

*Research Article*

Integrated Physical–Chemical Approaches to Reduce Plasticity in Extremely High-Plastic Soils using Bamboo Leaf Ash: Geotechnical and Microstructural Evaluation

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Abstract: Extremely high plasticity soils, such as bentonite, present substantial challenges in geotechnical applications due to their high water retention capacity and expansive behaviour. This study evaluates an integrated physical–chemical stabilization approach using bamboo leaf ash (BLA) to reduce the plasticity of such problematic soils. Bentonite was selected as a sample of soil with extremely high plasticity. BLA, which was made from three types of bamboo and treated through controlled burning, was used as a chemical stabilizer. Mayan bamboo was chosen for soil stabilization owing to its high silica (SiO_2) content and pozzolanic reactivity. Numerous geotechnical tests, such as Atterberg limits and compaction tests, were performed following the ASTM standards. Scanning Electron Microscopy (SEM) combined with Energy Dispersive Spectroscopy (EDS), X-Ray Fluorescence (XRF), and X-Ray Diffraction (XRD) investigations were used to check how the soil changes at a microscopic level, particularly the shape and mineral content after stabilization. The results showed that BLA greatly lowered the plasticity index (PI) from 455.41% to 180% and the liquid limit (LL) from 568.70% to 270%, with only small changes in the plastic limit (PL). The microscopic analysis showed the formation of cement-like materials such as calcium silicate hydrate (C-S-H) and calcium alumino-silicate hydrate (C-A-S-H), which means that the pozzolanic reactions worked well. Using BLA along with compaction provides a sustainable and effective way to reduce the plasticity value of the soil and automatically increase the strength of soils with extremely high plasticity. These results show that BLA could be a green and practical option for soil stabilization using a large number of local plant materials.

Keywords: Bamboo leaf ash; Extremely high plasticity soil; Mayan bamboo; Plasticity index; Pozzolanic reactivity; Soil stabilization

1. Introduction

Soil plasticity is a fundamental aspect of geotechnical engineering, particularly in the analysis of soft clay soils. Soft clays exhibit unstable geotechnical properties characterized by high plasticity, high compressibility, and low bearing capacity. Consequently, this condition necessitates efficient stabilization methods to mitigate the inherent soft clay soil deficiencies. Studies by Almajed, 2024, Kodaz et al., 2022, Mugagga et al., 2011, and Kim, 2012 have shown the challenges posed by extremely plastic soils due to their expansive nature and sensitivity to moisture changes. These soils are usually classified as CH (clay with high plasticity) or OH (organic clay with high plasticity) under the USC. According to Daleon, 2022, they often have a plasticity index (PI) higher than 70%.

In Indonesia, bentonite is a prevalent example of extremely plastic soils. Bentonite is a type of clay mostly made of montmorillonite and is found throughout Java and Sumatra. Sisnayati

et al., 2022 explained that the layered structure of bentonite facilitates ion exchange and absorbs substances, making it very useful for environmental applications. Studies by Darmadi et al., 2021 and Jakfar and Azwar, 2023 have validated the use of bentonite as an adsorbent for heavy metals such as cadmium and mercury, while Zulkifli et al., 2023 demonstrated its effectiveness in removing copper ions. In the pharmaceutical sector, Rahardjo et al., 2011 reported its success in purifying ampicillin-contaminated wastewater. Additionally, Antari et al., 2020 explored the use of bentonite from Muratara Regency as a substitute for imported industrial-grade materials in drilling operations, highlighting its versatility. Cundari et al., 2025 further explored the capacity of bentonite to adsorb hexavalent chromium (Cr VI), underscoring its continued industrial and environmental significance in Indonesia.

Soil stabilization strategies for highly plastic clays are generally divided into physical and chemical approaches. Physical treatment, such as compaction, aims to reduce pore space and increase soil density, while chemical stabilization uses reactive binders, such as lime or cement, to bind particles and reduce plasticity. Ideally, soil stabilization should address both density and mineralogical stability. Physical stabilization alone, while increasing density, is often reversible; high-plasticity clays tend to swell again upon rewetting. Chemical stabilization relies on the formation of cementitious gels (C-S-H) to bind particles. However, without the mechanical densification provided by compaction, the chemical bonds may be weak due to large inter-particle voids. Therefore, integrating BLA treatment with mechanical compaction is essential for creating a dense, chemically bonded matrix that is resistant to both load and moisture fluctuations. James and Pandian, 2016 emphasized the effectiveness of chemical stabilizers in improving soil strength, despite persistent concerns over the environmental impact. Unfortunately, most studies have investigated these methods separately. For instance, Mollamahmutoglu et al., 2017 confirmed the effectiveness of lime and cement in improving the maximum dry density and lowering the optimum moisture content; however, they did not integrate these properties with mechanical compaction.

