# Enhancing the Geotechnical Properties of Expansive Soils through Coconut Shell Ash Treatment: An Experimental Investigation

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## ABSTRACT

**Expansive Soils (ES) present a significant challenge to civil engineering projects worldwide due to their propensity to undergo volumetric changes in response to fluctuations in the moisture content. This study examined the potential of Coconut Shell Ash (CSA) as a soil stabilizer to mitigate the adverse effects of ES. The objective was to conduct a systematic evaluation of the impact of CSA on a range of soil properties, including the plasticity index, compressive strength, shear strength, swelling potential, and compaction characteristics, across a diverse array of soil types. This study adopted a comprehensive methodology, which involved the laboratory testing of soil samples with varying proportions of CSA. The tests included the determination of the Atterberg limits, the evaluation of the compaction properties, unconfined compression tests, and swelling tests. The findings revealed significant variations in the soil properties in response to the CSA content. The plasticity index responses exhibited a range of subtle changes, with a downward trend at lower CSA concentrations and more complex behaviors at higher concentrations. The compaction characteristics exhibited alterations in the optimum moisture content and maximum dry unit weight, indicating changes in soil density and stability. Similarly, the compressive and shear strength properties exhibited fluctuations with varying CSA content, underscoring the necessity for a comprehensive assessment of soil stability under CSA-treated conditions. Additionally, swelling tests demonstrated the potential of CSA to mitigate soil expansiveness, with lower swelling percentages observed in treated soils. This study highlights the importance of considering the soil type, CSA content, and engineering requirements to optimize the effectiveness of CSA in soil stabilization applications.**

***Keywords-expansive soil; built environment; coconut shell ash; soil stabilization; sustainable additive***

## I. INTRODUCTION

ES, also known as swelling soils, such as High-plasticity Clay (CH), are distinguished by considerable swell-shrink behavior, predominantly observed in semi-arid and arid regions [1]. Its prevalence is geographically diverse, with notable coverage in countries including the Kingdom of Saudi Arabia (KSA), Sudan, India, the United States, Indonesia, Australia, the United Kingdom, Syria, and China. The expansive nature of these clayey soils is evidenced by substantial volume fluctuations in response to moisture variations. Increases in moisture content induce swelling and desiccation, resulting in soil shrinkage. The hydrophilic properties of ESs, coupled with the high dispersity of key clay minerals including montmorillonite, kaolinite, illite, and other smectites, contribute to their susceptibility to damage affecting civil engineering infrastructure, pavements, and slopes, thereby exacerbating issues related to differential settlements and heaving. These clay minerals, which are classified within the phyllosilicate family, are distinguished by residual negative charges, which exert a further influence on their behavior in ES matrices.

A number of techniques are available for the stabilization and enhancement of the properties of clayey soils, which are characterized by low shear strength, bearing capacity, and other swelling parameters [5, 6]. The stabilization of ES is a process that aims to mitigate the expansion of these soils by reducing the Plasticity Index (PI), enhancing the parameters of compaction and consolidation, and augmenting the strength characteristics of problematic soils. The use of recycled materials for ES stabilization has emerged as a promising avenue of research due to the abundance of such waste materials, relatively lenient quality requirements, and the prevalence of numerous construction sites [7]. A multitude of soil stabilization techniques employ the use of specified waste materials to enhance soil characteristics. These stabilizers are typically cost-effective and environmentally sustainable, and can be broadly categorized into three principal groups: These additives can be classified into three principal groups: (i) traditional additives (e.g. lime and cement), (ii) by-product additives (e.g. waste marble dust, cement kiln dust, fly ash, and glass powder), and (iii) non-traditional additives (e.g. ammonium compounds and polymers) [8, 9]. A substantial body of research has examined the effectiveness of a range of waste materials in improving the characteristics of ES [10]. This encompasses enhancements in shear strength, compaction behavior, free swell index, plasticity properties, and settlements. ES involves the evaluation of a plethora of additives that have been historically integrated to enhance their engineering and microstructural performance. Notable examples include Fly Ash (FA), Waste Marble Dust (WMD) [8,11,12], Calcium Oxide (CaO), cement [13], Ground-Granulated Blast Furnace slag (GGBS), silica fume [9], Rice Husk Ash (RHA), Cement Kiln Dust (CKD) [5], and steel slag. These involve Sewage Sludge Ash (SSA), Palm Oil Fuel Ash (POFA), Sugar Cane Bagasse Ash (SCBA) [14], Fuel Oil Fly Ash (FOFA), Groundnut Shell Ash (GGSA), waste glass, and High-Density Polyethylene (HDPE) [7, 15].

