

Effects of Bamboo Leaf Ash on the Residual Strength of Extremely High Plasticity Soils

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ABSTRACT

Soils with Extremely High Plasticity (EHP) are improper for structural applications due to their low shear strength and high compressibility. Therefore, the development of soil stabilizers has become a primary focus in the efforts to enhance the engineering properties of soil, thus making it suitable for construction. Recent advancements in sustainable engineering have drawn attention to using environmentally friendly stabilizers. Bamboo Leaf Ash (BLA), obtained from abundant bamboo resources, offers a great potential for soil stabilization. With silica content up to 70% as one of its main chemical components, BLA has significant potential as a pozzolanic material for soil improvement. In this study, the residual shear strength of cohesive soil under drained conditions is measured and the optimal BLA mixture variation for improving soil stability is determined. Bentonite was used as the soil sample, and the residual shear strength was evaluated utilizing a ring shear test under drained conditions. Torque was applied to the remolded specimen to generate a shear plane until a constant shear strain was achieved, representing the residual shear strength. The results revealed that the optimal variation for enhancing residual shear strength is achieved at a 5% BLA mixture, where a balance is found between plasticity reduction and soil stability improvement. The experiment results also demonstrate that BLAs can significantly enhance the engineering properties of bentonite by reducing the Plasticity Index (PI) and increasing both peak and residual shear strength.

Keywords: peak strength; residual strength; deformation; stress; bamboo leaf ash

I. INTRODUCTION

EHP soils are, often characterized by their ability to deform due to changes in water content, thus they present unique challenges in both agriculture and civil engineering. These soils primarily consist of expansive clay minerals, such as montmorillonite, which exhibit drastic swelling and shrinking behavior depending on their moisture content. The PI, which

measures the range of water content in which the soil remains in a plastic state, is a crucial parameter in understanding the behavior of high plasticity soils. Studies have shown that expansive soils can have a PI greater than 35, indicating their high susceptibility to volume changes due to moisture fluctuations [1, 2]. The high plasticity behavior is largely influenced by the water content and mineral composition of the

soil. The critical role of minerals, particularly montmorillonite, in expansive and shrinkage behaviors of clays, has been studied in [3, 4]. Furthermore, essential theories link the low cohesion and high internal friction angles of soft clays to their instability under horizontal stresses [5].

In [6, 7], PI values ranging from 14.11% to as high as 121% for different clay deposits are reported, reflecting a wide spectrum from medium to very high plasticity. Such soils also exhibit high liquid limits, which are directly associated with increased compressibility and a significant tendency to swell or shrink with changes in moisture content [8]. These conditions make EHP soils particularly problematic for construction and infrastructure development, necessitating sustainable and effective soil improvement methods.

The behavior of EHP soils is also influenced by particle size distribution. Soils with a higher proportion of fine particles, particularly those classified as silty clay tend to exhibit greater plasticity and lower bearing capacity [9]. Additionally, the presence of expansive clay minerals, such as montmorillonite, exacerbates the swelling and shrinkage characteristics of these soils, making them particularly problematic for construction and engineering applications [10, 11].

EHP soils are generally considered unsuitable for structural applications due to their low shear strength and high compressibility. Because of the variation in moisture, these soils can experience significant volume changes, which can compromise structural stability [12]. In civil engineering applications, managing EHP soils is critical for construction and infrastructure projects. This type of soil can cause structural issues due to its tendency to expand when wet and shrink when dry, potentially leading to cracks and instability in foundations and roads [13, 14]. Stabilization techniques, such as adding fly ash or other industrial by-products, have been explored to mitigate these negative effects and enhance the mechanical properties of EHP soil [14, 15]. The effectiveness of these stabilization methods often depends on the specific characteristics of the soil, including its PI and moisture content [2, 16, 17]. These techniques aim to reduce plasticity, enhance shear strength, and improve load-bearing capacity, addressing the challenges posed by these problematic soils.

Therefore, the urgent need for innovative stabilization techniques to address the inherent weaknesses of EHP soils is being highlighted. Recent advancements in sustainable engineering are highly focused on the use of eco-friendly stabilizers for soil improvements. BLA derived from abundant bamboo resources, offers a promising alternative due to its high silica content, which can reach up to 70%, as reported in [17]. As an effective pozzolanic material, BLA has been studied in Nigeria, to reduce soil plasticity and enhance shear strength, making it a cost-effective and environmentally responsible solution for stabilizing high-plasticity soils [18, 19]. The current study evaluates the effectiveness of BLA for residual strength enhancement of bentonite.

The effect of BLA on the increasing residual strength in EHP soil is examined. The BLA was derived from a mixture of three local bamboo species in Indonesia, namely Mayan

bamboo (*Gigantochloa robusta*), Kuning bamboo (*Bambusa vulgaris*), and Sembilang bamboo (*Gigantochloa apus*), all of which are rich in silica and mineral oxides. After preliminary evaluation, the bamboo species with the optimal combustion efficiency and ash yield was selected. This selection ensured ash production with superior mineral content and physical properties that enhance soil quality while supporting the efficient and sustainable use of local resources. The objective of this study is to determine the optimal proportion of BLA content for improving the residual strength of bentonite and to analyze its behavior in this condition.

II. MATERIALS AND METHODS

A. Materials

The primary materials used are bentonite and BLA. Bentonite, which is high plasticity clay, was chosen for its low shear strength and susceptibility to deformation under stress. The BLA was obtained by burning locally sourced bamboo leaves to ash. To ensure quality, the bamboo leaves were dried and cleaned from contaminants, such as soil and wood debris before burning. The resulting ash was processed to maximize its silica (SiO_2) content, an essential component for its pozzolanic properties, contributing to enhanced soil stabilization.

