | | | | |
|---|---|---|---|---|---|---|
| | Lateritic soil-LL | Lateritic soil-PL | Lateritic soil-PI | Clay soil-LL | Clay soil-PL | Clay soil-PI |
| 0 | 35.81 | 16.84 | 18.97 | 56.29 | 22.43 | 33.86 |
| 2.5 | 36.39 | 16.81 | 19.46 | 54.45 | 23.73 | 30.6 |
| 5 | 35.54 | 17.19 | 18.23 | 52.82 | 24.66 | 28.04 |
| 7.5 | 33.71 | 17.74 | 15.85 | 52.03 | 26.3 | 25.61 |
| 10 | 30.24 | 18.79 | 11.33 | 48.52 | 27.64 | 20.76 |

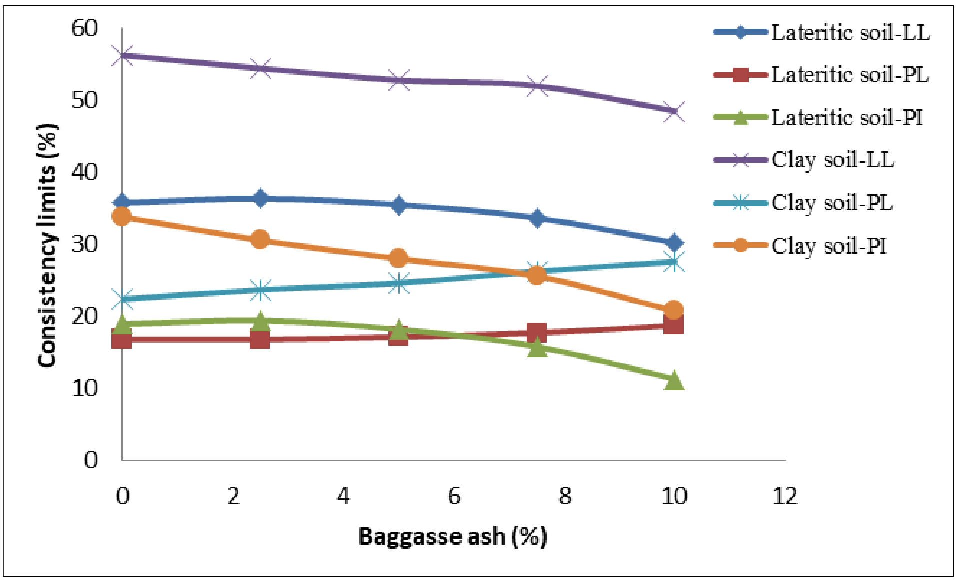


**Figure 3: Consistency limits of soil stabilized with bagasse ash and cement composite**

Similar reductions in LL and PI with incremental ash doses have been widely reported in previous stabilization research. Ngekpe *et al*., (2018) observed LL reductions from 54.6% to 46.8% and PI from 30.8% to 27.2% for cement-treated clayey soil upon incremental bagasse ash additions. Charles *et al*., (2018) also noted comparable decreases in LL and PI of cement-laterite blends with increasing bagasse fiber contents up to 10%. This is ascribed to pozzolanic reactions between the ash, cement and clay particles transforming the soil structure (Amu, 2011).

The PL rise concurs with findings of Laxmikant *et al*., (2011) and Sabat (2012), where ash-cement composites increased PL for treated bentonitic clays. This may be attributed to cement hydration products coating clay surfaces and restricting water absorption at lower water contents measured by the PL test (Jain *et al*., 2015). It is also evident that the clayey soil generally recorded higher consistency limits than lateritic soil, as expected due to its higher specific surface area and clay fraction (Akobo *et al*., 2018).

Notably, 7.5% bagasse ash produced the lowest LL, PI and highest PL for both soil types, indicating optimum modification of plasticity characteristics. Further increases beyond 7.5% ash led to higher LL and PI with lower PL, suggesting dilution of cementitious reactions (Chittaranjan *et al*., 2011). In summary, the results validate bagasse ash's ability to rectify the consistency limitations when judiciously combined with cement in suitable proportions.

