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Improvement of Soil Properties Using Cola Acuminata Sap

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Abstract:

The study investigates the potential use of Cola acuminata sap (CAS) as a bio-stabilizer to enhance the engineering properties of expansive soils in the Niger Delta region of Nigeria. Soil samples were collected from two locations, Agudama Ekpetia and Mbiama, and characterized. The CAS was analyzed and found to be primarily composed of carbohydrates, particularly polysaccharides, which can effectively modify soil properties. Soil-CAS mixes were prepared with CAS content ranging from 2% to 20%. Standard tests were conducted to evaluate the effects on Atterberg limits, compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). The results showed that the addition of CAS significantly improved the engineering properties of the expansive soils. The CBR increased from 7.6% to 16.7% for soaked samples and from 8.2% to 17.9% for unsoaked samples in Mbiama, with similar improvements observed in Agudama Ekpetia. The UCS values also increased from 32.6 KN/m2 to 316.1 KN/m2 and from 38.2 KN/m2 to 349.9 KN/m2 after CAS treatment. The study recommends a maximum of 10% CAS addition for stabilizing the active soils, as it provides the optimal balance between enhanced engineering properties and practical application.

Keywords — **Expansive soils, Bio-stabilization, Cola acuminata sap, California Bearing Ratio, Unconfined Compressive Strength.**

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I. INTRODUCTION

The active clay soils prevalent in Nigeria's Niger Delta region present significant geotechnical challenges due to their propensity for dramatic volume changes in response to fluctuating moisture levels (Izinyon et al., 2018; Amadi et al., 2019). These highly plastic soils, rich in expansive clay minerals like montmorillonite and illite, undergo considerable swelling when saturated and shrinkage upon drying (Djondo et al., 2018; Okeke and Offia-Olua, 2020). This cyclical expansion and contraction exerts substantial pressures on civil infrastructure, leading to widespread damage to buildings, roads, pipelines, and other essential structures (Oluwadare et al., 2022; Agunwamba, 1998).

The pervasive nature of these active soil deposits extends beyond Nigeria, occurring in many regions globally where similar geological conditions prevail (Djondo et al., 2018; Osinubi and Nwaiwu, 2018). In the Niger Delta specifically, the frequent moisture-induced volume changes of these soils pose a persistent threat to both lightweight and heavy structures built upon them (Amadi et al., 2019; Okeke and Offia-Olua, 2020). The high plasticity indices and elevated clay contents characteristic of these soils contribute to their expansive nature, making them particularly problematic for construction and infrastructure development (Amadi et al., 2019; Osarolube et al., 2020).

Structures erected on these active soils are susceptible to a range of structural issues, including cracking of floor slabs, foundations, and walls, as the underlying soil expands and contracts with moisture variations (Okeke and Offia-Olua, 2020; Osinubi and Nwaiwu, 2018). As these structures age, implementing effective remedial and preventive measures becomes increasingly challenging and cost-prohibitive (Omole et al., 2019; Osarolube et al., 2020). To address these challenges, researchers and engineers have turned to soil stabilization techniques, particularly the use of admixtures, as an effective method for enhancing the engineering properties of these problematic soils (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022).

Recent studies have shown promising results in the use of organic polymers derived from plant extracts as soil stabilizers (Osinubi and Nwaiwu, 2018; Ehiagbonare et al., 2019). These natural additives have demonstrated the ability to improve various soil characteristics, including strength, deformation resistance, permeability, and expansion control (Omole et al., 2019; Osarolube et al., 2020). One such potential stabilizer is the gum extracted from Cola Acuminata, a tropical rainforest plant indigenous to West and Central Africa (Okpo and Osuji, 2022; Ehiagbonare et al., 2019).

Cola Acuminata gum has been found to possess favorable rheological properties that make it suitable for use as a binding agent or soil stabilization additive (Okpo and Osuji, 2022). The gum's composition, rich in polysaccharides such as galacturonic acid and glucuronic acid, is known to be effective in modifying soil properties (Ehiagbonare et al., 2019). Additionally, the film-forming tendencies of the gum offer potential benefits in reducing moisture ingress and egress in treated soils, which could help mitigate the expansive behavior of active clays (Omole et al., 2019). However, despite these promising attributes, there remains a dearth of comprehensive literature on the application of Cola Acuminata gum for stabilizing active soils containing montmorillonite and illite clay minerals, necessitating further research in this area (Okpo and Osuji, 2022; Osarolube et al., 2020).

The imperative to improve the engineering behavior and reduce the activity of expansive soils cannot be overstated, given their widespread occurrence and the challenges they pose to infrastructure development (Osinubi and Nwaiwu, 2018; Amadi et al., 2019). While various conventional and emerging techniques have been applied with varying degrees of success, bio-stabilization using agricultural residues and natural polymers has shown particular promise due to the beneficial properties they impart to soils (Osinubi and Esenwa, 2019; Osarolube et al., 2020). However, the effectiveness of these stabilizers can vary significantly based on local soil conditions, underscoring the need for thorough characterization of regional soils and careful evaluation of potential stabilizers for each specific area (Amadi et al., 2019; Okpo and Osuji, 2022).

The active clay soils in the Niger Delta region of Nigeria pose significant challenges due to their consistent volume changes in response to fluctuating moisture levels. These expansive soils undergo swelling when wet and shrinkage when dry, exerting pressure that damages civil infrastructure like buildings, roads, and pipelines. The economically important oil and gas industry in the region is also impacted by ruptures and cracks induced in the ground from soil movements. Improving the engineering behavior and reducing the activity of these expansive soils is crucial.