B. Sample Preparation

BLA preparation followed a systematic procedure. First, dried bamboo leaves were collected and carefully inspected to ensure that they were free of contaminants, such as soil or debris. The leaves were further sun-dried to minimize their moisture content, as illustrated in Figure 1(a). Subsequently, they were combusted in a laboratory furnace at 600°C for two hours. After combustion, the resulting ash was cooled naturally to a room temperature 25°C , as portrayed in Figure 1(b). The cooled ash was then sieved through a 0.149 mm sieve to obtain fine particles, as shown in Figure 1(c). To maintain its quality and prevent contamination or moisture absorption, the sieved BLA was stored in an airtight container.

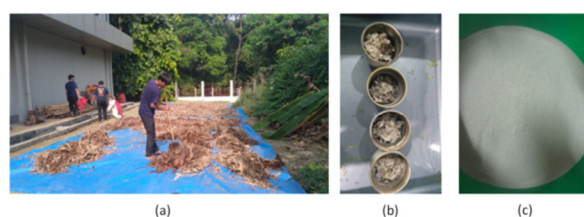


Fig. 1. BLA preparation stages.

C. Bamboo Species Selection for BLA Production

The three local bamboo species from West Java, Indonesia, namely Mayan bamboo (*Gigantochloa robusta*), Kuning bamboo (*Bambusa vulgaris*), and Sembilang bamboo (*Gigantochloa apus*), were selected based on their high silica and mineral oxide content. Combustion experiments were carried out at three different temperatures (500°C , 600°C , and 700°C) to evaluate the effect of temperature on the chemical composition of BLA. Table I shows the average chemical composition from these combustion tests. The silica (SiO_2)

content in the resulting ash was then analyzed using the X-Ray Fluorescence (XRF) method to identify the bamboo species and combustion temperature that yielded the most optimal silica content.

TABLE I. CHEMICAL COMPOSITION OF BLA

Bamboo	Bambusa vulgaris	Gigantochloa robusta	Gigantochloa apus
Al ₂ O ₃ (%)	0.9280	1.0316	0.6786
SiO ₂ (%)	70.4952	76.7395	68.0876
K ₂ O (%)	12.3781	9.5473	10.6959
CaO (%)	4.8921	3.9570	8.0158
MgO (%)	4.5593	2.8443	3.5685

The chemical composition analysis reveals significant variations among the three bamboo species. *Gigantochloa robusta* exhibited the highest silica (SiO₂) content at 76.74%, followed by *Bambusa vulgaris* at 70.50%, and *Gigantochloa apus* at 68.09%. Other mineral oxides, such as Al₂O₃, K₂O, CaO, and MgO, were also observed in various proportions, potentially influencing ash properties.

D. Chemical Compositions of BLA

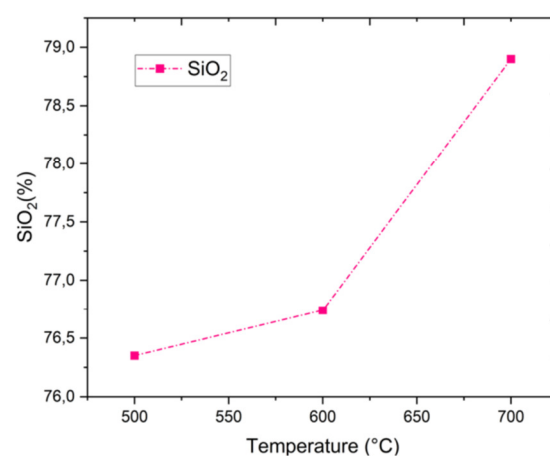
Compared to ordinary combustion methods, the silica content in BLA can be significantly increased through high-temperature combustion (800-1000°C) in a furnace [20]. This kind of combustion has been shown to produce BLA with silica content reaching 75.90% [21]. In the current study, the production of BLA via controlled combustion of bamboo leaves in a laboratory furnace at temperatures of 500°C, 600°C, and 700°C for two hours is investigated. The observations made revealed that optimal ash formation occurs at 600°C, which ensures efficient combustion while preserving pozzolanic properties. Maintaining 600°C allows for a complete combustion of organic matter and preserves the amorphous silica structure, which is necessary for effective pozzolanic reactions. Table II displays the oxide compositions of *Gigantochloa robusta* BLA, highlighting a significant presence of silicon dioxide (SiO₂) content, as determined by the performed analysis.

The results are consistent with those of previous studies that stress the crucial role of combustion temperature in determining the quality of silica-rich ash. Recent studies have indicated silica contents up to 90% when processed under optimal thermal conditions [22, 23]. The effectiveness of BLA as a pozzolanic material is attributed to its ability to react with calcium hydroxide, resulting in the formation of calcium silicate hydrate, which contributes to the mechanical strength of concrete [24].

The results indicate a steady increase in silica content (SiO₂) as the combustion temperature rises, peaking at 79% at 700°C, as can be seen in Figure 2. However, despite this higher silica content, ash produced at 700°C exhibits lower reactivity due to the formation of the cristobalite [25]. This temperature reduces the amorphous silica content that is critical for reactivity, thereby diminishing the effectiveness of the ash for practical applications. In contrast, ash produced at 600°C has a silica content of 77%, which is slightly lower, but remains effective and has high reactivity.

TABLE II. CHEMICAL COMPOSITION OF GIGANTOCHLOA ROBUSTA BLA.

BLA Chemical composition	Temperature (°C)		
	500	600	700
MgO (%)	3.3633	2.8443	2.8000
Al ₂ O ₃ (%)	1.0219	1.0316	1.1000
SiO ₂ (%)	76.3508	76.7395	78.9000
P ₂ O ₅ (%)	2.403	2.5295	2.2000
SO ₃ (%)	2.3245	1.6232	0.6000
Cl (%)	1.3529	1.264	0.7000
K ₂ O (%)	7.5439	9.5473	9.0000
CaO (%)	5.0599	3.957	4.1000
Sc ₂ O ₃ (%)	0.0044	0.0027	0.0000
TiO ₂ (%)	0.0345	0.0254	0.0000
MnO (%)	0.2141	0.1595	0.2000
Fe ₂ O ₃ (%)	0.2458	0.214	0.2000
ZnO (%)	0.0264	0.0266	0.1000

Fig. 2. SiO₂ content in BLA with different combustion temperatures.