In response to sustainability concerns, alternative stabilization materials derived from agricultural waste have gained attention. Bamboo leaf ash (BLA) has emerged as a promising sustainable stabilizer. BLA exhibits pozzolanic properties; when mixed with lime or calcium-rich soil, it reacts to form cementitious compounds, specifically Calcium Silicate Hydrate (C-S-H) and Calcium Alumino-Silicate Hydrate (C-A-S-H). Ameen, 2021 and Kabdiyono et al., 2024 reported that BLA exhibits pozzolanic properties and, when combined with lime, forms cementitious compounds that significantly reduce the liquid limit (LL) and plasticity index (PI) of lateritic soils by Kabdiyono et al., 2025 and Yilmaz and Demir, 2019 supported this by demonstrating that BLA can effectively improve the geotechnical performance of high-plasticity soils, making it a viable substitute for conventional materials. Ahmed et al., 2024 and Pujiastuti et al., 2024 showed that BLA contributes to the development of flocculated structures within the soil matrix, thereby enhancing the load-bearing capacity and reducing the moisture sensitivity. The advantages of BLA as a sustainable pozzolanic material have been widely highlighted in various studies. Amu and Babajide, 2011 and Amu and Adetuberu, 2010 demonstrated that BLA significantly improves the engineering properties of soils, particularly in reducing plasticity and enhancing strength when used as a stabilizing additive. Iorliam et al., 2013 and Iorliam et al., 2012 further confirmed its effectiveness in increasing the bearing capacity and durability of stabilized soils, making it a viable alternative to conventional stabilizers. Dada and Faluyi, 2015 reinforced these findings by showing that BLA exhibits strong pozzolanic reactivity, which contributes to better soil stabilization and improved performance under load. More recently, Kabdiyono, 2019 talked about the good things that BLA does for the environment, especially how it helps in building in a way that is better for the planet by using agricultural waste. Wijaya, 2021 also stated that BLA makes cement mixtures stronger and more durable. Nnochiri et al., 2021 reported that BLA is useful for creating eco-friendly engineering solutions. These studies show that BLA has great qualities, such as making soil less sticky, making things stronger and longer-lasting, and helping the environment by using waste from plants.

However, experimental studies combining physical and chemical stabilization in an integrated framework are lacking. Most research has focused on individual approaches without examining their synergistic interactions. In this regard, Boluk et al., 2021 highlighted that the use of agricultural wastes such as BLA not only enhances soil behavior but also offers environmental and economic benefits by reducing dependence on high-emission materials such as cement and lime. Despite the growing interest in biomass ash, limited research has systematically evaluated the use of Bamboo Leaf Ash specifically for stabilizing extremely high-plasticity bentonite clays ($PI > 400\%$). Few studies have bridged the gap between macro-mechanical improvements and micro-structural mechanisms in an integrated physicochemical framework. This research fills this gap by providing a dual-level analysis correlating standard geotechnical parameters with advanced microstructural evidence to validate the efficacy of BLA as a standalone stabilizer for problematic bentonite soils.

This study aims to evaluate the effectiveness of an integrated physical–chemical stabilization approach to reduce the plasticity of soils with extremely high plasticity using BLA as a chemical stabilizer along with mechanical compaction. Geotechnical parameters, such as LL, PI, and compaction characteristics, will be assessed in accordance with the British Standards. X-ray fluorescence (XRF) was used to determine the elemental chemical composition of the materials. Phase changes and mineralogical compositions will be identified using X-ray diffraction (XRD). Additionally, Scanning Electron Microscopy (SEM) combined with Energy Dispersive Spectroscopy (EDS) will be employed to visualize the surface morphology and analyze the elemental distribution at the micro-scale. This combination allows for a detailed observation of how the formation of C-S-H and C-A-S-H gels modifies the soil structure. Advanced microstructural characterization techniques, such as X-ray fluorescence (Qingya et al., 2022; Tóth et al., 2019; Arnoldussen and van Os, 2015), X-ray diffraction (Hokkanen et al., 2019; Minkina et al., 2018; Zhao and Tan, 2018; Singh and Agrawal, 2012; Kahle et al., 2002), and scanning electron microscopy (SEM), will be employed to investigate the chemical composition, mineral phases, and morphological changes resulting from the treatment (Moretti et al., 2020; Eisenhauer et al., 2015; Siqueira et al., 2011).

This research contributes theoretically by expanding knowledge on soil stabilization mechanisms through interactive physical–chemical processes and by promoting the use of locally available, environmentally sustainable materials. The integration of geotechnical testing and microstructural analysis provides a comprehensive understanding of the effects of BLA on soil behavior. This study uses Indonesia's rich natural resources, such as bentonite and bamboo leaf ash, to create eco-friendly soil improvement methods that work well in soils with extremely high plasticity in tropical areas.

2. Materials and Methods

A comprehensive experimental program was designed to achieve the study's objectives, using a fully experimental analysis approach. The research framework investigates the integrated effect of chemical stabilization (using Bamboo Leaf Ash) and physical stabilization on clay with extremely high plasticity.

2.1 Extremely high plasticity soil (Bentonite)

Bentonite is a type of clay mineral that is mostly made up of a substance called montmorillonite (Elkhatib et al., 2022; Srivastava and Singh, 2017). It can be found in large amounts in Indonesia, especially in the Pacitan area in East Java. Bentonite has special qualities, such as the ability to absorb water, be easily molded, and exchange ions, making it useful in many industries. These include making drilling fluids and construction materials, and helping to clean up the environment. This summary looks at the importance of bentonite in Pacitan, the different ways it is used, and the impact it has, based on research and local activities.

The geology of Pacitan includes sedimentary rock layers, and bentonite deposits and other

minerals are found within these layers. The bentonite in this area is mostly sodium bentonite, which can swell when it comes into contact with water. This property makes it useful in drilling mud, which is important for oil and gas drilling Antari et al., 2020. The way sodium bentonite holds together through ionic bonds helps to keep the walls of the drill hole stable during the drilling process (Antari et al., 2020). This allows local industries to take advantage of these naturally occurring resources.

Bentonite is used in many industries in Indonesia, particularly in drilling fluids, foundry sand, and construction materials. One important use is in drilling mud, where it helps control the thickness of the wells and keeps them stable. The mining and drilling activities in Pacitan could benefit from the local bentonite resources. As mentioned in Antari et al., 2020, this would help reduce the need to import materials and support local economic development. The soil sample used in this study was a commercially available bentonite branded as Indobent (Drillux). Due to its superior sealing and lubricating properties, this material is widely used in horizontal drilling, bored pile cement mixtures, and dam wall construction. It was selected to represent an environment with extremely high plasticity.