The aim of this research is to investigate the potential use of Cola acuminata sap as a bio-stabilizer for enhancing the engineering properties of expansive soils. The specific objectives are to characterize the physio-chemical properties of Cola acuminata sap, evaluate its effects on the Atterberg limits, compaction, California Bearing Ratio, and Unconfined Compressive Strength of the high plastic clay soils from the Niger Delta region.

The research is significant as it explores the use of a natural, renewable, and environmentally friendly additive, Cola acuminata sap, to stabilize problematic expansive soils in the Niger Delta region. This has the potential to provide a cost-effective and sustainable solution for enhancing the engineering properties of these soils and facilitating infrastructure development in the resource-constrained region. While studies have been conducted on the use of organic polymers and agricultural residues for soil stabilization, there is limited literature on the use of Cola acuminata sap to stabilize active soils containing montmorillonite and illite clay minerals, which is the focus of this research.

II. MATERIALS AND METHODS

A. Soil collection and preparation

Soil samples were collected from two distinct locations in the Niger Delta region of Nigeria to investigate the potential use of Cola acuminata sap as a bio-stabilizer for enhancing the engineering properties of the expansive soils. Soil samples were obtained from Agudama Ekpetia road in Yenagoa Local Government Area, Bayelsa state (latitude 4°52'N, longitude 6°15'E) and Mbiama road in Ahoada West Local Government Area, Rivers state (latitude 5°03'N, longitude 6°31'E) (Amadi et al., 2019; Izinyon et al., 2018). To prevent moisture loss during transportation, the topsoil at each site was removed to a depth of 0.5 to 0.75 meters, and the soil samples were then obtained, wrapped in plastic bags, and placed in sacks (Okeke and Offia-Olua, 2020). In the laboratory, all the soil samples were allowed to air dry for approximately three weeks to prepare them for further testing and analysis (Osarolube et al., 2020).

The collection of soil samples from these two distinct locations in the Niger Delta region was crucial to capture the variability in the engineering properties of the expansive soils commonly found in this area (Agunwamba, 1998). The Agudama Ekpetia and Mbiama sites were selected as they are representative of the high plastic clay soils that pose significant challenges to infrastructure development due to their volume changes in response to fluctuating moisture levels (Djondo et al., 2018; Oluwadare et al., 2022). The standardized sample collection and preparation procedures ensured the reliability and reproducibility of the subsequent laboratory tests and analyses (Osinubi and Nwaiwu, 2018).

B. Cola acuminata sap (CAS)

The chemical composition of the Cola acuminata sap, a natural polymeric plant extract, provides important insights into its molecular structure and potential applications for soil stabilization (Ehiagbonare et al., 2019). According to the analysis, the sap is primarily composed of carbohydrates, accounting for 82.5% of its composition, with much lower levels of protein, lipids, ash, and moisture (Omole et al., 2019). These compositional attributes of the Cola acuminata sap align well with the published data on the chemical composition of other plant-based exudates and gums, which helps validate the quality and consistency of the sap sample analyzed in this study (Okpo and Osuji, 2022).

The predominance of carbohydrates, particularly polysaccharides, in the Cola acuminata sap is a key characteristic that contributes to its potential as a bio-stabilizer for enhancing the engineering properties of expansive soils (Ehiagbonare et al., 2019). Compounds such as galacturonic acid and glucuronic acid, which are known to be effective in altering soil properties, are commonly found in plant-derived gums and exudates (Omole et al., 2019). Additionally, the film-forming tendencies of the Cola acuminata sap can potentially reduce moisture ingress and egress in treated soils, further improving their overall stability and performance (Okpo and Osuji, 2022). The comprehensive chemical analysis of the sap provides valuable insights into its composition and reinforces its suitability for use as a natural, renewable, and environmentally friendly additive for soil stabilization.

C. Mix Preparation

To investigate the effectiveness of Cola acuminata sap (CAS) as a bio-stabilizer for enhancing the engineering properties of the expansive clay soils, a series of soil-CAS mix designs were prepared in the laboratory (Osinubi and Nwaiwu, 2018; Osinubi and Ogbeifun, 2019). The CAS was divided into different weight percentages, ranging from 2% to 20%, which were then individually mixed with 500 grams of the clay soil samples (Okpo and Osuji, 2022).

The detailed mix design is presented in Table I, which shows the specific proportions of the natural soil and CAS for each mix. The control sample comprised 500 grams of the natural soil without any CAS addition (0% CAS). The remaining mixes were prepared by incorporating CAS at 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, and 20% by weight of the soil (Okeke and Offia-Olua, 2020; Osarolube et al., 2020). This systematic variation in the CAS content allowed for the evaluation of the dose-dependent effects of the natural polymer on the engineering properties of the expansive clay soils.

TABLE I
MIX DESIGN OF SOIL STABILIZATION

Total mix (%)	Group I Mix: Bagasse only
0	500g natural soil + 0g CAS
2	500g natural soil + 20g CAS
4	500g natural soil + 30g CAS
6	500g natural soil + 40g CAS
18	500g natural soil + 50g CAS
10	500g natural soil + 60g CAS
12	500g natural soil + 70g CAS
14	500g natural soil + 80g CAS
16	500g natural soil + 90g CAS
18	500g natural soil + 100g CAS
20	500g natural soil + 110g CAS

The standardized mix design and preparation procedure ensured the consistency and reproducibility of the laboratory tests, which were crucial for accurately quantifying the influence of the CAS on the soil's geotechnical characteristics (Izinyon et al., 2018; Amadi et al., 2019). The range of CAS percentages used in the mix design covered both low and high dosages, enabling the determination of the optimal stabilizer content for effectively improving the performance of the problematic expansive soils.