Furthermore, combustion at 600°C is significantly more energy-efficient than at 700°C, making it a sustainable choice for large-scale production. Ash produced at 600°C not only provides the highest reactivity, but also avoids the drawbacks of greater loss on ignition and suboptimal performance associated with ash produced at 500°C [26]. These findings exhibit that 600°C provides an optimal balance between energy consumption, reactivity, and silica content, ensuring technical and economic feasibility. The X-ray diffraction (XRD) pattern, as depicted in Figure 3, shows that the material is primarily composed of quartz, as indicated by several sharp peaks labeled "Q". Quartz is the crystalline form of SiO₂, meaning its atoms are arranged in a repeating three-dimensional pattern. The 2θ positions at approximately 20°, 26.6°, 50°, and 60° correspond to the characteristic angles for the quartz crystal structure. It is notable that the peak at 2θ = 26.6° exhibits the highest intensity, signifying the dominant orientation of quartz crystals in the material. This XRD analysis confirms that quartz is the main phase present in the sample, which also displays a well-defined crystalline structure. The prevalence of quartz in this material suggests its suitability for applications that benefit from the mechanical and chemical properties of quartz, particularly in the context of BLA. The incorporation of BLA into materials could enhance their performance due to quartz stability and strength.

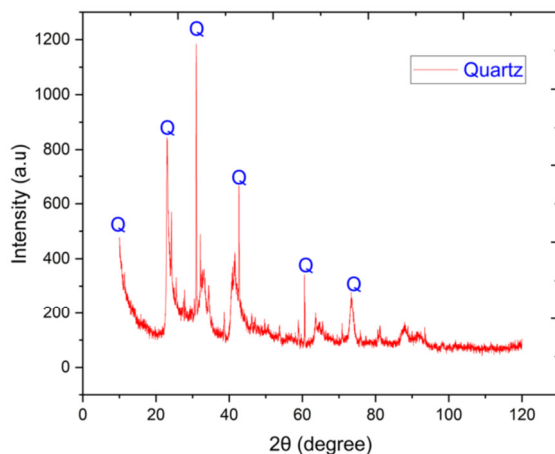


Fig. 3. XRD of BLA.

The soil sample used is bentonite soil, a commercially available material obtained through a thorough preparation process, resulting in a dry powder. It was mixed with BLA in varying proportions of 0%, 5%, 10%, and 20% by dry weight. These mixtures were carefully homogenized to ensure an even distribution of the stabilizing agent throughout the soil, providing consistency for subsequent testing analysis.

E. Experimental Set-Up

The experimental program was prepared to evaluate the impact of BLA on the physical and mechanical properties of bentonite soil. The physical properties were assessed through tests measuring water content, specific gravity, and Atterberg limits, following ASTM standards.

The mechanical properties of the soil-BLA mixtures were analyzed using a Ring Shear Test apparatus, as presented in Figure 4. This device measures both the peak and residual shear strengths of the sample. For this test, cylindrical soil samples were prepared and subjected to incremental shear stresses while maintaining constant normal loads in a controlled environment. The testing apparatus was calibrated to ensure accurate and reliable measurements of the shear strength parameters at various stages of deformation.

The torsional ring shear test measures the residual shear strength of cohesive soils under drained conditions, following ASTM D6467-13 standards. The test primarily uses reconstituted specimens due to the challenges involved in obtaining intact slip surfaces. The procedure entails specimen preparation, including sieving, mixing with distilled water, and rehydration for 24 hours. The specimen is then placed in a ring shear apparatus with water immersion, followed by pre-consolidation, pre-shearing, and shearing at a controlled displacement rate to minimize excess pore water pressure, as evidenced in Figure 5. The test finishes when the shear stress with displacement curve stabilizes, indicating residual strength. The equipment used includes a ring shear testing machine, specimen container, water bath, and a Linear Variable Displacement Transducer (LVDT) for displacement measurement. The collected data are analyzed utilizing shear stress with displacement and normal stress graphs to ensure accurate interpretation and reproducibility.

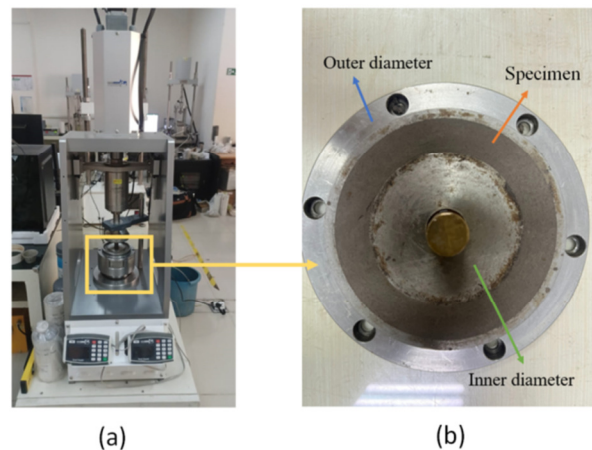


Fig. 4. (a) Ring shear apparatus, (b) sample preparation.