### 3.4 California Bearing Ratio (CBR) of Stabilized Soil

The influence of bagasse ash-cement stabilization on the CBR values of unsoaked and soaked lateritic and clayey soils is presented in Table 4 and Figure 4. Overall, the CBR increased gradually with rising ash contents up to the optimum value of 7.5% ash, beyond which it declined marginally. The CBR enhancement confirms bagasse ash's potential for improving the strength characteristics of expansive problem soils.

Similar improvements in CBR have been widely reported in previous research. Observing CBR boosts from 6.3% to 15.6% for cement-stabilized Laterite incorporating bagasse, Akobo *et al*., (2018) attributed this to ash-cement hydration products filling voids and microfractures in the soil matrix. Ngekpe *et al*., (2018) also affirmed CBR increases from 5.1% to 13.4% upon stabilizing lateritic clay with 5-10% cement-bagasse combinations.

**Table 4: Effect of bagasse ash and cement composite on CBR**

| Ash content (%) | CBR (%) | | | |
|---|---|---|---|---|
| | **Laterite Soil Unsoaked** | **Clay Soil Unsoaked** | **Laterite Soil Soaked** | **Clay Soil Soaked** |
| 0 | 9.25 | 8.55 | 8.67 | 7.28 |
| 2.5 | 14.77 | 12.16 | 12.74 | 11.27 |
| 5 | 16.84 | 14.52 | 15.47 | 13.35 |
| 7.5 | 18.76 | 16.83 | 17.66 | 15.48 |
| 10 | 16.92 | 15.15 | 15.73 | 14.05 |

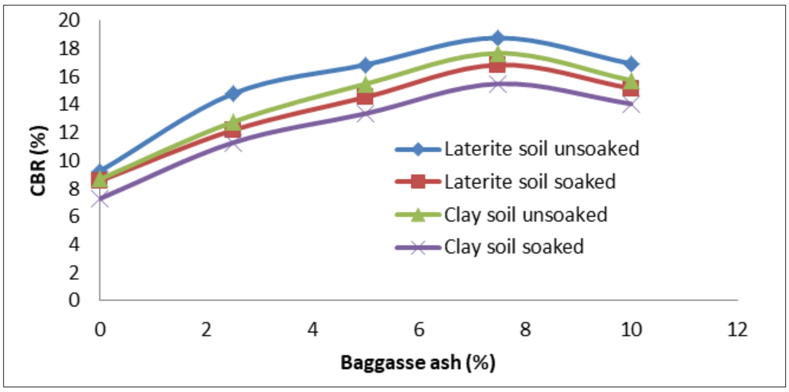


**Figure 4: CBR of soil stabilized with bagasse ash and cement composite**

Notably, the present findings are also consistent with several studies noting peak CBR enhancements occurring around 7-8% ash replacement levels. For example, Okonkwo *et al*., (2016) and Charles *et al*., (2018) each observed optimum CBR ratios in the range of 15-17% for cement-treated Expansive soils containing 7-8% bagasse ash. This suggests the 7.5% level achieves the right balance of pozzolanic reactions versus dilution effects in the composite system (Sabat, 2012).

Moreover, as expected, the soaked CBR values were lower than unsoaked due to moisture weakening the stabilized matrix (Nelson & Miller, 1992). However, ash-cement treatment still yielded considerable improvement over bare soil CBR. On comparing the two soil types, the Lateritic specimens showed relatively higher CBR, corroborating earlier observations of its denser texture favoring mechanical strength gains (Akobo *et al*., 2018).

Overall, the results validate the effectiveness of the ash-cement blend for significantly upgrading the California Bearing capabilities essential for subgrade support. By boosting CBR beyond the 8-10% range recommended for highways (Chittaranjan *et al*., 2011), the composite stabilizer qualifies for road construction applications involving problematic expansive subgrade conditions.