In addition to drilling, bentonite is also used as a binder in making foundry sand for metal casting. Its ability to hold moisture and create molds helps strengthen the metal castings. Studies have shown that bentonite clays work well with agricultural byproducts, such as rice husk ash, to improve the strength and performance of the sand used in investment casting Nanda et al., 2018.

The bentonite used in this study was bought from a company and is made especially for drilling. This type of bentonite is widely used as drilling mud in civil engineering, mining, and geotechnical industries. It stabilizes boreholes, lubricates the drill bit, and transports drill cuttings to the surface. In the context of this research, bentonite is not used as an additive in the drilling process, but rather as a representative material of extremely high plasticity soil, due to its high plasticity index (PI), excellent water absorption, and dominant montmorillonite mineral content. Thus, the commercial drilling bentonite used in this research meets the technical specifications for drilling fluid applications and can be used for a reliable and consistent simulation of highly plastic clay. Therefore, it is suitable for laboratory-based stabilization studies using BLA as a chemical additive.

2.2 Bamboo Leaf Ash – BLA

The production of bamboo leaf ash aims to generate a pozzolanic material with high silica (SiO_2) content. The study used leaves from three main bamboo species: yellow bamboo (*Bambusa vulgaris*), mayan bamboo (*Gigantochloa robusta*), and sembilan bamboo (*Gigantochloa atter*). Leaves were collected from plants over one year old to ensure a sufficiently high silica content. The leaves were collected in Cibinong, West Java, Indonesia, where plants grow naturally under optimal conditions. The leaves were sun-dried for 48 h after collection to significantly reduce the moisture content. Drying was performed at a relative humidity of approximately 70% to ensure that the leaves were adequately dried before incineration.

2.3 Fabrication of BLA

In Figure 1, dried bamboo leaves were subsequently incinerated in a laboratory furnace at regulated temperatures of 500°C, 600°C, and 700 °C. The combustion process was continued for 2 h at each temperature and was monitored closely to ensure consistency. Combustion refers to the chemical process in which a substance combines with oxygen and releases heat and light energy. It is a vital process in engines, fires, and various industrial operations. These temperatures were chosen based on earlier research showing that the maximum temperature range of silica is between 500°C and 700°C Villar Cociña et al., 2018).

The resulting ash exhibited a range of colors, from pale gray to white, signifying a high purity level. The texture of the ash varied from coarse to fine, depending on the combustion tem-

perature. The ash generated at elevated temperatures was generally more refined and contained a greater amount of silica compared with that at reduced temperatures.



Figure 1 Scheme for the preparation method of bamboo leaf ash

After cooling, the ash was passed through a No. 100 mesh sieve to ensure that all particles were the same size. The sieving was done by hand until all the big pieces were gone, leaving behind fine ash that was ready to use as a soil stabilizer. This helped make the material uniform for future testing. The sieved bamboo leaf ash was kept in sealed containers to prevent it from getting dirty or wet. The containers were stored at room temperature in a low-humidity environment to maintain the quality and stability of the materials throughout the study.

The silica content of the ash obtained from each combination of bamboo species and burning temperature was analyzed using X-ray fluorescence (XRF). The silica content analysis results were then used to determine the most effective burning temperature and the bamboo leaf type that yielded the highest silica concentration. A critical aspect of using Bamboo Leaf Ash (BLA) is assessing its carbon footprint compared to conventional stabilizers, such as cement and lime. Although the production of BLA involves burning, the environmental impact is significantly lower than that of the cement production for two primary reasons. First, the production temperature and energy consumption are considered. Conventional Ordinary Portland Cement (OPC) requires clinkerization temperatures of approximately $1,450^{\circ}\text{C}$, consuming massive amounts of fossil fuel energy. In contrast, the transformation of bamboo waste into reactive pozzolanic ash typically requires controlled burning at 600°C – 800°C . This lower temperature requirement substantially reduces embodied energy and associated emissions. The second factor is the carbon emitted. The CO_2 released during BLA production is classified as biogenic carbon that was recently sequestered from the atmosphere during the rapid growth cycle of bamboo. This represents a closed carbon loop. Conversely, cement production releases CO_2 from the chemical decomposition of limestone CaCO_3 and the burning of fossil fuels, resulting in a net addition of greenhouse gases to the atmosphere.

2.4 Research Instruments

This study used a range of geotechnical laboratory equipment and advanced analytical tools designed to evaluate the physical, mechanical, and microstructural properties of the soil samples. For the physical and index property tests, the instruments included a moisture content testing device (following ASTM D2216) to determine the natural water content of the soil, an Atterberg

limits apparatus (ASTM D4318) to assess the liquid limit (LL), plastic limit (PL), and plasticity index (PI), and a standard Proctor compaction apparatus (ASTM D698) used to identify the soil-BLA mixtures' optimum moisture content (OMC) and maximum dry density (MDD).

Several advanced laboratory instruments were employed to support further analysis of the chemical composition and mineralogical changes due to stabilization. These include X-ray fluorescence (XRF) to identify the elemental composition of the BLA and the stabilized soil; X-ray diffraction (XRD) to detect changes in mineral phases; and a scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) and elemental mapping to observe the microstructural morphology, pore structure, and elemental distribution at the microscopic level. Together, these instruments provide comprehensive insights into the macroscopic (geotechnical) and microscopic (chemical and structural) behavior of the treated soil, enabling a holistic evaluation of the effects of BLA stabilization.