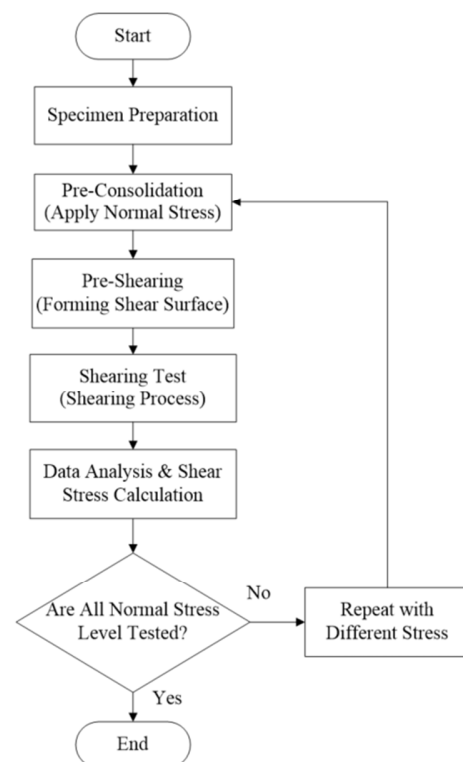


Fig. 5. Flowchart of torsional ring shear test procedure.

III. RESULTS AND DISCUSSION

A. Index Properties of Bentonite

The soil is classified as of high plasticity (CH) according to the Unified Soil Classification System (USCS) and as of EHP (CE) according to The British Standard Soil Classification System. The measurement results, listed in Table III, indicate that the bentonite exhibits exceptionally high plasticity, a characteristic that contributes to its excellent water retention and stability. This makes it highly suitable for applications where water stability is critical. However, its mechanical

stability requires careful evaluation and enhancement to address potential limitations in structural performance.

TABLE III. PROPERTIES OF BENTONITE

Test	Results
Moisture Content	10.60%
PI	455.41%
Liquid Limit (LL)	568.70%
Plastic Limit (PL)	113.29%
Specific Gravity (Gs)	2.79
Optimum Moisture Content (OMC)	62.04%
Maximum Dry Density (MDD)	9.25 kN/m ³
USCS classification	CH

B. Extremely High Plasticity of Bentonite

Bentonite is a type of clay characterized by a high proportion of clay mineral montmorillonite, which imparts it with EHP [27-29]. This property arises from its high LL and PL, as well as its colloidal behavior [30]. The bentonite under study exhibits very high plasticity, as reflected in its LL of 568.70%, as shown in Table III. This indicates an extraordinary capacity to absorb water before transitioning to a liquid state. The PL, measured at 113.29%, represents the moisture content at which the material transitions from a plastic phase to a semi-liquid phase.

The large disparity between LL and PL highlights the substantial flexibility and deformation potential of bentonite. The PI, calculated as the difference between the LL and PL, is 455.41%. This high PI value underscores the material's capacity for significant volume changes in response to variations in moisture content. These characteristics make bentonite promising for applications requiring high water stability. However, its mechanical stability requires careful consideration to mitigate the potential challenges related to structural integrity under varying conditions.

The comparison of soil plasticity values, which are characterized by very high LL and PI, is presented in Table IV. Soils with very high plasticity typically have a PI greater than 40. This behavior is largely attributed to the presence of active clay minerals, such as montmorillonite, which exhibit a strong capacity to absorb water and undergo significant deformation.

However, soil with such high plasticity poses challenges for stabilization due to its excessive water absorption capacity that can compromise the soil's structural integrity. To mitigate these issues, stabilization methods are often employed, including the incorporation of pozzolanic materials, like BLA. These materials improve the soil's mechanical properties by reducing plasticity and enhancing overall stability.

TABLE IV. COMPARISON OF SOIL PLASTICITY VALUES

Ref.	Year	LL	PL	PI
[31]	2015	83 - 140%	39 - 48%	44 - 92
[32]	2015	559%	51%	508%
[33]	2003	485.7%	34.2%	451.5%
[34]	2019	343 - 419%	98 - 193%	155 - 331%
[35]	2023	371%	42%	329%
Current study	2024	568.70%	113.29%	455.41%.

C. Effect of Bamboo Leaf Ash on the Plasticity of Bentonite

Soils with a PI greater than 450 exhibit EHP, posing significant challenges for construction and engineering applications. Stabilization is therefore essential to enhance their structural integrity and usability.

Figure 6 illustrates the relationship between the Atterberg Limit and the percentage of BLA, showing the reduction in the PI and improvement in soil strength following stabilization. Adding BLA as a chemical stabilizer significantly decreases PI, while the shear testing demonstrates enhanced soil strength, particularly for soils with high PI.

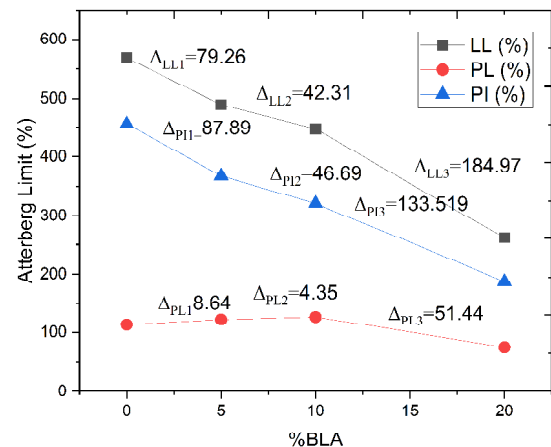


Fig. 6. The relationship between the Atterberg limit and the percentage of BLA.

At the PL condition, a gradual decrease in shear strength is observed as the percentage of BLA increases. Specifically, from 0% to 5% BLA, the reduction is approximately 13.94%, followed by a decrease of 8.65% from 5% to 10% BLA, and a substantial drop of 41.37% from 10% to 20% BLA. The gradual reduction between 0% and 10% BLA is shown, indicating a controlled stabilization process.

As the BLA content rises from 0% to approximately 10%, PL increases from approximately 113.29% to around 126.29%. In contrast, PI decreases from 455.41% at 0% BLA to 187.31% at 20% BLA. The findings suggest that around 5% BLA is optimal for improving key parameters, such as the LL, PL, and PI values, resulting in favorable effects on soil variations with BLA.

