ASTONJADRO

pISSN 2302-4240
eISSN 2655-2086

Volume 15, Issue 1, March 2026, pp.0151-0160
DOI: http://dx.doi.org/10.32832/astonjadro.v15i1.20727 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

Soil Improvement Using Bamboo Leaf Ash and Cement on Triaxial UU Testing

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| Submitted: June19, 2025 | Revised: October 10, 2025 | Accepted: Febaruary 24, 2026 |

| Published: March 02, 2026 |

ABSTRACT

Soft soils, particularly those classified as low-plasticity silt (ML) according to ASTM D2487, pose considerable challenges in geotechnical engineering due to their low shear strength, high compressibility, and limited bearing capacity. This study evaluates the effectiveness of bamboo leaf ash (BLA), Portland Composite Cement, and their combination as stabilizing agents for ML-type soft soil. Laboratory investigations were conducted to assess changes in physical and mechanical properties, including Atterberg limits, specific gravity, compaction characteristics, and unconsolidated undrained (UU) triaxial shear strength. Four stabilization mixtures were analysed: untreated soil, soil with 10% BLA, soil with 5% cement, and a mixture of soil with 10% BLA and 5% cement. The results indicate that BLA alone enhances the internal friction angle from 11.03° to 38.84°, primarily through physical densification, but reduces cohesion from 64.49 kPa to 46.12 kPa. Cement treatment increases both cohesion 55.38 kPa and the friction angle 49.16° due to hydration and the formation of a cementitious bond. The combination of 10% BLA and 5% cement yielded the highest cohesion 102.59 kPa and a friction angle of 31.79°, highlighting the synergistic effect of pozzolanic reactions between reactive silica in BLA and calcium compounds from cement hydration. The study concludes that the BLA–cement mixture significantly improves the mechanical behaviour of soft silty soil, offering a sustainable and effective alternative to conventional soil stabilization methods, particularly when supported by controlled parameters such as ash fineness, burning temperature, and curing duration.

Keywords: soft soil stabilization, bamboo leaf ash, cement, Mohr–Coulomb, shear strength, UU triaxial.

INTRODUCTION

In many cities near the seashore, soft soil has been a great problem during construction of infrastructure near the sea. The soil is known to have low bearing capacity, high compressibility and low permeability. Due to those characteristics, soft soil poses a risk of excessive settlement, structural cracking, and even construction failure if not properly addressed.

Stabilization of soft soils were promoted by many engineers to deal with its problems. Soil stabilization is the procedure for enhancing the stability of soils, which involves treating natural soil to enhance its engineering characteristics. Chemical stabilization using binders like lime and cement became widely adopted. These materials chemically react with clay minerals, improving the strength, stiffness, and durability of soft soils. Cement, in particular, is highly effective but poses environmental concerns; its production accounts for approximately 7–8% of global CO_2 emissions, mainly due to the calcination of limestone and high-temperature kiln operations. As sustainability becomes a priority in civil engineering, research has shifted toward supplementary cementitious materials such as fly ash, rice husk ash, and bamboo leaf ash (BLA)**.** BLA, derived from the controlled burning of bamboo leaves, is rich in reactive silica and has shown promising results in improving soil strength, reducing plasticity, and enhancing durability. Studies indicate that incorporating 6–10% BLA by weight can significantly improve the California Bearing Ratio (CBR) and unconfined compressive strength of soft soils, while offering a low-carbon alternative to cement

[1]. Thus, BLA represents a viable and eco-friendly material for modern soft soil stabilization practices.

Since it would significantly Ωimprove soil strength and durability. However, cement production is energy-intensive and contributes substantially to carbon dioxide emissions. The majority of carbon dioxide (CO_2) emissions stem from the calcination process, where limestone ($CaCO_3$) is converted into lime (CaO). Additionally, fuel combustion to achieve the high temperatures necessary for calcination generates further CO2 emissions. Cement manufacturing is responsible for approximately 7% of global CO2. Cement is commonly used for soil stabilization because it significantly improves soil strength and durability.