3. Results and Discussion

3.1 Bentonite Characterization

This section presents the measurement results regarding the Bentonite index properties. The test results on the characteristics of bentonite in Table 1 indicate that this material has a very high plasticity index (PI) of 455.41%, with a liquid limit (LL) of 568.70%, and a PL of 113.29%. These extreme values confirm that bentonite soil has an extremely high degree of plasticity and a strong ability to absorb large amounts of water. The specific gravity of bentonite is 2.79, which is within the normal range for clay minerals, whereas the optimum moisture content is 62.039%. The maximum dry density of only 9.25 kN/m³ indicate that even after compaction, bentonite still has a relatively low density and requires a large amount of water to achieve its optimum condition.

Table 1 The result of bentonite properties

Testing	Result
Plasticity Index (PI)	455.41%
Liquid Limit (LL)	568.70%
Plastic Limit (PL)	113.29%
Specific Gravity	2.79
Optimum Moisture Content	62.039%
Maximum Dry Density	9.25 kN/m ³

Figure 2 shows a scanning electron microscope (SEM) image of the microstructure of the material at a magnification of 1.25 kx at a scale of 50 m. The surface appears rough and porous, indicating a high surface area, and very thin, flat flakes are present.

Table 2 Mineral Composition of Bentonite

Mineral	Illite	Albite	Quartz	Pyrite	Calcite	Cristobalite	Monmorillonite
Bentonite							
Quantitative Analysis (%)	45.3	23.8	20.9	4.4	2.9	1.6	1.1

The quantitative XRD analysis in Table 2 reinforced the findings, which identified illite (45.3%) as the dominant mineral, followed by albite (23.8%) and quartz (20.9%), with only 1.1% montmorillonite, and minor phases including calcite, pyrite, and cristobalite.

Table 3 shows that the consistency across techniques is further supported by the XRF bulk chemistry: the very high SiO₂ content (66.97%) and Al₂O₃ (20.70%) yield a SiO₂/Al₂O₃ ratio of ~3.24, typical of aluminosilicate matrices with strong contributions from quartz/cristobalite and

layered silicates. The presence of Fe_2O_3 (5.76%) supports Fe-bearing phases, aligning with Fe detected in EDS and pyrite identified in XRD (reported by XRF in oxide equivalent). CaO (2.54%) correlates with calcite, whereas MgO (1.72%) and TiO_2 (0.55%) contribute to calcination. The relatively low K_2O (0.38%), despite the dominance of illite, may indicate K-depleted illite/mixed-layer illite–smectite or low-K illite, which is still compatible with the strong albite (Na-feldspar) signal in XRD. SEM–EDS provides textural and elemental information, XRD confirms crystalline mineral phases, and XRF validates the bulk chemistry: all three converge to characterize the sample as an illitic bentonite with high silica content, supported by quartz/cristobalite and feldspars, with minor carbonates and Fe phases—making it suitable for soil stabilization and pozzolanic additive applications, with predictable reactivity toward Ca-based activators.

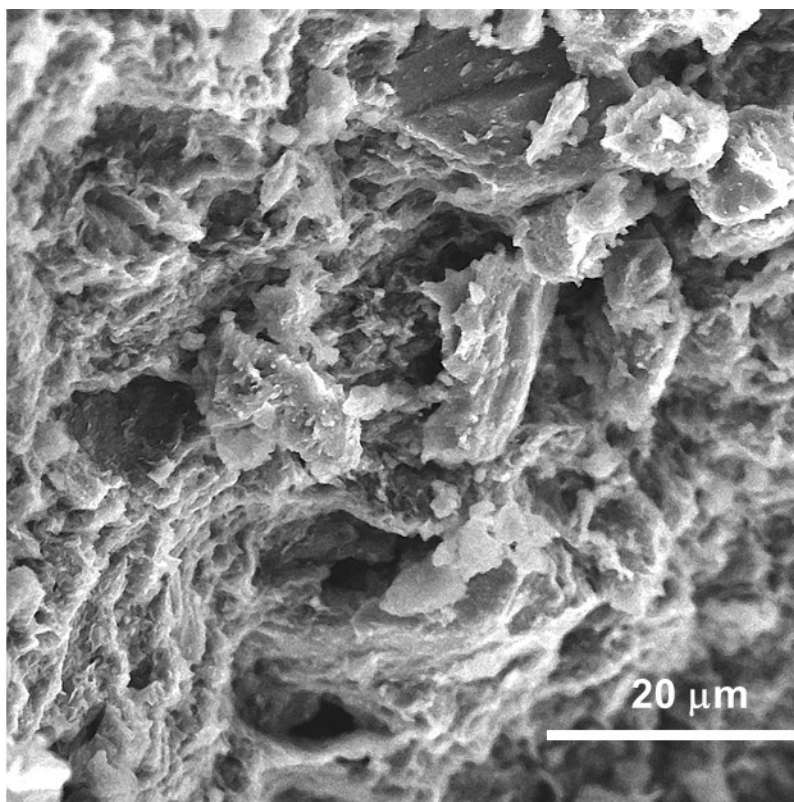


Figure 2 Microstructure photo of Bentonite at 3,500 magnification Scanning Electron Microscope (SEM)

Table 3 Chemical Composition of Bentonite

Chemical Content	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	MnO	Fe_2O_3	SrO
Unit	%	%	%	%	%	%	%	%	%	%	%
Quantity	1.723	20.698	66.965	1.298	0.382	2.535	0.553	0.03	0.032	5.756	0.027

3.2 BLA Characterization

Characterization of BLA was carried out to determine its physical, chemical, and mineralogical properties before being used as an additive material in this study. The combustion process of bamboo leaves produces ash with a greyish to whitish color, indicating a relatively high amorphous silica content. In terms of chemical composition, X-ray fluorescence (XRF) analysis shows that BLA is rich in silica (SiO_2) content of more than 60%, accompanied by small amounts of alumina (Al_2O_3) and iron oxide (Fe_2O_3).