D. Effect of Bamboo Leaf Ash on Peak and Residual Strength in Torsional Ring Shear Test

The torsional ring shear test, as depicted in Figure 4, conducted under drained conditions on remolded specimens, applies torque to generate a shear plane until a constant shear strain is achieved. This constant shear strain represents the residual strength of the soil, which is critical for evaluating the drained residual strength of cohesive soils. The ring shear device is a widely utilized instrument for studying the shear behavior of soil, particularly in measuring shear resistance at large displacements. Unlike the triaxial testing equipment, which is limited to measuring at 0° and 90° angles, the ring

shear apparatus allows the determination of shear strength parameters at any angle of principal stress rotation. This versatility makes it invaluable for investigating the shear resistance of soil under varied stress conditions.

Ongoing development and enhancement of modern ring shear devices have been taking place for over 40 years, as a collaborative effort by the Imperial College of Science & Technology in the UK and the Norwegian Geotechnical Institute in the 1970s. Technological advancements in geotechnical instrumentation have further improved the testing functions and capabilities of the ring shear apparatus [36, 37]. A significant advantage of the ring shear apparatus lies in its ability to simulate field conditions on pre-existing shear surfaces in slow-moving landslides. It facilitates shear at a soil-to-soil interface, allowing a more accurate assessment of the residual shear strength of soils. This capability is crucial for evaluating the stability of reactivated landslide slopes [38, 39]. Moreover, it has been employed to study the strain-softening behavior of clay under varying conditions, including rapid shear rates, pre-consolidation pressures, and different shear rates. Understanding these behaviors is essential for analyzing the response of soils in sliding zones that experience rapid shearing. Additionally, modifications to the device by some researchers have enabled long-term observations of plastic deformations in soils during torsional shear tests, providing quantitative assessments of permanent deformation components [40].

The relationship between shear stress and strain at varying percentages of BLA (0%, 5%, 10%, and 20%) under normal stresses of 50 kPa, 100 kPa, and 200 kPa was examined, as presented in Figures 7-10.

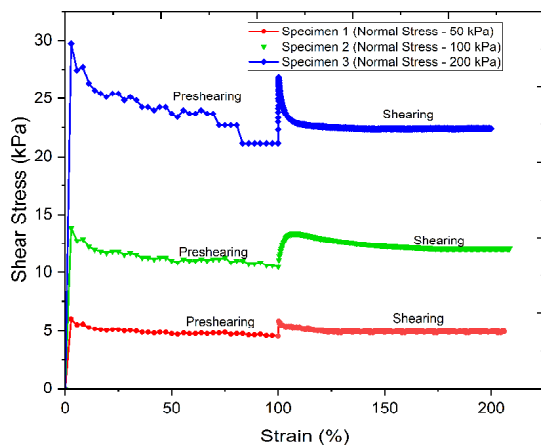


Fig. 7. Stress and strain relationship at 0% BLA variation.

It was observed that higher normal stresses (200 kPa) consistently result in greater shear stress, regardless of the BLA percentage. BLA addition significantly enhanced shear stress, particularly at 5% and 10%, with diminishing returns beyond 10%. The most pronounced improvements are noted at higher normal stresses, where the combination of 5–10% BLA with 200 kPa normal stress demonstrates the best performance. Based on the test results, a BLA percentage of 5% was found to

be the optimal choice. In this variation, PI decreases significantly without requiring a large amount of BLA material, up to 20%.

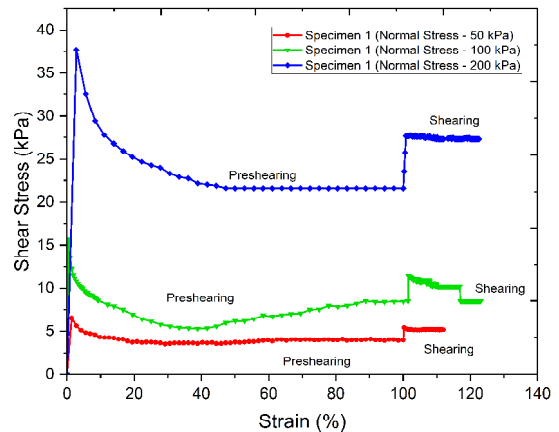


Fig. 8. Stress and strain relationship at 5% BLA variation.

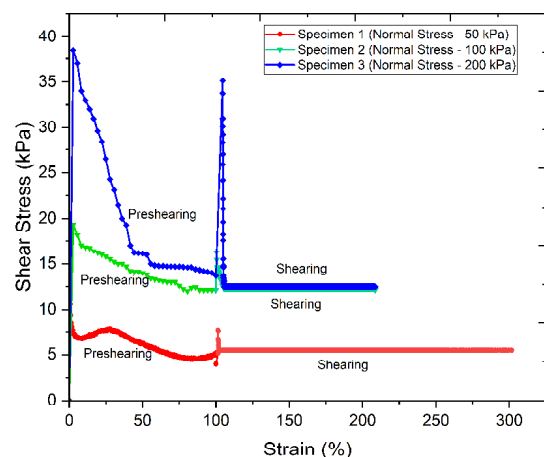


Fig. 9. Stress and strain relationship at 10% BLA variation.

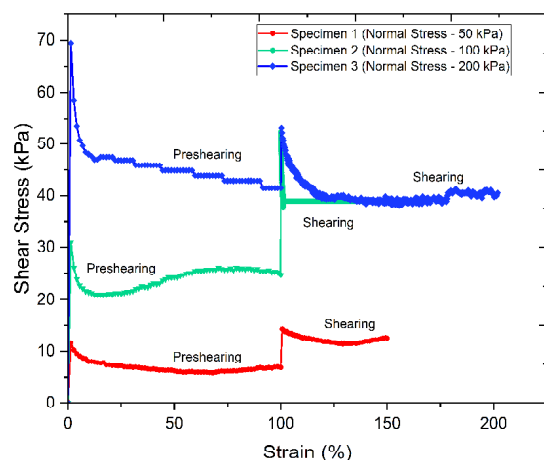


Fig. 10. Stress and strain relationship at 20% BLA variation.