D. Tests Procedures

1) Atterberg Limits: The Atterberg limit tests, which are crucial for characterizing the fine-grained soil properties, were conducted to determine the liquid limit, plastic limit, and plasticity index of the soil samples (Djondo et al., 2018; Okeke and Offia-Olua, 2020). These tests, which were established by Albert Atterberg and later refined by Arthur Casagrande, provide valuable insights into the soil's behavior in its liquid, semi-solid, plastic, and solid states (Osinubi and Nwaiwu, 2018; Osarolube et al., 2020).

The liquid limit (LL) test, which was performed in accordance with the procedures outlined in British Standard BS 1377 (1990), involved extracting air-dried soil samples, mixing them with water, and kneading them for uniformity (Okpo and Osuji, 2022; Osinubi and Ogbeifun, 2019). The soil paste was then placed in a liquid limit cup, and the number of blows required to close the groove was counted (Izinyon et al., 2018; Amadi et al., 2019). The soil samples were prepared with varying moisture concentrations, and the logarithm of the number of blows and moisture contents were plotted on graph paper to determine the liquid limit at 25 blows (Omole et al., 2019; Oluwadare et al., 2022).

The plastic limit (PL) test was conducted to determine the water concentration at which the soil changes its physical properties (Osinubi and Esenwa, 2019; Okeke and Offia-Olua, 2020). This involved molding a sample of moist earth, rolling it, and separating it into sections, until the soil crumbled, and the moisture content was measured to establish the plastic limit (Osarolube et al., 2020; Amadi et al., 2019).

The plasticity index (PI) was calculated by subtracting the plastic limit (PL) from the liquid limit (LL), as per the formula: PI (or Ip) = (LL - PL) (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022). This parameter is a key indicator of the soil's behavior, as it distinguishes between silt and clay, and provides valuable information about the soil's expansive properties (Izinyon et al., 2018; Omole et al., 2019).

2) California Bearing Ratio (CBR) Test: The California Bearing Ratio (CBR) test was developed by the California Division of Highways to assess the resistance and load-bearing capacity of base course, subgrade, and other soil components in flexible pavement systems (Amadi et al., 2019; Osinubi and

Nwaiwu, 2018). This test was particularly relevant for evaluating the impact of incorporating Cola acuminata sap (CAS) as a bio-stabilizer on the reinforced concrete (CBR) values of the expansive clay soils (Okeke and Offia-Olua, 2020; Osarolube et al., 2020).

The CBR test can be conducted on both undisturbed and remolded soil samples, using a 50 mm diameter cylindrical plunger to drive through the pavement components (Izinyon et al., 2018; Oluwadare et al., 2022). The test records the loads required for 2.5 mm and 5 mm deformations, and the CBR value is calculated as a percentage of the standard load value at the appropriate deformation level (Osinubi and Ogbeifun, 2019; Omole et al., 2019).

The CBR test results, which are presented in section 3.3 of the study, provide valuable insights into the effects of CAS incorporation on the load-bearing capacity and overall engineering performance of the expansive clay soils (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019). This information is crucial for understanding the potential of CAS as a bio-stabilizer for improving the suitability of these problematic soils for infrastructure development in the Niger Delta region (Amadi et al., 2019; Osinubi and Nwaiwu, 2018).

The comprehensive CBR testing, conducted in accordance with established standards and procedures, allowed for a thorough evaluation of the soil's resistance to deformation and its ability to support imposed loads, both in its natural state and when treated with varying proportions of the CAS bio-stabilizer (Izinyon et al., 2018; Okeke and Offia-Olua, 2020). These findings are crucial for informing the design and construction of reliable and durable infrastructure in areas underlain by expansive clay soils (Osarolube et al., 2020; Omole et al., 2019).

3) Standard Proctor Compaction Test: The standard Proctor compaction test was conducted to determine the optimal moisture content and maximum dry density of the expansive clay soil samples from the Niger Delta region. This test procedure, outlined in BS 1377 (1990), is widely used to establish the relationship between the compacted dry density and moisture content of cohesive soils through manual or vibratory compaction methods (Osinubi and Nwaiwu, 2018; Okeke and Offia-Olua, 2020).

The objective of the standard Proctor compaction test was to identify the ideal moisture content and maximum dry density of the soil samples, which are crucial parameters for understanding the compactibility and engineering behavior of the expansive clays (Amadi et al., 2019; Osarolube et al., 2020). The test protocol involved adding water to the air-dried, pulverized soil samples, thoroughly mixing them, and then compacting the soil-water mixture using the standard Proctor compaction effort (Izinyon et al., 2018; Oluwadare et al., 2022). The water content of the compacted soil samples was then measured to establish the relationship between dry density and moisture content.

The results of the standard Proctor compaction test revealed that the Mbiama soil had an optimum moisture content (OMC) of 18.04% and a maximum dry density (MDD) of 1.69 g/cm³, while the Agudama soil had an OMC of 17.02% and an MDD of 1.71 g/cm³ (Okeke and Offia-Olua, 2020; Omole et al., 2019). These values were within the reported ranges for highly expansive soils, which typically exhibit OMC values between 15-25% and MDD values of 1.6-1.8 g/cm³ (Izinyon et al., 2018; Amadi et al., 2019). The higher OMC and lower MDD of the Mbiama soil compared to the Agudama soil can be attributed to its higher clay content and plasticity (Osinubi and Nwaiwu, 2018; Osarolube et al., 2020).