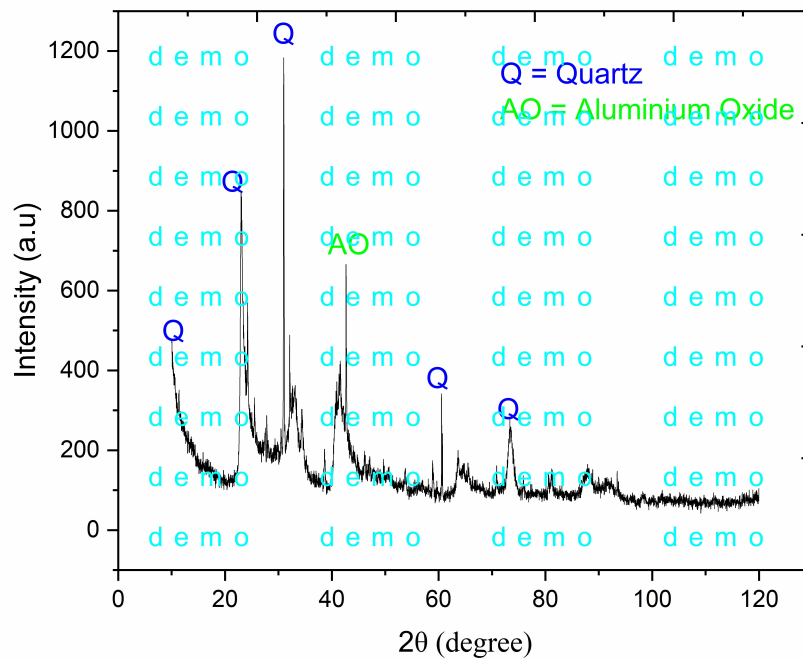


Figure 3 X-ray diffraction (XRD) of Bentonite

Figure 4 shows that the initial value at 500°C is approximately 76%, showing a slight increase at 600°C, and reaching its highest peak at around 78% at 700°C. This trend is represented by the linear regression equation $\%SiO_2 = 0.0127(T) + 69.683$, which has the steepest positive slope compared with the other two bamboo species. This indicates that Mayan Bamboo consistently produces higher SiO_2 content that increases with an increase in the combustion temperature. In contrast, the yellow bamboo shows a fluctuating pattern. The SiO_2 content at 500°C is relatively high (75%) but significantly decreases to nearly 70% at 600°C.

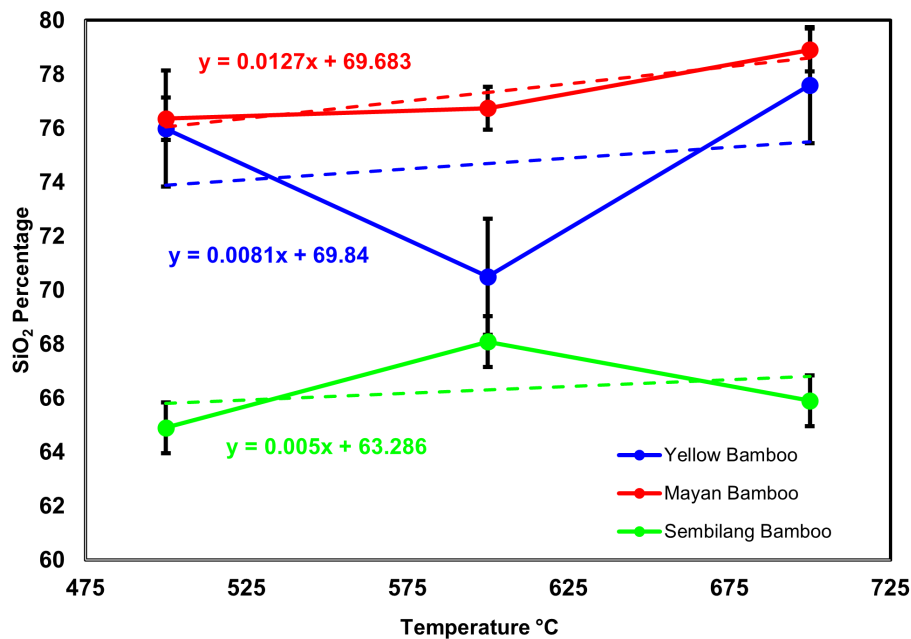


Figure 4 Comparison of SiO_2 Content in Various Bamboo Types Against Temperature

Thereafter, the content rises again to almost 77% at 700°C. This pattern suggests a critical point at 600°C, where mineral decomposition may occur before stabilizing at higher temperatures. Its regression equation, $\%SiO_2 = 0.0081(T) + 69.84$, shows an overall upward trend,

although with a smaller slope than that of the Bambu Mayan. Sembilang Bamboo has the lowest SiO₂ content among the three species. At 500°C, its SiO₂ content is approximately 64%, slightly increasing to 66% at 600°C, but then dropping again to approximately 65% at 700°C. The regression equation, %SiO₂ = 0.005(T) + 63.286, indicates a very slow upward trend with an almost flat tendency. This suggests that Sembilang Bamboo has less potential in producing high SiO₂ content, even at higher combustion temperatures. Overall, the results demonstrate that Mayan Bamboo is the most superior species in yielding high and stable SiO₂ content within the tested combustion temperature range, followed by Bambu Kuning, which exhibits mid-range fluctuations, while Sembilang Bamboo shows the lowest content with insignificant improvement.