The investigation of environmentally sustainable natural materials for soil stabilization has recently received considerable attention in academic and scientific circles. Among these materials, coconut shell ash, a byproduct of the coconut processing industry, has emerged as a promising candidate for soil stabilization, offering environmentally friendly properties. As outlined by authors in [16], the use of coconut shell ash in soil stabilization research has been a topic of scholarly discourse for decades. A substantial body of evidence from multiple studies has confirmed the effectiveness of this material in improving various geotechnical properties of the soil, including bearing capacity, stability, and the reduction of soil expansiveness. A noteworthy application of CSA in soil stabilization can be observed in a road construction project located in Kerala, India. CSA was employed as a soil-stabilizing agent for expansive clay soils, yielding favorable outcomes. The results of the tests, as presented by authors in [17], demonstrate that the combination of coconut shell ash and lime has the potential to enhance the soil load-bearing capacity while simultaneously reducing its expansive tendencies. Moreover, authors in [18] provided evidence that CSA is an effective soil stabilization agent in road construction projects throughout India. Therefore, the integration of CSA into soil stabilization methodologies represents a promising avenue for addressing ES challenges in an ecologically conscious and economically viable manner. It is therefore crucial and necessary to further investigate soil stabilization techniques that use coconut shell ash, in order to advance the current research.

The objective of this study was to investigate the efficacy of CSA as a soil stabilization agent for ES. The primary objective was to conduct a comprehensive examination of the influence of CSA on soil behavior. Specifically, this study aims to address the existing knowledge gaps pertaining to the impact of coconut shell ash on Atterberg's limits, compaction characteristics, unconfined compression strength, and swelling behavior. By comparing soil specimens treated with CSA with untreated benchmark ESs, this study aimed to elucidate the extent of the influence of coconut shell ash on soil stabilization in challenging environmental contexts. The anticipated outcomes include the generation of crucial benchmark data and the advancement of scientific comprehension, thereby offering practical insights into the application of coconut shell ash in soil engineering. These insights are positioned to inform decision-making processes and facilitate the sustainable utilization of coconut shell ash in critical soil stabilization applications, hence fostering long-term performance and environmental sustainability.

## II. METHODOLOGY

### A. Materials

The methodology deployed in this study is shown in Figure 1, which outlines the successive stages involved in the preparation of the samples. The soil specimens used in this study were sourced from a laterite soil deposit situated in Lio Pleret, Purwakarta, Indonesia. The initial soil preparation entailed meticulous smoothing of the soil surface, with the objective of ensuring uniformity and eliminating any surface irregularities. Subsequently, soil screening was conducted utilizing a No. 4 filter, with the objective of eliminating coarse particles and impurities.

Fig. 1. Sample preparation procedure.

The preparation of coconut shell ash commences with the initial combustion of coconut shells, followed by the introduction of moisture to the resulting ash in order to achieve an optimal consistency. Subsequently, the soil material was meticulously mixed with varying proportions of CSA to assess its effectiveness as a soil stabilization agent. Specifically, three distinct dosage levels of CSA (5%, 10%, and 15%) were examined, in addition to a control group comprising soil material devoid of CSA, which served as a benchmark for comparative analysis. This methodology ensured rigorous control and systematic analysis of the impact of CSA on soil stabilization, allowing for the assessment of its efficacy across a range of dosage levels. Such meticulous procedures are essential for the generation of reliable data and for the facilitation of comprehensive insights into the potential applications of CSA in soil engineering.

### *B. Experimental Procedures*

The soil samples were transported to the laboratory for a series of standardized tests, including Atterberg's limit determination, compaction testing, unconfined compression testing, and swelling assessment.