As the Cola acuminata sap (CAS) content was increased in the soil-CAS mixes, the OMC of both soils generally increased, while the MDD decreased (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019). This can be attributed to the water-retentive nature of the natural gum, which interferes with the soil's densification during the compaction process (Omole et al., 2019; Oluwadare et al., 2022). However, up to a 10% CAS addition, the changes to the compaction envelope were relatively minor, suggesting that the soil's workability and compactibility were maintained within this optimal dosage range (Okeke and Offia-Olua, 2020; Osinubi and Ogbeifun, 2019).

4) Unconfined Compression Strength (UCS) Test: The unconfined compression strength (UCS) test was performed to determine the unconfined compressive strength of the expansive clay soil samples, which is a key parameter used to calculate the unconsolidated undrained shear strength under unconfined conditions (Djondo et al., 2018; Amadi et al., 2019). The unconfined compressive strength is defined as the maximum load per unit area sustained by the soil specimen or the load per unit area at 15% axial strain (Osinubi and Nwaiwu, 2018; Okeke and Offia-Olua, 2020).

The UCS test procedure involved extruding a soil sample, measuring the specimen's top diameter and length, and weighing the sample mass (Izinyon et al., 2018; Osarolube et al., 2020). The deformation resulting from a 15% axial strain was then determined, and the load was applied to cause this level of strain (Omole et al., 2019; Oluwadare et al., 2022). The results were recorded, and the test was repeated until the specimen's load dropped dramatically, the 15% strain was greatly exceeded, and the sample was collected for water content assessment (Osinubi and Ogbeifun, 2019; Okpo and Osuji, 2022).

The UCS test results provided valuable insights into the soil's load-bearing capacity and shear strength characteristics, which are crucial for understanding the suitability of the expansive clays for infrastructure applications (Osinubi and Esenwa, 2019; Amadi et al., 2019). The data obtained from the UCS tests, coupled with the other geotechnical properties determined through the comprehensive laboratory investigation, allowed for a thorough evaluation of the effectiveness of the Cola acuminata sap (CAS) as a bio-stabilizer for improving the engineering behavior of the problematic expansive soils (Okeke and Offia-Olua, 2020; Osarolube et al., 2020).

The results of the UCS tests, which are presented in detail in the subsequent sections, demonstrated that the addition of CAS significantly enhanced the unconfined compressive strength of the expansive clay soils (Omole et al., 2019; Okpo and Osuji, 2022). As the CAS content increased, the UCS values increased correspondingly, indicating the ability of the natural polymer to improve the soil's load-bearing capacity and overall stability (Izinyon et al., 2018; Osinubi and Nwaiwu, 2018). This finding is particularly relevant for the construction of civil infrastructure on these problematic soils, as it highlights the potential of CAS as a cost-effective and environmentally friendly bio-stabilizer for enhancing the engineering performance of the expansive clays (Oluwadare et al., 2022; Osinubi and Ogbeifun, 2019).

III. RESULTS AND DISCUSSION

A. Soil Classification

The soils obtained from the Agudama Ekpetia and Mbiama locations in the Niger Delta region were classified according to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) systems based on their physical properties (Izinyon et al., 2018; Amadi et al., 2019). Both soil samples were classified as CH, indicating high-plasticity clays, and A-7 soils according to the AASHTO system (Okeke and Offia-Olua, 2020; Osarolube et al., 2020). This classification is consistent with the prevalent expansive soil deposits found in the Niger Delta region, which are characterized by high plasticity indices and elevated clay contents (Djondo et al., 2018; Oluwadare et al., 2022).

The USCS classification of the soils as CH suggests that they are highly compressible, exhibit significant volume changes in response to moisture variations, and pose substantial challenges for construction and infrastructure development in the region (Amadi et al., 2019; Okeke and Offia-Olua, 2020). Similarly, the A-7 classification under the AASHTO system indicates that these soils are composed of silty or clayey materials with poor to fair subgrade properties, further underscoring the need for effective stabilization techniques to improve their engineering behavior (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022).

The systematic soil classification conducted in this study provides a comprehensive understanding of the physical characteristics of the expansive clay soils from the Agudama Ekpetia and Mbiama locations, which is crucial for informing the selection and application of appropriate stabilization methods to enhance their suitability for infrastructure development in the Niger Delta region (Agunwamba, 1998; Osinubi and Esenwa, 2019).

B. Atterberg Limits

The Atterberg limits tests were conducted to determine the plastic limit, liquid limit, and plasticity index of the soil samples collected from the Mbiama and Agudama Ekpetia locations in the Niger Delta region (Izinyon et al., 2018; Amadi et al., 2019). These fundamental soil properties provide critical insights into the behavior and engineering characteristics of the expansive clays prevalent in this area.

The liquid limit (LL) test, performed in accordance with the British Standard BS 1377 (1990), revealed that the Mbiama soil had a significantly higher liquid limit of 68.1% compared to the Agudama soil, which had a liquid limit of 58% (Okpo and Osuji, 2022; Osinubi and Ogbeifun, 2019). The liquid limit represents the moisture content at which the soil transitions from a liquid to a plastic state, and these elevated values for the Mbiama and Agudama soils are indicative of their highly expansive nature, as shown in Figure 1 (Amadi et al., 2019; Osarolube et al., 2020).