The elongated layered structure is clearly visible in Figure 5, and it is likely that remnants of the bamboo leaf cellulose network are still preserved after the combustion process. This morphology reveals the presence of fine pores and small cavities distributed across the particle surface. Such porosity is highly significant because it increases the specific surface area, thereby enhancing the potential for pozzolanic reactions when BLA is incorporated into other materials, such as soil.

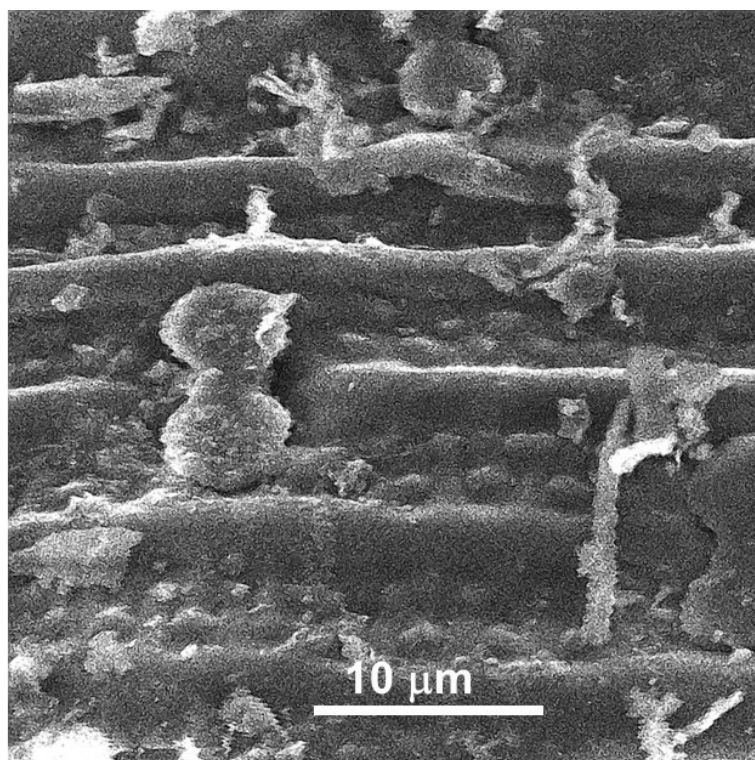


Figure 5 Microstructure photo of BLA at 5,000 magnification Scanning Electron Microscope (SEM)

3.3 Bentonite-BLA Composite

Figure 6 shows a significant decreasing trend in the Liquid Limit (LL) and Plasticity Index (PI) values as the additive percentage increases, while the Plastic Limit (PL) remains relatively stable with only slight fluctuations. The LL decreases from approximately 570% to 270%, with a regression equation of $y = -15.101x + 573.99$, indicating a reduction of approximately 15% for each 1% increase in additive content. This suggests that the soil gradually loses its plastic characteristics and becomes easier to stabilize. The PL values remain nearly constant, ranging from 110% to 120%, with a regression equation of $y = -2.0507x + 127.93$, indicating that the additive has only a minor effect on the PL. In contrast, the PI decreases sharply from approximately 460% to 180%, with a regression equation of $y = -13.05x + 446.96$, confirming that the additive significantly reduces the soil's SSP. Overall, these trends demonstrate that

the addition of the stabilizing material is effective in lowering soil plasticity and enhancing its geotechnical stability, which is highly beneficial for construction applications.

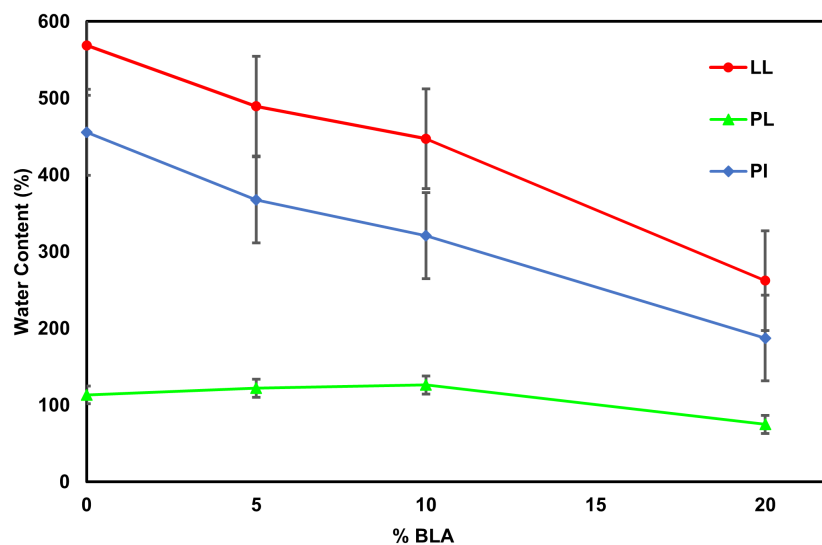


Figure 6 Relationship between BLA Percentage and Soil Water Content: Analysis of the Effect of LL, PL, and PI

3.4 Crystalline materials based on diffraction patterns using X-ray diffraction (XRD)

The identification of crystalline materials using X-ray diffraction (XRD) is an established technique that provides important insights into the structural properties of various materials, including BLA.

Figure 7 shows that the addition of BLA material to bentonite successfully changed the mineral composition of the soil. From what previously contained only ordinary clay minerals (Quartz and alumina) to a material containing cement compounds (C-S-H and C-A-S-H). The results were shown gradually from a mixture of 5%, 10%, and 20% BLA. BLA effectively acts as a stabilizing agent that can improve the mechanical properties (hardness/strength) of boronite.