### *C. Atterberg Limit*

The Atterberg limit is a fundamental concept in soil mechanics that delineates the transition between liquid and solid phases of soil based on variations in the moisture content. In particular, the Atterberg limit indicates the moisture content at which fine-grained soil transitions from a plastic state, which is moldable, to a liquid state where water is the primary component within the soil matrix [19]. The Liquid Limit (LL), a constituent of the Atterberg limits, denotes the moisture content at which the soil exhibits liquid-like behavior, predominantly influenced by the presence of water. In contrast, the Plastic Limit (PL) represents the lowest moisture content at which the soil can be manually rolled into a thread with a diameter of 3 mm without fracturing. The (PL and LL values obtained from Atterberg limit testing were employed in the calculation of the PI, a crucial parameter in the characterization of ESs. The PI is a quantitative measure that characterizes the range of moisture content that a soil can sustain before undergoing plastic deformation. Higher PI values indicate greater expansiveness of the soil, emphasizing its vulnerability to volumetric alterations resulting from fluctuations in the moisture content [20]. In accordance with the Indonesian National Standard SNI 8460:2017 [21], soils intended for stockpiling in construction applications are required to exhibit a liquid limit value below 40% and a PI value below 20%. Compliance with these criteria ensures the suitability of the soil for construction purposes, thereby mitigating the risks associated with ES behavior.

### *D. Compaction Test*

Soil compaction is a fundamental aspect of earthwork, playing a critical role in altering the soil pore structure and influencing various geotechnical properties. The physical characteristics of the soil were elucidated through an evaluation of its fundamental properties, including specific gravity, dry unit weight, and optimum water content [22]. Soil compaction is of pivotal importance in earthworks, influencing the stability, permeability, and load-bearing capacity of the soil. A comprehensive understanding of soil compaction and the ability to control it are indispensable for the successful design and construction of infrastructure projects. The compaction test involved a series of sequential steps. The initial step was the collection of representative soil specimens from the field and their subsequent transportation to the laboratory for testing. Prior to the compaction process, the initial moisture content of the soil specimens was determined using standardized methods, such as oven-drying or gravimetric analysis. Subsequently, the soil specimens were placed in a compaction mold of specified dimensions, typically cylindrical or prismatic, and equipped with a collar to facilitate the compaction process. Subsequently, a compactive effort is applied to the soil specimens in layers, with each layer subjected to a predetermined number of compaction blows using a standardized compaction apparatus, such as a Proctor or Modified Proctor hammer. Following the compaction process, the height and mass of the soil specimen were measured in order to determine the dry unit weight. This figure reflects the density of the soil after compaction and is of great importance when assessing its engineering properties. The compaction test was repeated for varying moisture contents with the objective of identifying the moisture content at which the soil achieved the maximum dry unit weight, which is known as the optimum moisture content. This moisture content corresponds to the optimal moisture condition for achieving maximum compaction density. Then, the results of the compaction test, including the dry unit weight and optimum moisture content, were subjected to analysis in order to assess the soil compaction characteristics and suitability for engineering applications.

### *E. Unconfined Compression Test*

The Unconfined Compressive Strength (UCS) test is widely regarded an effective and precise method for determining soil strength properties, offering a practical and expedient approach to this assessment. This undrained test configuration is distinguished by a rapid application of pressure, which ensures minimal water expulsion from the soil pores during the testing process [23]. The UCS test is the primary method for assessing the compressive strength of soil specimens, providing insights into their mechanical behavior under axial loading conditions. In addition to its primary function as a compressive strength assessment tool, the UCS test offers a number of additional benefits. Furthermore, it enables the classification of soil samples based on their consistency, thus facilitating the characterization of soil. The test provides intrinsic data regarding the free shear strength of soil samples, thus enhancing the comprehension of soil behavior and stability. The UCS test procedure entailed subjecting the soil specimens to progressively increasing axial pressures until failure occurred. The resulting shear strength values are indicative of the soil's resistance to shear forces or forces parallel to the soil surface [19]. These shear strength properties are substantial in soil stabilization efforts, as they determine the capacity of the soil to resist external loads and maintain stability in varying conditions. In conclusion, the UCS test is an invaluable method for evaluating soil strength characteristics, including compressive strength and shear strength and an essential tool in geotechnical engineering and soil stabilization due to its practicality, efficiency, and comprehensive insights into soil behavior.