E. Effect of Bamboo Leaf Ash on Peak Strength

The relationship between the BLA percentage and the maximum strength as well as the residual strength was examined under varying levels of normal stress (50 kPa, 100 kPa, and 200 kPa). Figures 11-13 present the variation in peak strength with different BLA percentages at normal stresses of 50 kPa, 100 kPa, and 200 kPa. Across all stress levels, peak strength increases as the percentage of BLA increases, with the most significant improvements being observed under higher normal stresses (200 kPa). This trend demonstrates the effectiveness of BLA in enhancing the soil's mechanical behavior.

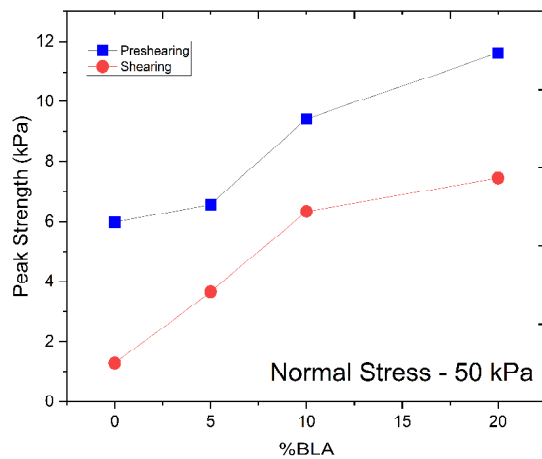


Fig. 11. Peak strength and percentage of BLA relationship at 50 kPa.

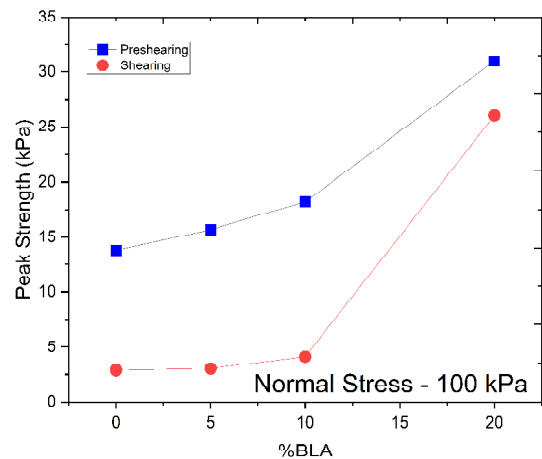


Fig. 12. Peak strength and percentage of BLA relationship at 100 kPa.

F. Effect of Bamboo Leaf Ash on Residual Strength

Figures 14-16 illustrate the relationship between BLA percentage and residual strength under the normal stresses of 50 kPa, 100 kPa, and 200 kPa, respectively. The results show that residual strength also increases with the addition of BLA, with the most pronounced improvements being observed at higher normal stresses, particularly at 200 kPa. This indicates that the stabilizing effect of BLA is more significant under greater loading conditions.

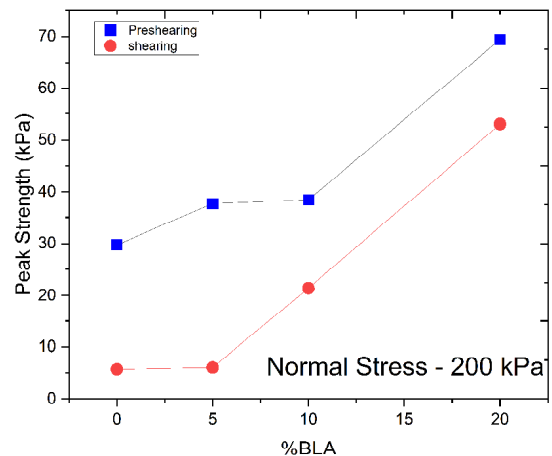


Fig. 13. Peak strength and percentage of BLA relationship at 200 kPa.

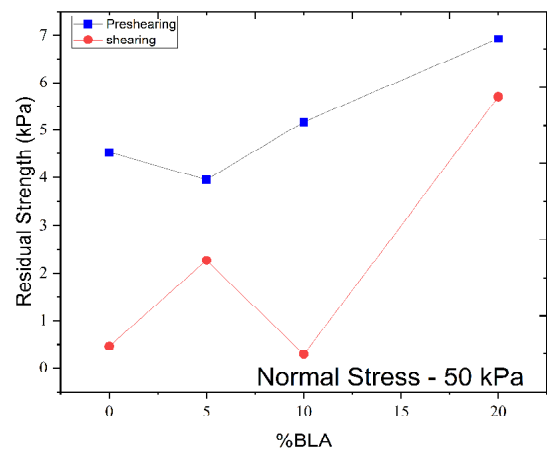


Fig. 14. Residual strength and percentage of BLA relationship at 50 kPa.

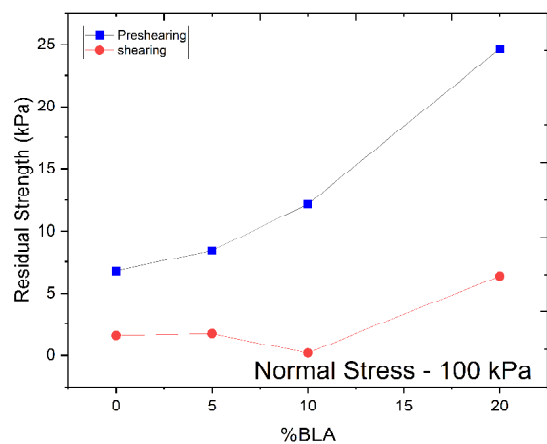


Fig. 15. Residual strength and percentage of BLA relationship at 100 kPa.