3.5 Morphological of Bamboo Leaf Ash and Bentonite using Scanning Electron Microscope (SEM)

Morphological analysis of bamboo leaf ash (BLA) and bentonite using scanning electron microscopy (SEM) is a technique used to examine the surface structure, particle size distribution, and microphysical characteristics of the material. SEM is a tool that allows high-magnification visualization of the material surface down to the nanometer level.

Figure 8a shows surface observations using a Scanning Electron Microscope (SEM) at 650× magnification, showing changes in the bentonite microstructure after the addition of 5% Bamboo Leaf Ash (BLA). The particle surfaces were rougher, adhered to each other, and formed a dense aggregate structure resembling a bound mass. This morphological characteristic indicates the formation of interparticle bonds due to a chemical reaction, which can be identified as an initial cementation process. This structure differs from that of pure bentonite, which generally has a looser and more dispersed particle arrangement. Figure 8b shows the SEM at 650× magnification, showing the morphology of bentonite after the addition of 10% BLA, which undergoes a significant transformation. The particle surfaces appear denser, smoother, and more tightly bonded, indicating interparticle bonding consistent with cementation. Figure 8c shows the microstructure after the addition of 20% BLA at 10,000x magnification. This sample exhibits a rough, heterogeneous, and porous surface morphology. Its primary structure is dominated

by irregular particle agglomerations that coalesce to form clumps (aggregates) with features resembling overlapping plates or flakes.

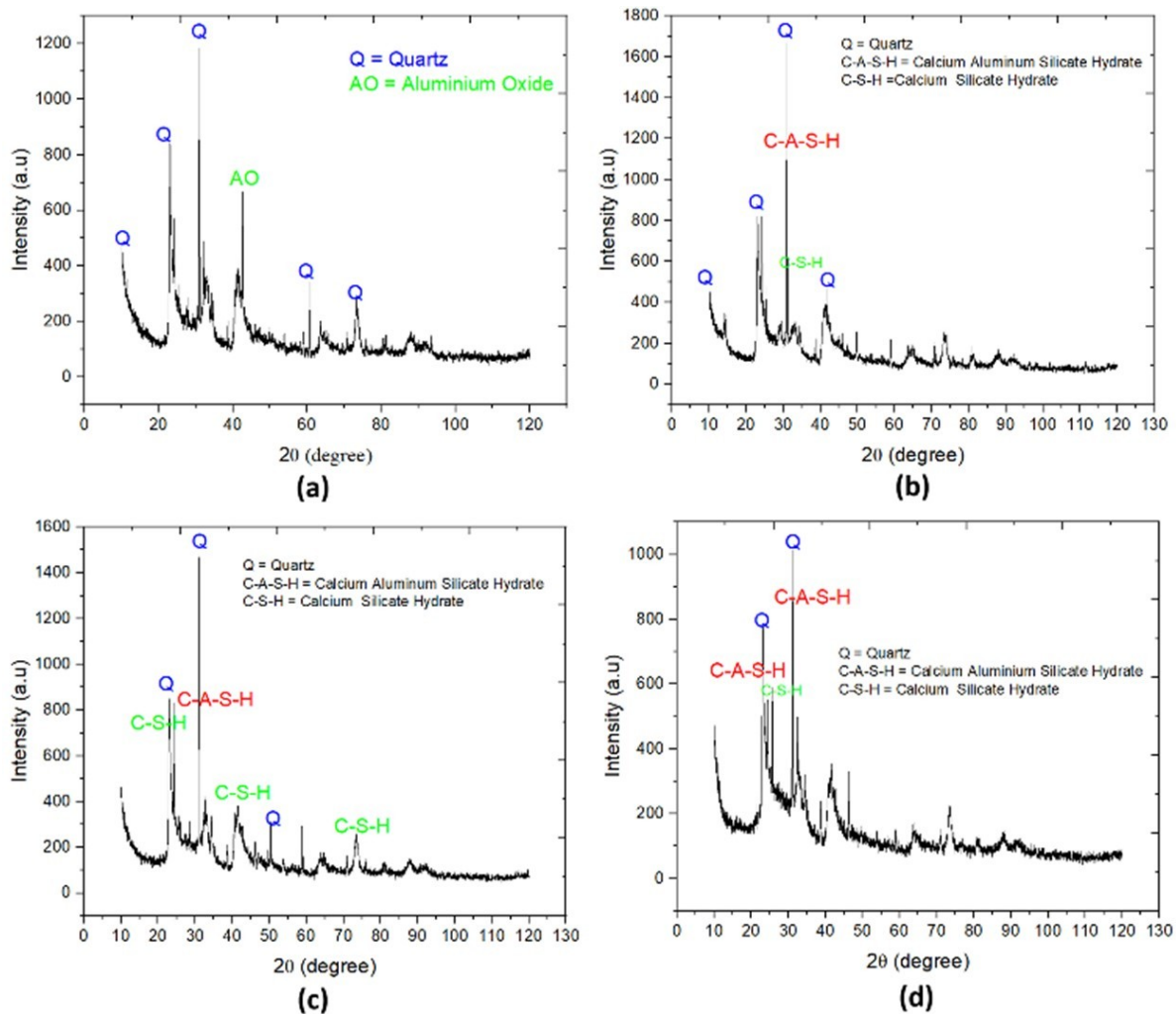


Figure 7 X-Ray Diffraction (XRD) of Bentonite (a) Bentonite, (b) bentonite + 5% BLA , (c) bentonite + 10% BLA , and (d) bentonite + 20% BLA

Table 4 shows that the largest chemical compound is SiO_2 for bentonite soil and BLA. The second-highest content is alumina Al_2O_3 . After bentonite is added with variations in BLA, changes in the behavior and composition of silica compounds occur due to the increase in Al_2O_3 values. This causes the SiO_2 content to decrease. Therefore, the addition of BLA can affect the ratio of SiO_2 to Al_2O_3 , which will later affect the mechanical properties (strength) of the final material.