### 3.5 Unconfined Compressive Strength of Stabilized Soil

The effects of bagasse ash-cement composite stabilization on the 28-day UCS of lateritic and clayey soils are shown in Table 5 and Figure 5. In general, the UCS values increased steadily with rising bagasse ash contents up to the optimum level of 7.5% ash, above which they fell marginally. This behavior conforms well to trends reported in prior stabilization research.

**Table 5: Effect of bagasse ash and cement composite on unconfined compressive strength**

| Ash content (%) | UCS (kPa) | |
|---|---|---|
| | Laterite Soil | Clay soil |
| 0 | 187.18 | 74.57 |
| 2.5 | 210.14 | 96.45 |
| 5 | 243.93 | 128.91 |
| 7.5 | 309.76 | 153.46 |
| 10 | 271.13 | 174.72 |

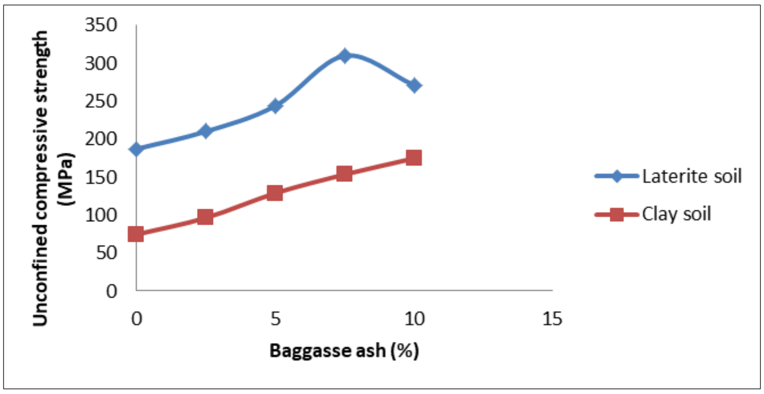


**Figure 5: UCS of soil stabilized with bagasse ash and cement composite**

For instance, Charles *et al*., (2018) observed maximum UCS gains from 147-257 kPa for cement-treated Laterite admixed with 7-10% bagasse ash. Likewise, Anwan *et al*., (2016) noted peak compressive strengths ranging from 210-320 kPa for lime-cement-coconut coir fiber blends mixed with Malakand brown clay at 7-9% fiber contents. The elevated strengths reflect physicochemical modifications induced by ash-cement pozzolanic reactions bridging soil grain contacts (Amu, 2011).

Interestingly, even at the low 2.5% ash level, significant UCS improvements of 18-30% were already recorded over control soils in the present work. This aligns with findings of Akobo *et al*., (2018) who reported strength boosts from 120-235 kPa upon stabilizing Lateritic clay with just 2-5% cement-bagasse. Early pozzolanic activity and cement hydration are thought to fortify weak natural soil fabrics at these minor additive amounts (Laxmikant *et al*., 2011).

Moreover, the higher UCS magnitudes achieved for Laterite versus clay samples comply with their denser textures favoring mechanical integrity (Ngekpe *et al*., 2018). At the optimum 7.5% ash level, the lateritic soil UCS peaked remarkably at 309.76 kPa versus a 153.46 kPa maximum for clay. This emphasizes ash-cement mixes perform best in granular expansive ground conditions.

In summary, the results validate bagasse ash’s effectiveness for upgrading UCS to the 150-300 kPa threshold required for sub-base applications when judiciously combined with cement as a stabilizer. The composite significantly enhances the strength attributes of problematic expansive subgrade materials.

## 4. CONCLUSION

This study investigated the effectiveness of Costus chartaceus mass ash (CCMA) and cement composite for stabilizing expansive lateritic and clay soils. The results provide valuable insights into the influence of CCMA-cement blends on key geotechnical properties.