The production of Ordinary Portland Cement (OPC) is widely recognized as a significant contributor to global carbon emissions, accounting for approximately 7–8% of total anthropogenic CO_2 emissions due to its energy-intensive manufacturing and limestone calcination processes. To address this challenge, researchers in civil engineering have turned to alternative supplementary cementitious materials (SCMs) derived from agricultural waste, one of which is BLA is obtained through the controlled combustion of bamboo leaves and is particularly attractive due to its high silica content—typically ranging from 70–84%—which imparts strong pozzolanic activity. This silica reacts with calcium hydroxide in cement to form additional calcium-silicate-hydrate (C–S–H), enhancing the strength and durability of concrete composites. Studies have shown that partial replacement of OPC with BLA, particularly at 8–12% by weight, can maintain or even improve 28-day compressive strength, while also refining pore structure and enhancing resistance to sulfate attack, chloride penetration, and alkali-silica reaction. For instance, concrete with 10% BLA has demonstrated significantly reduced water permeability and improved resistance to degradation, making it suitable for durability-critical infrastructure. However, due to the finer particle size and porous nature of BLA, adjustments in water demand and curing conditions may be necessary. The application of BLA not only contributes to reduced greenhouse gas emissions but also promotes the beneficial reuse of agricultural waste, aligning with sustainable construction practices and circular economy principles.

Indicates that bamboo leaf ash has a chemical composition comparable to that of cement, particularly due to its high silica content. The ash is produced through a gradual combustion process, beginning with open combustion and then continuing in a closed furnace at 600°C for two hours. This method yields ash with a high content of amorphous silica, which can potentially act as a pozzolanic material. This means it can react with calcium hydroxide ($Ca\ (OH)_2$) from cement to form secondary binding compounds in the form of calcium silicate hydrate (C–S–H), which helps to strengthen soil structure. Using bamboo leaf ash at a 10% concentration combined with 5% cement has been shown to significantly increase the compressive strength of soft soil. The active silica content in bamboo leaf ash improves the physical and mechanical properties of the soil by reducing plasticity and enhancing cohesion and stiffness.

Bamboo leaf ash (BLA) has significant pozzolanic potential due to its high silica content. However, its effectiveness as a standalone binder for soft soil stabilization is limited because it contains a low concentration of calcium oxide (CaO). Unlike cement, which quickly forms strength-giving calcium silicate hydrates (C–S–H), BLA primarily provides reactive silica, which cannot initiate sufficient pozzolanic reactions on its own without an external source of calcium.

Therefore, BLA is most effective when used in combination with cement, which supplies the necessary CaO for activation. Demonstrated that blending 8% cement with 8% BLA significantly improved both soaked and unsoaked California Bearing Ratio (CBR) values of lateritic soils, achieving results between 60% and 90%. Similarly, Obilade et al. (2015) found that incorporating BLA at a 6% replacement level enhanced the CBR of treated soil from 6.2% to 35%. However, higher replacement levels led to a decline in strength due to insufficient calcium available for a complete pozzolanic reaction.

Discovered that a minimal cement percentage of 2% combined with 10% BLA yielded optimal strength and compaction in stabilized soils. These findings indicate that while BLA can help reduce cement usage and lower CO_2 emissions, it acts best as a supplementary binder rather than a complete replacement for cement. Therefore, achieving a balanced mix ratio is essential, with BLA serving as a sustainable enhancer in hybrid systems. This ensures acceptable geotechnical performance while promoting environmental benefits.

Stabilization of soft soil using cement and BLA is still under rigorous study, especially to many soil samples. Thus, this study conducted a series of laboratory tests to evaluate the effect of soft soil stabilization using cement, BLA, and a mixture of BLA+cement to its index properties characteristics and its strength properties.

RESEARCH METHODS

Materials

Soil

In this study, the soil material was taken from Pantai Indah Kapuk, North Jakarta, from a test pit at a depth of 3-6 m. The soil was taken in December 2023. The soil was taken in bags and is classified as a disturbed soil sample. According to the geological the soil sample was in the Qa formation, which consists of silty clay, gravelly sand, gravel, and shale. Visually the soils appear dark gray, smooth and cohesive with wet surface.