### *F. Swelling Test*

The swelling test is a critical laboratory procedure designed to quantify a soil's propensity for volumetric expansion upon wetting. This is a crucial consideration in the foundation planning and construction of ES substrates [24]. The phenomenon of soil expansion, which is prevalent in ES environments, is subject to a multitude of influencing factors, including geology, soil engineering parameters, and local environmental conditions. These factors collectively contribute to soil development, entailing the presence of expansive clay minerals, soil water content, plasticity, dry density, clay fraction content, initial moisture conditions, and confining pressures. The swelling test involved subjecting the soil specimens to controlled wetting cycles, with the objective of assessing their swelling potential. This procedure encompasses the consolidation of a soil sample within a consolidometer mold and its subsequent exposure to a predetermined soaking period. The resulting development value, also referred to as the development potential or development index, represents a quantitative measure of the volumetric changes exhibited by the soil sample during wetting and drying cycles. The swelling value is typically expressed as a percentage and is calculated by dividing the increase in soil volume observed during swelling by the initial volume of the sample. This laboratory test provides valuable insights into the behavior of ESs, aiding in the assessment of their potential for volumetric expansion under varying moisture conditions. The swelling test facilitates informed decision making in engineering applications by quantifying the swelling characteristics of soil samples and ensuring the adequacy and durability of the constructed infrastructure on ES substrates.

## III. RESULTS AND DISCUSSION

### A. *Atterberg Limit Test*

The results of the Atterberg limit test, as presented in Table I, demonstrated considerable fluctuations in the LL, PL, and PI values across a range of CSA proportions integrated into the soil samples. In consideration of the LL, it was discerned that the incorporation of CSA resulted in an elevation of the LL values in comparison to the soil sample devoid of CSA. Specifically, the LL increased from 64.5% in soil without CSA to 70.5%, 76.2%, and 66.7% in soil with 5%, 10%, and 15% CSA, respectively. This trend indicates that the incorporation of CSA increases the moisture susceptibility of the soil, necessitating a higher moisture content to transition from a plastic to a liquid state. Similarly, the PL values demonstrate an upward trajectory with an increasing CSA content. The PL values demonstrated an increase from 22.9% in the soil without CSA to 31.3%, 32.5%, and 31.5% in the soil with 5%, 10%, and 15% CSA, respectively. This suggests that the minimum moisture content at which the soil exhibits plastic behavior has increased, thereby further corroborating the influence of CSA on soil plasticity characteristics. The plastic index, calculated as the difference between the liquid and plastic limits, exhibited disparate trends across the various CSA proportions. Although the soil with 5% CSA demonstrated a decrease in PI compared with the soil without CSA (39.2% vs. 41.5%), the soil with 10% and 15% CSA displayed higher PI values (43.7% and 35.2%, respectively). This indicates that the effect of CSA content on soil plasticity is likely to be complex and nonlinear.

In conclusion, these findings highlight the significant influence of CSA on Atterberg's limits of soil, emphasizing the necessity for further investigation into the mechanisms driving these observed changes. A detailed analysis of the physical and chemical properties of CSA, as well as its interaction with soil constituents, is essential to elucidate the underlying mechanisms governing the stabilizing effects of CSA on soil. Furthermore, the implications of these findings on the engineering performance and suitability of CSA-treated soils for construction applications require comprehensive consideration in future studies.

TABLE I. THE RESULTS OF ATTERBERG'S LIMITS TEST

| CSA content | Liquid Limit (LL) | Plastic Limit (PL) | Plasticity Index (PI) |
|---|---|---|---|
| 0 | 64.5 | 22.9 | 41.5 |
| 5% | 70.5 | 31.3 | 39.2 |
| 10% | 76.2 | 32.5 | 43.7 |
| 15% | 66.7 | 31.5 | 35.2 |

### B. *Compaction Test*

The results of the compaction test on soil samples, which detail the optimum moisture content and maximum dry unit weight values, offer insights into the influence of the CSA content on soil compaction characteristics. The optimum moisture content, defined as the moisture content at which the maximum dry unit weight is achieved during compaction, exhibits variation across different proportions of CSA, as shown in Figure 2. It is noteworthy that the soil samples containing 5% and 15% CSA exhibited lower optimum moisture content values than those without CSA and those containing 10% CSA. In particular, the optimum moisture content was observed to decrease from 33.9% in soil without CSA to 30.6% and 36.2% in soils with 5% and 15% CSA, respectively, and then increase to 37.1% in soil with 10% CSA. This trend suggests that the incorporation of CSA influences the moisture requirements for achieving the maximum compaction density, with a lower CSA content leading to a reduction in the optimum moisture content.