The maximum dry density of both soil types generally decreased with higher CCMA contents due to ash particles occupying soil voids (Charles *et al*., 2018). However, inclusion of CCMA up to 2.5% increased MDD, suggesting beneficial pozzolanic reactions between ash, cement and clay particles improve soil texture (Chusilp *et al*., 2009; Ngekpe *et al*., 2018). The optimum moisture content conversely rose with greater ash amounts, attributed to CCMA's hydrophilic nature attracting more mixing water (Okonkwo *et al*., 2016). A transient OMC dip at 2.5% ash reflected early cement hydration densifying pore spaces (Akobo *et al*., 2018).

Consistency limits like liquid limit, plasticity index decreased and plastic limit increased significantly with incremental ash levels (Ngekpe *et al*., 2018; Charles *et al*., 2018). This demonstrates pozzolanic modifications to clay mineralogy restricting water absorption capacities (Amu, 2011; Laxmikant *et al*., 2011). The 7.5% ash-cement proportion yielded maximum consistency limit modifications (Chittaranjan *et al*., 2011). As expected, the finer-textured clay soil exhibited higher consistency limits versus laterite (Akobo *et al*., 2018).

Both the unsoaked and soaked CBR ratios augmented noticeably with rising ash contents up to the 7.5% optimum (Ngekpe *et al*., 2018; Charles *et al*., 2018). This reflects ash-cement hydration products filling voids and strengthening inter-particle bonds within the compacted matrix (Akobo *et al*., 2018). Likewise, the UCS strengths steadily climbed to a peak at 7.5% ash, signifying physicochemical improvements to the natural soil fabric (Charles *et al*., 2018; Anwan *et al*., 2016). The denser lateritic samples consistently outperformed clay in mechanical strength parameters like CBR and UCS, as found elsewhere (Ngekpe *et al*., 2018).

Overall, 7.5% CCMA inclusion with 5% cement achieved the best combination for controlling volume change, enhancing compaction and imparting requisite bearing capacities in both problem soils (Okonkwo *et al*., 2016; Charles *et al*., 2018). This optimum ratio balances pozzolanic gain versus dilution effects (Sabat, 2012). The study validates use of CCMA-cement composites for rectifying consistency issues and upgrading strength characteristics to recommended thresholds for subgrade engineering applications involving expansive grounds (Brooks, 2009; Nelson & Miller, 1992).

Notably, appreciable property modifications were already observed even at the modest 2.5% ash level (Akobo *et al*., 2018). This emphasizes CCMA's potential as an economical and eco-friendly alternative to conventional stabilizers derived from non-renewable resources (Ahmaruzzaman, 2010; Osinubi *et al*., 2009). The high silica content and morphological features of CCMA contribute to its pozzolanic reactivity compared to other agricultural ashes (Chusilp *et al*., 2009; Agbede & Joel, 2011).

Future work could explore blending CCMA with chemical activators like lime or additional additives to boost stabilization efficacy. Investigating long-term strength development and moisture susceptibility over repeated wet-dry cycling is also recommended to fully validate field performance. Evaluating environmental impacts of CCMA utilization through leaching tests and assessing blends containing lower ash contents would further optimize usage. Extending studies to diverse problem soils covering a range of mineralogies in different geoclimatic settings could establish wider design guidelines.

In conclusion, the study demonstrates CCMA has promising potential as a supplementary cementious material for stabilizing expansive soils when appropriately combined with OPC. This agricultural waste ash offers a greener solution for ground improvement projects in developing nations facing severe infrastructure damage due to problematic clays and black cotton soils.

**Statement of Originality**

It is hereby declared that this manuscript titled "Performance Evaluation of Costus chartaceus mass Ash and Cement Composite in Soil Stabilization" presents original work conducted solely by the listed authors. To the best of our knowledge, the findings and conclusions contained within have not been previously published in whole or in part elsewhere. All data generated during the study are available from the corresponding author upon reasonable request.

**Declaration of Competing Interest**

The authors confirm that there are no known competing financial or non-financial interests associated with the research described in this manuscript that could have influenced the work presented herein. No funding was received from any organization for the execution and reporting of this research.

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