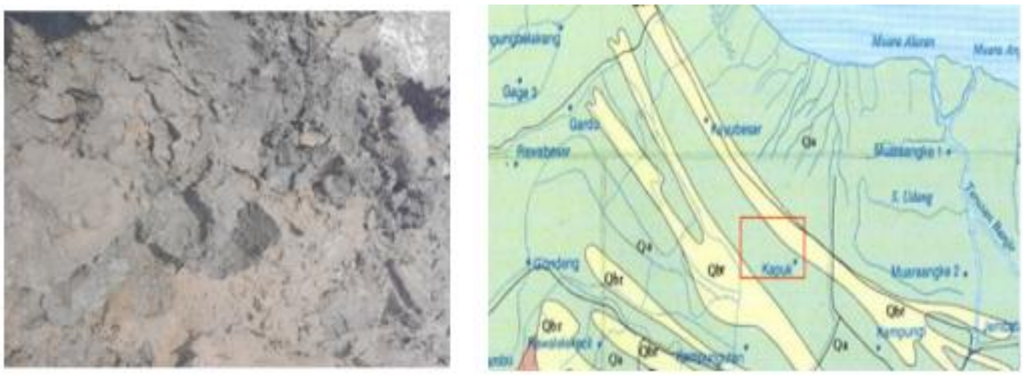

Figure 1. Soil sample and the geological Map

The soil was taken to the Soil Mechanics Laboratory at University of Indonesia and dried at 110ºC for 24 hours to ensure that the water content of the soil is quite small and easier to mix with the stabilizers.

Bamboo Leaf Ash (BLA)

Bamboo leaf ash in this study uses Mayan bamboo (*Gigantochloa robusta Kurz*), which is procured from BRIN Cibinong. The bamboo leaves were heater for 2 hours at 600 °C to produce high pozzolanic activity. Bamboo leaf ash (BLA) is considered effective for soil stabilization primarily due to its high silica (SiO_2) content**,** which typically ranges from 65% to 85%.

Portland Composite Cement

This study used Portland Composite Cement, which is a composite hydraulic binder comprising slag Portland cement mixed with one or more inorganic materials. One of the key reasons PCC is commonly chosen for soil stabilization and general infrastructure projects in Indonesia is its availability and compatibility with local construction practices, especially in combination with pozzolanic materials like bamboo leaf ash. Its relatively lower environmental footprint—due to the partial substitution of clinker—makes PCC a more sustainable choice compared to Ordinary Portland Cement (OPC), while still delivering reliable mechanical performance and durability under tropical conditions

Methods

This experimental study was conducted in the Soil Mechanics Laboratory of the University of Indonesia over a six-month period from January to June 2024. The objective of the research was to evaluate the influence of bamboo leaf ash (BLA) and Portland Composite Cement (PCC) on the physical and mechanical properties of soft clay soil. The investigation included comparisons among untreated soil, soil treated with BLA, soil treated with cement, and soil treated with a combination of BLA and cement.

Stabilization Mixture Procedure

The dry soft soil was blended thoroughly with BLA and o cement in accordance with the mix design. Water was added to each mixture based on the optimum moisture content, determined through a preliminary standard Proctor Compaction Test. Each mixture was then compacted into cylindrical molds and sealed to prevent moisture loss. All samples were cured at room temperature (~30°C) for 24 hours.

Tests Performed on the Stabilized Mixture

This study focuses on the changes in the physical and mechanical properties of soft clay soil as a result of stabilization using bamboo leaf ash (BLA), cement, and their combination. The physical properties assessed include the optimum moisture content and maximum dry density, determined using the Modified Proctor Compaction Test, specific gravity, tested in accordance with [3], and the Atterberg limits, including the liquid limit and plastic limit, following [4]. For mechanical behaviours, the primary test conducted was the Unconsolidated Undrained (UU) Triaxial Compression Test [5]. This test was selected to simulate undrained field conditions, in which no consolidation or drainage occurs during loading. The UU triaxial test provides insight into the short-term shear strength of soft soils, making it a critical assessment for evaluating the immediate performance of stabilized ground.

Unconsolidated Undrained (UU) Triaxial Compression Test

The Unconsolidated Undrained (UU) Triaxial Compression Test was conducted in accordance with [5] to evaluate the short-term shear strength of both treated and untreated soft clay samples. This test was selected because it simulates undrained field conditions, where pore water does not have time to dissipate during rapid loading, such as during embankment or foundation construction on saturated soils.