Table 4 Chemical Composition Based on SEM EDS and XRF Analysis

%	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	SrO
BLA	2.844	1.032	76.740	2.530	0	3.957	0.025	0.160	0.214	0.116
0	1.547	19.016	69.29	1.301	0.382	2.465	0.517	0.034	5.423	0.025
5	1	23.909	63.391	1.383	0.262	2.006	0.8	0.055	0.037	7.157
10	1.314	17.307	71.362	1.368	0.389	2.5	0.496	0.035	5.206	0.024
20	0.913	13.315	76.61	1.384	0.38	2.091	0.37	0	4.928	0.009

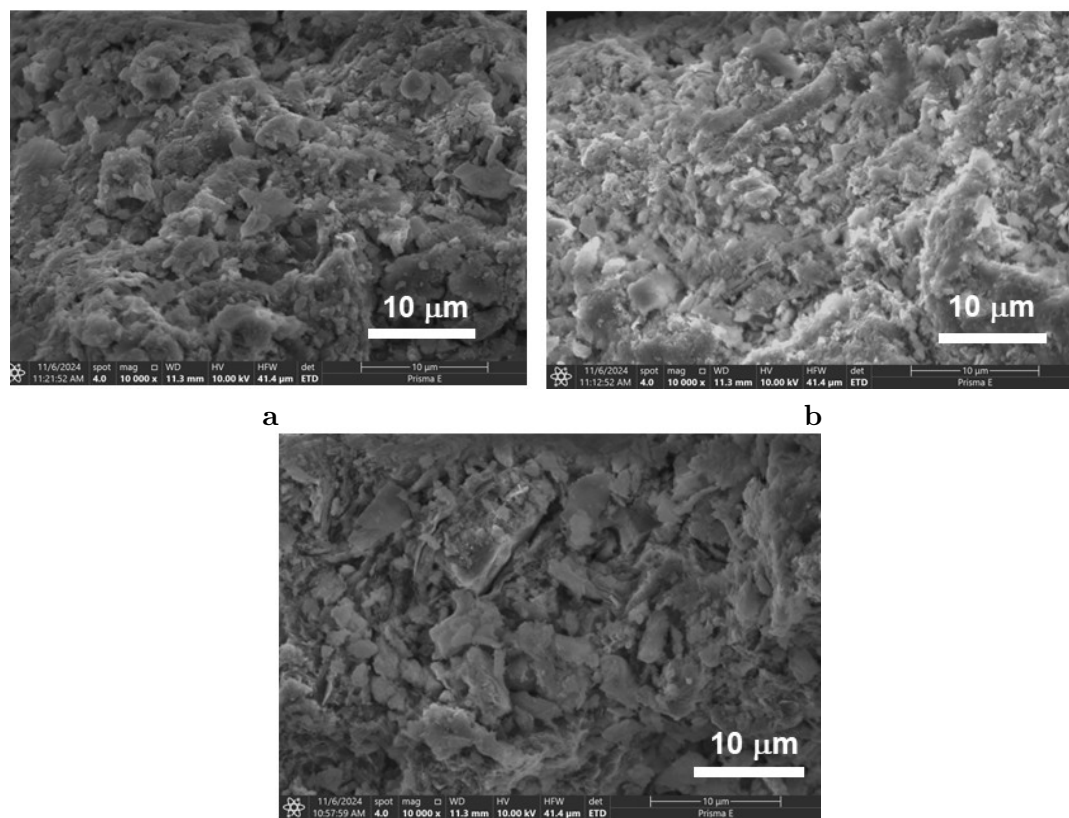


Figure 8 Scanning Electron Microscope (SEM) of (a) Bentonite + 5% BLA, (b) Bentonite + 10% BLA, and (c) Bentonite + 20% BLA

4. Conclusions

This study demonstrated that the integrated physical–chemical stabilization method using BLA as a pozzolanic additive is highly effective in reducing the plasticity of soils with extremely high plasticity, specifically bentonite. The laboratory investigation confirmed a significant decrease in Plasticity Index (PI) and Liquid Limit (LL), indicating a substantial improvement in the geotechnical behavior of the treated soil. The addition of BLA, especially at dosages up to 20%, successfully reduced the PI from 455.41% to 180% and LL from 568.70% to 270%, while the PL remained relatively stable. These changes reflect a marked improvement in soil workability and a decrease in swelling potential. Microstructural characterization by scanning electron microscopy (SEM) revealed progressive agglomeration and cementation effects, particularly with higher BLA content, whereas X-ray diffraction (XRD) showed mineralogical transformations indicative of pozzolanic reactions, including the formation of cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H). The energy-dispersive X-ray spectroscopy (EDS) and X-ray fluorescence (XRF) analyses confirmed the dominance of silica and alumina, validating the chemical reactivity of BLA. The main conclusion of the study may be presented in a short Conclusions section, which can stand alone. It should avoid repeating the Results and instead focus on highlighting the study’s significant findings and contributions.

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Author Contributions

Era Agita Kabdiyono: Recourses, Data Curation, Writing-original draft, Writing review & editing. Wiwik Rahayu: Conceptualization, Methodology, Investigation, Review. Budi Susilo Soepandji: Data curation, Formal analysis, Sri Wulandari: Writing review & editing.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Declaration of AI

During the preparation of this manuscript, the authors used artificial intelligence (Grammarly) to improve sentence structure and grammar. The authors have reviewed and edited the tool's output and take full responsibility for the content of this publication.

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