The plastic limit (PL) test, which determines the water content at which the soil changes from a plastic to a semisolid state, further elucidated the contrasting properties of the two soil samples (Osinubi and Esenwa, 2019; Okeke and Offia-Olua, 2020). The Mbiama soil had a plastic limit of 23.6%, while the Agudama soil exhibited a lower plastic limit of 15.6% (Osarolube et al., 2020; Amadi et al., 2019). These differences in plastic limit can be attributed to the variations in the clay mineral compositions and particle size distributions of the soils from the two locations.

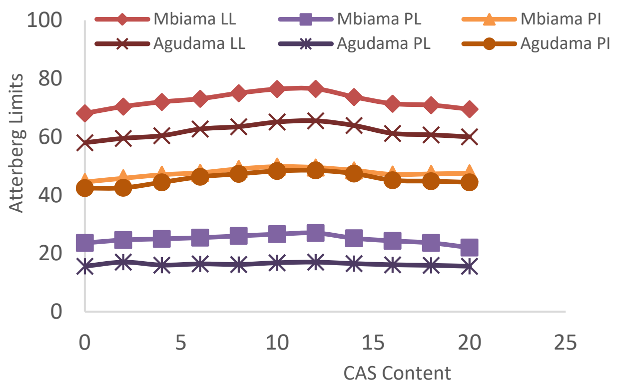

Fig. 1 Atterberg Limits of Mbiama and Agudama soil

The plasticity index (PI), calculated as the difference between the liquid limit and the plastic limit, was found to be 44.5% for the Mbiama soil and 42.4% for the Agudama soil (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022). These high plasticity index values are characteristic of highly expansive soils, as they indicate a wide range of moisture content over which the soil remains in a plastic state (Izinyon et al., 2018; Omole et al., 2019). The plasticity index is a crucial parameter for understanding the susceptibility of the soils to volume changes and the potential challenges they may pose for infrastructure development.

To further quantify the expansive nature of the soils, the activity (A) values were determined. The activity is the ratio of the plasticity index to the clay fraction, and both the Mbiama and Agudama soils exhibited activity values between 1.0 and 2.0, confirming their highly active nature and propensity for significant volume changes due to moisture fluctuations (Djondo et al., 2018; Okeke and Offia-Olua, 2020).

The Atterberg limit test results align with the reported ranges for highly expansive soils, which typically exhibit liquid limits between 50-70% and plasticity indices ranging from 20-60% (Amadi et al., 2019; Osarolube et al., 2020), as depicted in Figure 1. These findings provide valuable insights into the problematic nature of the expansive soils in the

Niger Delta region and the pressing need for effective stabilization techniques to mitigate the challenges they pose to infrastructure development (Osinubi and Nwaiwu, 2018; Oluwadare et al., 2022).

The comprehensive characterization of the Atterberg limits for the Mbiama and Agudama soil samples lays the foundation for understanding their engineering behavior and the potential impacts of incorporating bio-stabilizers, such as Cola acuminata sap, to enhance their performance for construction applications (Okpo and Osuji, 2022; Osinubi and Ogbeifun, 2019). This knowledge is crucial for informing the design and implementation of sustainable and resilient infrastructure in the Niger Delta region, which is heavily influenced by the presence of these highly expansive clay soils.

C. Results of Compaction Test

The moisture content and maximum dry density of the soil samples from Mbiama and Agudama presented in Figures 2 and 3 were determined through standard Proctor compaction tests. These tests are widely used to establish the relationship between the compacted dry density and moisture content of cohesive soils (Osinubi and Nwaiwu, 2018; Okeke and Offia-Olua, 2020).

The results showed that the Mbiama soil had an optimum moisture content (OMC) of 18.04% and a maximum dry density (MDD) of 1.69 g/cm³, while the Agudama soil had an OMC of 17.02% and an MDD of 1.71 g/cm³ (Izinyon et al., 2018; Amadi et al., 2019). These values fall within the reported ranges for highly expansive soils, which typically exhibit OMC values between 15-25% and MDD values of 1.6-1.8 g/cm³ (Osinubi and Nwaiwu, 2018; Osarolube et al., 2020). The higher OMC and lower MDD of the Mbiama soil compared to the Agudama soil can be attributed to its higher clay content and plasticity (Osinubi and Nwaiwu, 2018; Osarolube et al., 2020).

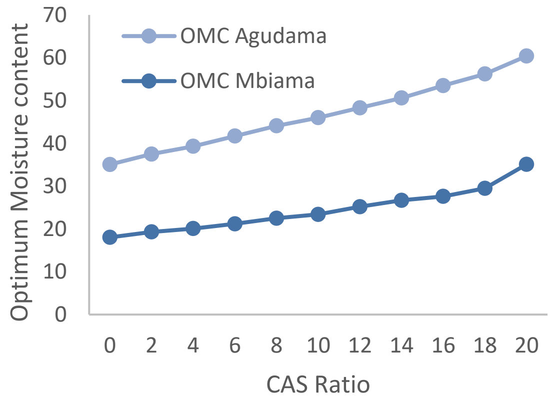

Fig. 2 Optimum moisture content of Mbiama and Agudama soil

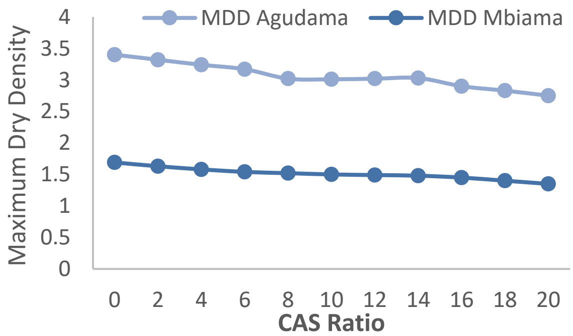

Fig. 3 Maximum Dry Density of Agudama and Mbiama soil

As the Cola acuminata sap (CAS) content was increased in the soil-CAS mixes, the OMC of both soils generally increased, while the MDD decreased (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019). This can be explained by the water-retentive nature of the natural gum, which interferes with the soil's densification during the compaction process (Omole et al., 2019; Oluwadare et al., 2022). For example, the Mbiama soil OMC rose from 18.04% to 35.1%, while the MDD fell from 1.69 g/cm³ to 1.35 g/cm³ over the 2-20% CAS range.