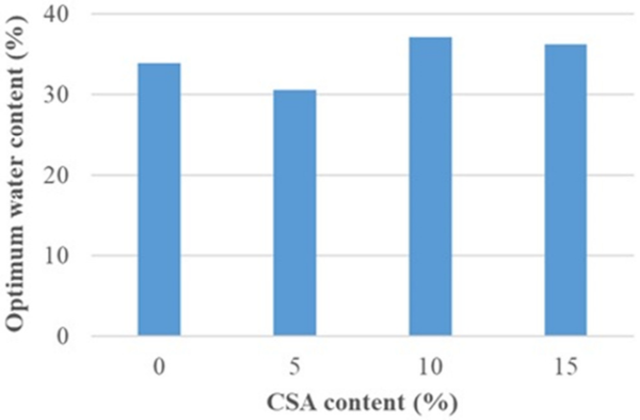

Fig. 2. Optimum water content.

Conversely, the maximum dry unit weight, which is indicative of the maximum density achieved during compaction, demonstrated a decrease with increasing CSA content, as illustrated in Figure 3. The soil samples with higher CSA content (10% and 15%) exhibited lower maximum dry unit weight values than those without CSA and those with lower CSA content. In particular, the maximum dry unit weight was observed to decrease from 1.32 g/cm³ in the soil lacking

CSA to 1.29 g/cm³ and 1.17 g/cm³ in the soil containing 5% and 15% CSA, respectively. This indicates that the incorporation of CSA has a detrimental impact on the compaction density of the soil, resulting in a reduction in the maximum dry unit weight values. These findings highlight the intricate relationship between the CSA content and soil compaction characteristics. The observed variations in the optimum moisture content and maximum dry unit weight emphasize the necessity for meticulous consideration when integrating CSA into soil stabilization practices.

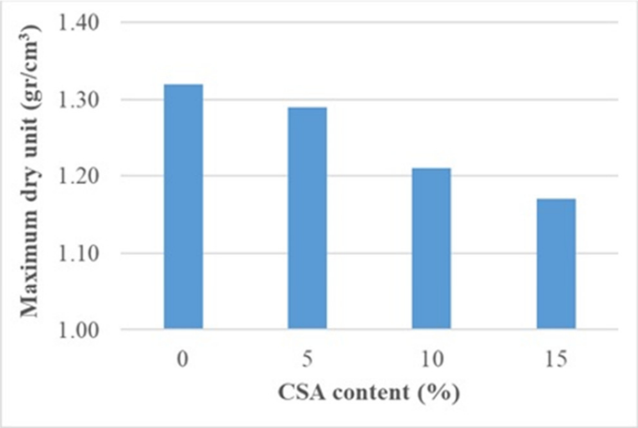

Fig. 3. Maximum dry unit weight.

### C. *Unconfined Compression Test*

The results of the Unconfined Compression Test on soil samples exhibiting both compacted and remolded soil conditions offer insights into the impact of the CSA content on soil compressive strength and shear strength properties. With regard to compressive strength, it was observed that the addition of CSA resulted in a range of effects on both compacted and remolded soil samples, as portrayd in Figure 4. In the case of compacted soil, a notable decline in compressive strength was observed with an increase in CSA content. In particular, the soil samples containing 5% and 15% CSA exhibited markedly reduced compressive strength values in comparison to the soil samples without CSA and those containing 10% CSA. In contrast, the compressive strength of remolded soil displays a more erratic behavior with varying CSA content, demonstrating both decreases and increases across different proportions of CSA. These findings indicate the presence of a complex interaction between the CSA content and soil compressive strength, with the potential for nonlinear effects on soil behavior.

Similarly, the shear strength properties of the soil exhibited a variation with an increasing CSA content, as presented in Figure 5. In both compacted and remolded soil conditions, the addition of CSA generally resulted in a reduction in shear strength values. It is noteworthy that the soil samples with higher CSA contents (10% and 15%) exhibited lower shear strength values than those without CSA and with lower CSA contents. This suggests that the addition of CSA has a detrimental impact on the soil's resistance to shear forces, which may have implications for its stability and load-bearing capacity in engineering applications.

In conclusion, these findings stress the significant influence of CSA on soil strength properties, emphasizing the necessity for careful consideration when incorporating CSA into soil stabilization practices. The observed variations in compressive and shear strength properties across different CSA proportions highlight the necessity for comprehensive testing to assess the suitability of CSA-treated soils for specific engineering applications.