However, an exception is evidenced at 10% BLA, where the residual strength is often lower than that at 5% and 20% BLA. This anomaly could be attributed to an imbalance in the pozzolanic reactions at this specific concentration, potentially resulting in incomplete stabilization or the formation of

intermediate reaction products that do not optimally contribute to soil strength. Further investigation into the microstructural changes at this BLA level could provide insights into the particular behavior. Overall, the addition of BLA enhances both the peak strength and residual strength of the soil, with more substantial effects being noted during the shear tests. These improvements can be attributed to the pozzolanic reactions induced by BLA, which strengthen the soil matrix and improve its mechanical behavior.

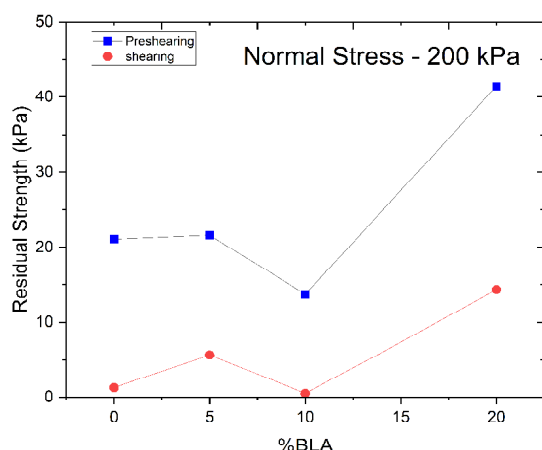


Fig. 16. Residual strength and percentage of BLA relationship at 200 kPa.

G. Identification of Crystalline Materials Using X-ray Diffraction

The XRD patterns (Figure 17) illustrate the change in crystalline structure and mineral composition of bentonite, stabilized with varying proportions of BLA (0%, 5%, 10%, and 20%). The addition of BLA introduces reactive silica into the bentonite matrix, leading to progressive alterations in the soil's mineralogical composition.

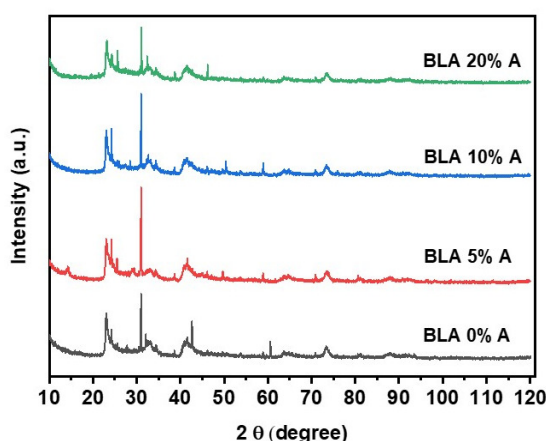


Fig. 17. XRD of materials in various percentages of BLA.

In the 0% BLA sample, the diffraction pattern shows 2θ positions at approximately 20°, 26.6°, 50°, and 60° corresponding to the characteristic angles for the quartz crystal structure. In the 5% BLA, the diffraction pattern exhibits

changes in intensity and peak distribution compared to the 0% BLA sample. While the main peak at $2\theta = 26.6^\circ$ remains dominant, indications of altered crystallinity are observed due to BLA addition. Additional peaks emerge around 30° and 40°, suggesting possible interactions between the BLA and the matrix material, potentially leading to the formation of new phases or modifications in the crystal structure.

In the 10% BLA sample, the diffraction pattern shows more pronounced changes, with an increased intensity at several 2θ angles, particularly within the 20°–40° range. This suggests an increase in the amorphous phase or a redistribution of crystals within the system. The intensity of the peak at $2\theta = 26.6^\circ$ begins to decrease slightly compared to the 5% BLA sample, implying that the quartz structure is being disrupted by the higher BLA concentration.

For the 20% BLA sample, the diffraction pattern undergoes further transformation, with a noticeable reduction in overall peak intensity, indicating a decline in crystallinity. The previously dominant peak at $2\theta = 26.6^\circ$ weakens significantly, suggesting a shift toward a more amorphous structure. This indicates that increasing the BLA concentration contributes to structural modifications, either through the formation of new phases or an enhancement of non-crystalline characteristics. For the 20% BLA sample, the diffraction pattern undergoes further transformation, with a noticeable reduction in overall peak intensity, indicating a decline in crystallinity. The previously dominant peak at $2\theta = 26.6^\circ$ weakens significantly, suggesting a shift toward a more amorphous structure. This demonstrates that increasing the BLA concentration contributes to structural modifications, either through the formation of new phases or an enhancement of non-crystalline characteristics.

H. Morphology of Bamboo Leaf Ash and Bentonite Analysis using Scanning Electron Microscope

The morphology of BLA and Bentonite was analyzed using Scanning Electron Microscope (SEM), a powerful technique for examining surface structures, particle sizes, distributions, and micro-physical characteristics of materials. SEM provides high-magnification visualization, allowing a detailed observation of material surfaces at the micro and nanometer scales. The analysis reveals critical insights into the structural and textural properties of both BLA and bentonite. For BLA, the SEM images highlight its porous and irregular surface morphology, which contributes to its high reactivity in pozzolanic reactions. The bentonite samples exhibit a layered structure typical of clay minerals, with plate-like particles and interparticle voids. These morphological characteristics significantly influence the interaction between BLA and bentonite, enhancing the stabilization process by facilitating pozzolanic reactions and improving soil mechanical properties.

The SEM analysis, outlined in Figures 18-21, indicates that the gradual addition of BLA to bentonite (at 0%, 5%, 10%, and 20%) significantly modifies the microstructure of the soil. At 0% BLA, the microstructure is dominated by large, loosely bonded clay particles, characteristic of the high plasticity soil. With the addition of 5% BLA, smaller particles begin to fill the voids between the clay particles, increasing soil density and reducing void spaces.