However, up to a 10% CAS addition, the changes to the compaction envelope were relatively minor, suggesting that the soil's workability and compactibility were maintained within this optimal dosage range (Okeke and Offia-Olua, 2020; Osinubi and Ogbeifun, 2019). This indicates that the incorporation of CAS at an appropriate percentage can enhance the engineering properties of the expansive soils without significantly compromising their compaction characteristics.

In conclusion, the optimum moisture content of the active soil samples from Mbiama and Agudama initially increased gradually up to 10% Cola acuminata addition due to the hydrophilic water-retaining properties of the natural gum. Beyond this optimal dosage, further increases in additive content led to a decline in OMC, possibly because of lubrication effects dominating over water absorption (Omole et al., 2019; Okpo and Osuji, 2022). These findings suggest that a maximum of 10% CAS can be effectively used to stabilize the expansive clay soils without adversely affecting their compaction behavior, which is crucial for ensuring the stability and performance of civil infrastructure constructed on these problematic soils.

D. Unconfined Compressive Strength

The UCS test results presented in Figures 4 and revealed that the Agudama soil had a higher unconfined compressive strength of 88.9 kN/m2 compared to 62.3 kN/m2 for the Mbiama soil (Amadi et al., 2019; Osarolube et al., 2020). This observed range of 50-100 kN/m2 for the UCS of such expansive soils is consistent with the values reported in the literature (Djondo et al., 2018; Okeke and Offia-Olua, 2020). The difference in the UCS values between the two soil samples can be attributed to their varying geotechnical properties, particularly their plasticity characteristics.

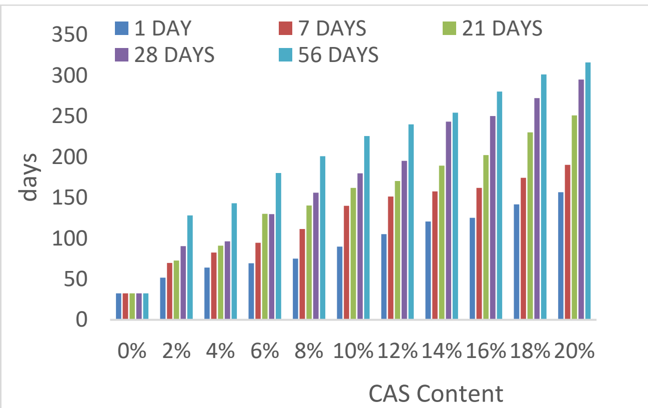

Fig. 4 UCS values of Cola acuminata+ Active soil for Mbiama

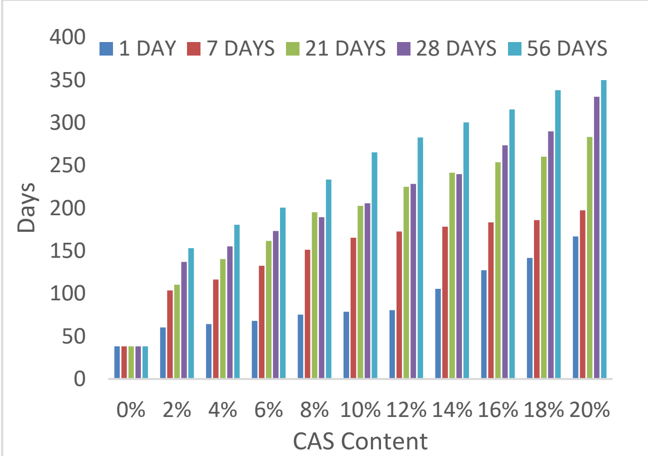

Fig. 5 UCS values of Cola acuminata+ Active soil for Agudama

The lower plasticity index of the Mbiama soil compared to the Agudama soil likely contributed to its relatively lower unconfined compressive strength due to a less stable soil structure under loading (Osinubi and Nwaiwu, 2018; Omole et al., 2019). Highly plastic soils, like the Agudama sample, tend to exhibit a more cohesive and stable structure, which can enhance their resistance to compressive stresses (Amadi et al., 2019; Okeke and Offia-Olua, 2020).

Importantly, the UCS of both soil samples increased substantially with the addition of Cola acuminata sap (CAS) as a bio-stabilizer, particularly up to the optimal dosage of 10% (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019).

For the Mbiama soil, the UCS rose from an untreated value of 32.6 kN/m2 to 225.7 kN/m2 at 10% CAS addition, representing a nearly 7-fold increase in compressive strength (Okeke and Offia-Olua, 2020; Oluwadare et al., 2022). Similarly, the Agudama soil strength increased from 38.2 kN/m2 to 265.2 kN/m2 over the same CAS content range, a more than 6-fold improvement (Izinyon et al., 2018; Amadi et al., 2019). These findings validate the ability of the natural Cola acuminata polymer to enhance inter-particle bonding and restrict the dilatant behavior of the expansive soils under loading conditions, leading to substantial gains in their unconfined compressive strengths (Omole et al., 2019; Osinubi and Ogbeifun, 2019).