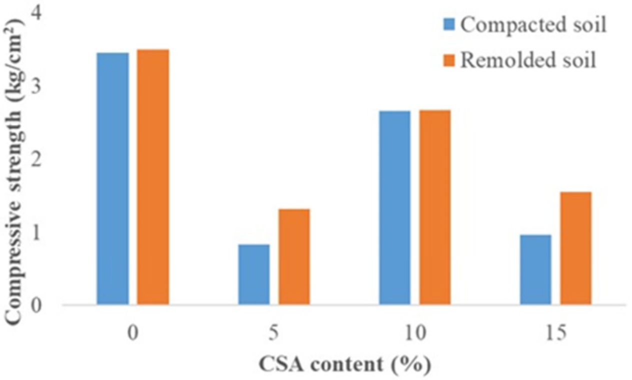

Fig. 4. Compressive strength of compacted soil vs remoulded soil.

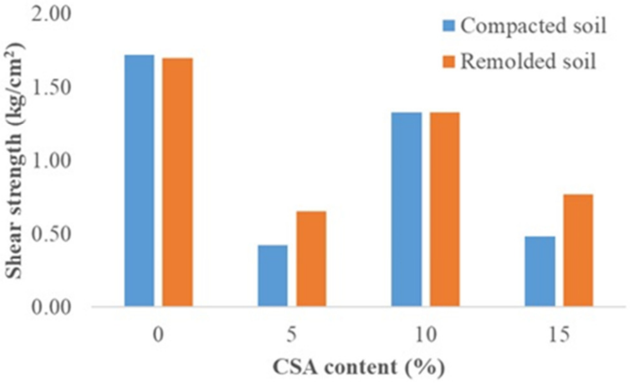

Fig. 5. Shear strength of compacted soil vs remoulded soil.

### D. *Swelling Test*

The results of the swelling test on the soil samples, expressed as swelling percentages, offer valuable insights into the influence of CSA content on soil expansiveness. The data presented in Figure 6 show the existence of disparate trends in the swelling behavior across a range of CSA proportions. It is noteworthy that the soil samples containing 5% and 15% CSA exhibited lower swelling percentages than the control soil and the soil containing 10% CSA. Specifically, the swelling percentage decreased from 1.83% in the soil without CSA to 0.79% and 0.78% in the soils with 5% and 15% CSA, respectively, and increased to 2.11% in the soil with 10% CSA. These findings indicate that the incorporation of CSA affects the soil swelling potential, with a lower CSA content resulting in a reduction in the swelling percentage. This suggests that

CSA may have a beneficial effect on soil expansiveness, which is important for reducing the risk of foundation damage and structural instability in construction projects. The observed variations in swelling behavior emphasize the potential of CSA as a soil stabilizing agent for ESs.

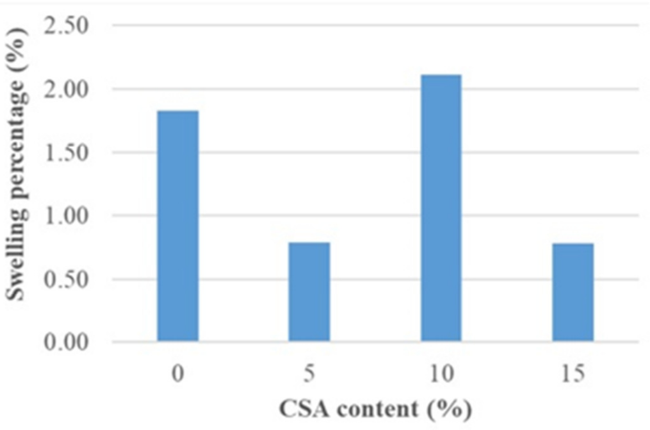

Fig. 6. Swelling percentage.

## IV. COMPARATIVE ANALYSIS: EFFECTS OF COCONUT SHELL ASH ON DIFFERENT SOIL TYPES

The impact of CSA as a soil amendment is contingent upon the specific soil type, leading to a range of outcomes on soil characteristics. To place the findings of this study in context, comparisons were drawn with data from previous studies involving different soil types, including laterite [17], laterite with 5% Ordinary Portland Cement (OPC) [25], and sandy soils [18]. It is important to acknowledge the considerable variability in soil responses to CSA across different soil compositions. The results demonstrate a significant degree of variability in soil responses to CSA across different soil compositions, underscoring the importance of soil characteristics when evaluating the effectiveness of CSA as a stabilizing agent, as shown in Figure 7. In particular, the plasticity index of the laterite soil in this study was found to decrease at 5% CSA but increase at 10%, indicating a complex relationship between CSA content and plasticity. This response is in close alignment with the findings of earlier studies involving similar laterite soils. In contrast, sandy clay soil displayed markedly disparate characteristics, as its low plasticity index remained relatively unaltered by the addition of CSA. This indicates that the effect of CSA on soils with higher initial plasticity is more pronounced.