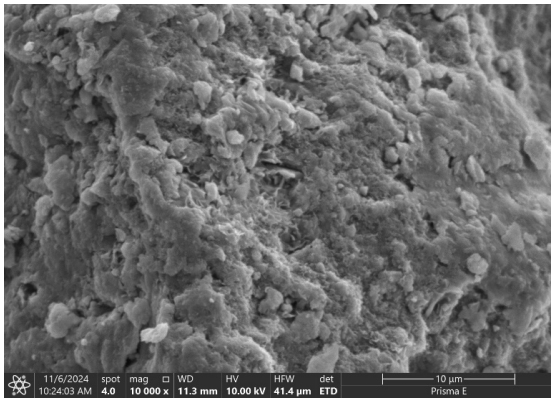


Fig. 18. SEM image of Bentonite with no BLA (×10,000 magnification).

The addition of 5% of BLA exhibits a denser, more homogeneous microstructure with a more uniform particle distribution compared to other variations. The bamboo ash particles in the 5% BLA appear to be more evenly distributed within the soil matrix, creating a more stable bond and reducing the number of voids or excess porosity that could weaken the structure.

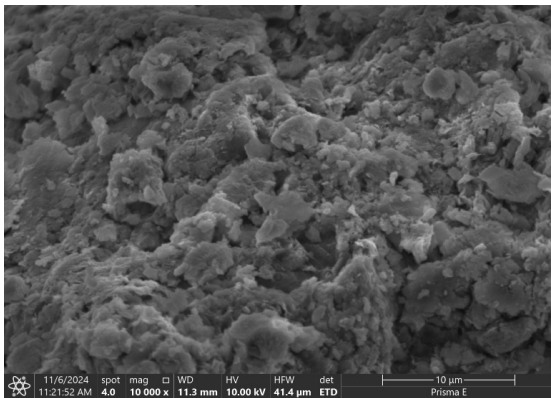


Fig. 19. SEM image of Bentonite with 5% BLA (×10,000 magnification).

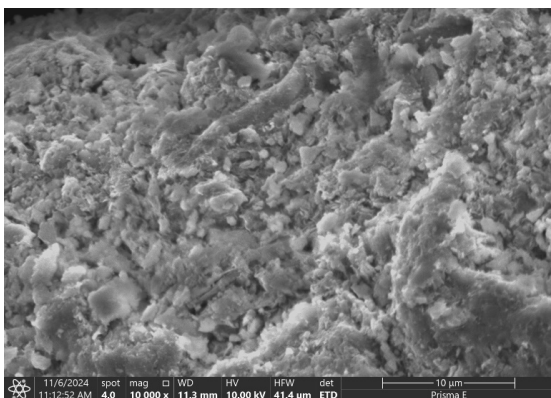


Fig. 20. SEM image of Bentonite with 10% BLA (×10,000 magnification).

Overall, BLA addition significantly improves soil stability and shear strength. The optimal results are achieved at 5%-10% BLA, where the microstructure demonstrates reduced

plasticity, increased density, and enhanced residual strength. These findings highlight the effectiveness of BLA as a stabilizing agent for high-plasticity soils.

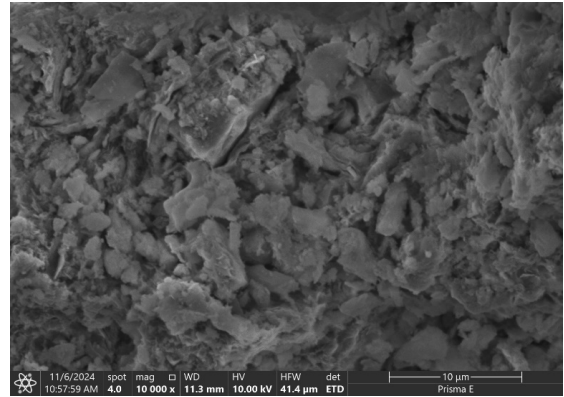


Fig. 21. SEM image of Bentonite with 20% BLA (×10,000 magnification).

IV. CONCLUSION

The analysis of the Plasticity Index (PI) indicates that the value for bentonite reaches 455.41%, signifying its Extremely High Plasticity (EHP) ($PI > 90\%$). The changes in PI demonstrate that the addition of Bamboo Leaf Ash (BLA) significantly reduces the plasticity of bentonite soil. This is evidenced by a 19.30% decrease when BLA increases from 0% to 5%, a 12.70% decrease from 5% to 10%, and a drastic 41.62% reduction from 10% to 20%. The most significant reduction occurs at 20% BLA, indicating a stronger pozzolanic effect at higher BLA levels, which accelerates soil stabilization. Meanwhile, the more gradual reduction at 5% BLA suggests an optimal balance.

BLA addition significantly influences the improvement of residual strength in bentonite soil under different levels of normal stress. At 0% BLA, the residual strength is recorded as 0.46 kPa at 50 kPa, 1.59 kPa at 100 kPa, and 1.26 kPa at 200 kPa, indicating the soil's limited strength. With 5% BLA, the residual strength increases to 2.27 kPa at 50 kPa, 1.74 kPa at 100 kPa, and 5.67 kPa at 200 kPa. However, at 10% BLA, the residual strength decreases to 0.29 kPa at 50 kPa, 0.19 kPa at 100 kPa, and 0.49 kPa at 200 kPa, indicating that excessive BLA weakens the soil structure. Conversely, at 20% BLA, the residual strength significantly increases to 5.70 kPa at 50 kPa, 6.40 kPa at 100 kPa, and 14.30 kPa at 200 kPa.

Overall, BLA addition, particularly at 20%, greatly enhances soil stability under high loads. Meanwhile, the 5% BLA variation proves to be the most effective in improving the residual strength of bentonite soil compared to other variations. The formation of these compounds greatly enhances soil strength, as confirmed by X-Ray Fluorescence (XRF), X-ray diffraction (XRD), and Scanning Electron Microscope (SEM) analyses. Thus, soil stabilization reaches its optimal condition at 5% BLA.

This research contributes to advancing soil stabilization techniques while promoting sustainability in geotechnical

engineering, aligning with the global emphasis on eco-friendly practices.

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