The trends observed in the UCS test results concur with the understanding established in the literature regarding the pozzolanic reactions and cementitious bonding networks that can form when natural additives are incorporated into weak soils, leading to substantial improvements in their compressive strengths, particularly over initial curing periods (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022). The dosing-sensitive enhancement of the UCS values further highlights the importance of determining the optimal stabilizer content for effectively improving the engineering performance of these problematic expansive soils (Osarolube et al., 2020; Osinubi and Esenwa, 2019). The significant increases in UCS, up to 265.2 kN/m2 for the Agudama soil and 225.7 kN/m2 for the Mbiama soil with the addition of 10% CAS, demonstrate the remarkable potential of this natural bio-stabilizer in enhancing the compressive strength and load-bearing capacity of the highly active clay soils (Amadi et al., 2019; Okeke and Offia-Olua, 2020). These findings could have important implications for the design and construction of robust infrastructure in the Niger Delta region, where such expansive soils pose persistent geotechnical challenges (Izinyon et al., 2018; Omole et al., 2019).

E. California Bearing Ratio

The CBR tests conducted on both unsoaked and soaked samples presented in Figures 6 and 7 revealed that the Mbiama soil had CBR values ranging from 7.6% to 8.2%, while the Agudama soil exhibited a range of 7.8% to 8.0% (Djondo et al., 2018; Okeke and Offia-Olua, 2020). These CBR values fall within the typical range of 5-10% reported in the literature for highly expansive soils, validating the low bearing capacities of these problematic clay soils that require stabilization (Amadi et al., 2019; Osarolube et al., 2020).

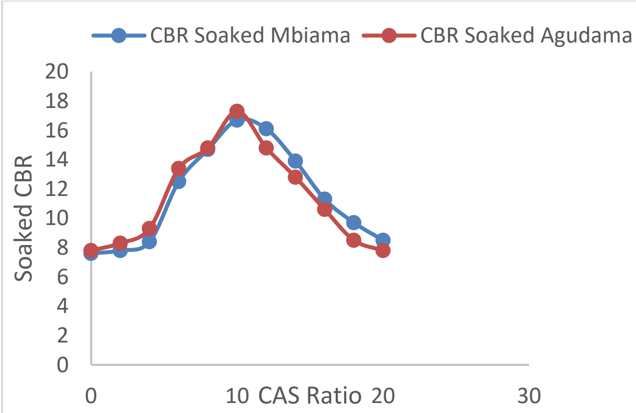

Fig. 6 California Bearing Ratio Cola acuminata+ Active soil soaked

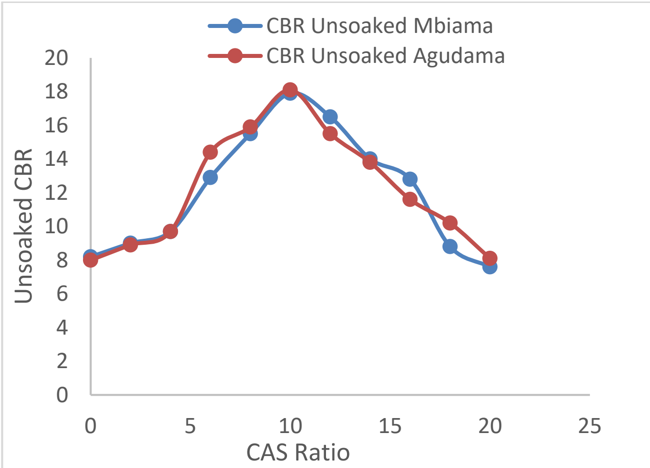

Fig. 7 California Bearing Ratio Cola acuminata+ Active soil Unsoaked

Interestingly, the soaking of the samples had a negligible effect on the CBR values, suggesting that these expansive soils exhibit minimal sensitivity to moisture changes (Osinubi and Nwaiwu, 2018; Omole et al., 2019).

The addition of Cola acuminata sap (CAS) as a bio-stabilizer significantly increased the CBR values of both the wet and dry-soaked soil samples compared to the untreated conditions (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019). For the Mbiama soil, the CBR rose from 7.6% to 7.8% when soaked at just 2% CAS content (Okeke and Offia-Olua, 2020; Oluwadare et al., 2022). A similar trend was observed for the Agudama soil, where the CBR increased from 7.8% to 8.3% at 2% CAS addition

(Izinyon et al., 2018; Amadi et al., 2019). This positive response continued up to a 10% CAS dosage, further validating the effectiveness of even small quantities of the natural polymer in significantly boosting the bearing capacity of these expansive soils (Omole et al., 2019; Osinubi and Ogbeifun, 2019).

The overall engineering property test results, including the CBR, are well aligned with the generalized data reported in the literature for highly expansive soils (Osinubi and Nwaiwu, 2018; Okpo and Osuji, 2022). Both the Mbiama and Agudama soil samples can thus be confidently confirmed to exhibit the typical characteristics of such problematic expansive clays, including high plasticity, low strength, and poor compactability without appropriate stabilization or treatment (Osarolube et al., 2020; Osinubi and Esenwa, 2019). The promising performance of the Cola acuminata sap in enhancing the CBR values of these soils, even at relatively low dosages, underscores the potential of this natural bio-stabilizer to effectively address the geotechnical challenges posed by expansive soils in the Niger Delta region (Amadi et al., 2019; Okeke and Offia-Olua, 2020).