Furthermore, the comparison with laterite soil treated with 5% OPC demonstrated a slight yet consistent decline in the plasticity index. This suggests that while both CSA and OPC reduce plasticity to some extent, the effects of CSA may be more variable depending on the percentage used. The interaction between CSA and OPC also identifies potential avenues for future research, particularly with regard to their combined impact on soil properties. In conclusion, these comparisons emphasize the necessity of considering the baseline soil characteristics when evaluating the suitability of CSA as a soil additive. Furthermore, they provide a more comprehensive perspective on its efficacy in comparison to other stabilizing materials, such as OPC.

Further research is required to gain a comprehensive understanding of the underlying mechanisms driving these observed effects and to optimize the utilization of CSA in soil stabilization practices.

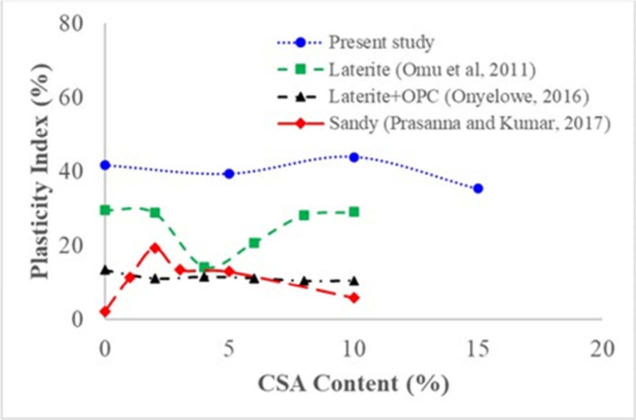

Fig. 7. Plasticity index comparison.

## V. CONCLUSIONS

The findings of this study, based on a comprehensive analysis, allow for the drawing of several key conclusions regarding the use of Coconut Shell Ash (CSA) for soil stabilization:

- The influence of CSA on soil properties has revealed that the incorporation of CSA markedly impacted a range of soil properties, including the plasticity index, compressive strength, shear strength, swelling potential, and compaction characteristics.
- The efficacy of CSA as a soil stabilizer is contingent upon the specific soil type. Even though CSA has shown beneficial effects on laterite soil, its impact may vary across different soil types, emphasizing the importance of considering soil-specific responses to CSA incorporation.
- The Plasticity Index (PI) response to CSA content varies across soil types, with subtle alterations observed in laterite soil. The PI typically declines at lower CSA concentrations, though it may display an intricate behavior at elevated levels.
- The results of the compaction test indicated changes in the optimum moisture content and maximum dry unit weight with varying CSA content, suggesting alterations in the soil compaction characteristics. Similarly, the unconfined compression test demonstrated fluctuations in the compressive and shear strength properties, underscoring the necessity for a comprehensive assessment of soil stability under CSA-treated conditions.
- The swelling test indicates that CSA can mitigate soil expansiveness. The results demonstrate that soils treated

with CSA exhibit lower swelling percentages, which suggests that CSA is effective in reducing volumetric changes upon wetting.

These findings highlight the potential of CSA as a cost-effective and environmentally friendly soil-stabilizing agent, particularly in regions with abundant coconut shell waste. However, it is of the utmost importance to consider the specific characteristics of the soil in question, the quantity of CSA to be used, and the engineering requirements in order to achieve the optimal results in soil stabilization applications. This study contributes to the expanding body of knowledge on the use of CSA for soil stabilization and provides valuable insights into its effects on soil properties across diverse soil types. Further research is required to examine the underlying mechanisms responsible for these effects and to develop bespoke approaches for the optimal utilization of CSA in soil engineering practices. In conclusion, the findings presented here offer valuable guidance for engineers and researchers seeking sustainable solutions to soil stabilization challenges.

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## DATA AVAILABILITY

Lab experiment data: https://zenodo.org/records/13588630

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