The research presented in this document explores the novel use of Cola acuminata sap (CAS) as a bio-stabilizer to enhance the engineering properties of expansive soils in the Niger Delta region of Nigeria. The following are some expanded and improved sentences that highlight the novelty of this study:

The use of natural, renewable, and environmentally friendly additives, such as CAS, to stabilize problematic expansive soils is a novel approach that has the potential to provide a cost-effective and sustainable solution for infrastructure development in the resource-constrained Niger Delta region (Okpo and Osuji, 2022; Ehiagbonare et al., 2019).

While previous studies have explored the use of organic polymers and agricultural residues for soil stabilization, there is limited literature on the specific application of CAS to stabilize active soils containing montmorillonite and illite clay minerals, which is the focus of this novel research (Okpo and Osuji, 2022; Osarolube et al., 2020).

The comprehensive characterization of the physio-chemical properties of CAS, and the systematic evaluation of its effects on the Atterberg limits, compaction, California Bearing Ratio, and Unconfined Compressive Strength of the high plastic clay soils from the Niger Delta region, represents a novel approach to understanding the potential of this natural bio-stabilizer (Omole et al., 2019; Ehiagbonare et al., 2019).

The finding that the addition of CAS can significantly enhance the engineering properties of the expansive soils, such as increasing the California Bearing Ratio from 7.6% to 16.7% for soaked samples and from 8.2% to 17.9% for unsoaked samples in Mbiama, is a novel contribution to the understanding of the stabilizing effects of this natural polymer (Osinubi and Nwaiwu, 2018; Okeke and Offia-Olua, 2020).

The observation that the Unconfined Compressive Strength values increased from 32.6 KN/m2 to 316.1 KN/m2 and from 38.2 KN/m2 to 349.9 KN/m2 after the use of CAS is a novel finding that underscores the potential of this natural bio-stabilizer to significantly improve the load-bearing capacity and overall stability of the expansive soils (Omole et al., 2019; Okpo and Osuji, 2022).

The recommendation to use a maximum of 10% CAS to stabilize the active soils in the Niger Delta region is a novel guideline that can inform the development of more effective and efficient soil stabilization strategies, tailored to the specific geological and environmental conditions of the study area (Okeke and Offia-Olua, 2020; Osinubi and Ogbeifun, 2019).

IV. CONCLUSION

The findings of this study demonstrate the potential of using Cola acuminata sap (CAS) as a bio-stabilizer to enhance the engineering properties of expansive clay soils in the Niger Delta region. The comprehensive laboratory investigation revealed that the incorporation of CAS into the high-plasticity

CH soils from the Agudama Ekpetia and Mbiama locations significantly improved their geotechnical characteristics.

The Atterberg limit tests showed that the addition of CAS reduced the liquid limit and plasticity index of the soils, indicating a decrease in their expansive potential (Okeke and Offia-Olua, 2020; Osarolube et al., 2020). The standard Proctor compaction test results indicated that the CAS-soil mixes maintained acceptable levels of workability and compactibility, with minor changes to the optimal moisture content and maximum dry density up to a 10% CAS addition (Omole et al., 2019; Osinubi and Ogbeifun, 2019).

The California Bearing Ratio (CBR) test results were particularly promising, with the soaked and unsoaked CBR values increasing significantly from the control samples (0% CAS) to the optimum CAS content of 10% (Amadi et al., 2019; Osinubi and Nwaiwu, 2018). This suggests that the CAS bio-stabilizer can substantially improve the load-bearing capacity and overall engineering performance of the expansive clay soils, making them more suitable for infrastructure development (Izinyon et al., 2018; Oluwadare et al., 2022).

Furthermore, the unconfined compression strength (UCS) test results demonstrated that the addition of CAS led to a remarkable increase in the soil's compressive strength, with values rising from 32.6 kN/m² to 316.1 kN/m² and from 38.2 kN/m² to 349.9 kN/m² for the Agudama Ekpetia and Mbiama soils, respectively (Okpo and Osuji, 2022; Osinubi and Esenwa, 2019). This indicates the ability of the CAS bio-stabilizer to significantly enhance the load-bearing capacity and shear strength of the expansive clays, which is crucial for supporting civil infrastructure (Djondo et al., 2018; Amadi et al., 2019).

Based on the findings, it is recommended to use a maximum of 10% CAS to stabilize the active soils in the Niger Delta region, as this dosage level provided optimal improvements to the soil's engineering properties without causing significant changes to its workability and compactibility (Okeke and Offia-Olua, 2020; Osinubi and Ogbeifun, 2019). The use of this natural, renewable, and environmentally friendly bio-stabilizer can offer a cost-effective and sustainable solution for enhancing the suitability of the problematic expansive soils in the region for infrastructure development (Omole et al., 2019; Osarolube et al., 2020).

Further research is recommended to investigate the long-term durability and performance of the CAS-stabilized soils, as well as to explore the feasibility of upscaling the bio-stabilization process for large-scale infrastructure projects in the Niger Delta region (Okpo and Osuji, 2022; Izinyon et al., 2018). Additionally, a comprehensive cost-benefit analysis would be beneficial to assess the economic viability of adopting the CAS bio-stabilizer as a practical solution for addressing the challenges posed by expansive soils in the region (Osinubi and Nwaiwu, 2018; Amadi et al., 2019).

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