Cylindrical specimens with a standard dimension of 38 mm diameter and 76 mm height were prepared from each mix. After 24 hours of curing, the samples were removed from molds, carefully trimmed, and wrapped with a thin rubber membrane before being mounted inside the triaxial cell. No drainage was allowed before or during loading, and no back pressure was applied to maintain the undrained condition. Each specimen was subjected to a range of confining pressures 50, 100, and 150 kPa to develop Mohr-Coulomb failure envelopes.

RESULT AND DISCUSSION

Specific gravity (GS)

Specific gravity (GS) is a measure of the density of soil particles relative to water. The GS values in this research are presented in Table 1.

Table 1. Results of measurement of Specific Gravity

Sample Code	GS Value	Remarks
Sample 1	2,63	0% BLA, 0% Cement
Sample 2	2,68	Soil+ 10% BLA
Sample 3	2,69	Soil+ 5 % Cement
Sample 4	2,71	Soil 10%+5 Cement

From Table 1, the addition of BLA and Cement increases the Specific Gravity of the stabilized soft soil. The main reason of the increase of specific gravity is due to the minerals. For instance, an

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eISSN 2655-2086
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addition of 10% BLA increases the Specific Gravity from 2.63 to 2.68. This increase is attributed to the silicate compounds in BLA, which enhance the density of the mixed soil. Addition of 5% cement (Gs = 3.10), to the soil raised the stabilized soil further, from 2.63 to 2.69. The change due to the 5% cement occurs because the specific gravity of ordinary Portland cement (OPC) is higher than that of the original soil. However, The highest specific gravity value is achieved by mixing 5% cement with 10% BLA in the soil. The increasing specific gravity is in line with previous research (input riset lain yang nulis kalau Gs naik biar bisa support) During this mixing process, both the cement and BLA fill the spaces between soil particles, leading to an increase in the overall density of the mixture and thereby enhancing soil density [6]. An increase in Gs generally indicates a higher proportion of mineral-rich particles in the soil, which is advantageous for stabilization. Higher specific gravity corresponds to better packing of soil particles, reduced porosity, and greater dry density [7]. These characteristics enhance the soil's ability to resist deformation under loading, thereby improving its load-bearing capacity and shear strength. Furthermore, elevated Gs values often correlate with improved resistance to volume change and increased durability of the stabilized soil layer [8]. Therefore, the observed increase in Gs in this study demonstrates a positive contribution of both BLA and cement toward improving the physical integrity of soft soils for geotechnical applications.

Atterberg Limit

The test results from plastic limit and liquid limit tests in this study are summarized in Table 2.

Table 2. Results of Atterberg Limit

Sample Code	**LL**	**PL**	**PI**	**Classification**
(0% BLA, 0% Cement)	40%	35,64%	4,79%	ML
(Soil+ 10% BLA)	38,20%	32,28%	5,92%	ML
(Soil+ 5 % Cement)	61,85%	44,88%	16,97%	CH
(Soil 10%+5 Cement)	47,70%	27,52%	20,18%	CL

Liquid limit (LL) values below 35% indicate low plasticity, 35–50% indicate medium plasticity, 50–70% high plasticity, and 70–90% very high plasticity. In this study (Table 2), the untreated soft clay falls into the low plasticity category. The addition of 10% bamboo leaf ash (BLA) did not significantly alter plasticity, suggesting limited change in clay mineral behavior. However, adding 5% cement elevated plasticity into the high plasticity range, indicating increased cohesion and water affinity. The combination of 10% BLA + 5% cement produced the highest plasticity index (PI), revealing a notable shift toward more plastic soil behavior. Although higher PI may suggest increased susceptibility to moisture change, it can also reflect improved soil–binder interaction and enhanced cohesiveness—conditions that often contribute to greater strength and stability once cured. This finding aligns with [7], who reported that BLA enhanced the liquid limit of clayey soil from approximately 40% to around 55%, signaling improved stabilizer–soil interaction and stabilization potential

According to [9], the A-line on the plasticity chart is used to classify fine-grained soils based on their liquid limit (LL) and plasticity index (PI). Soils that plot above the A-line with LL < 50% are typically classified as CL (inorganic clay of low to medium plasticity), while those that plot below are classified as ML (inorganic silt). Based on the data in Table 2 and visualized in the A-line chart, the original soft clay sample (LL = 38%, PI = 6%) plots just above the A-line, placing it within the CL–ML transition zone, often interpreted as a low to medium plasticity clay-silt mixture.

When 10% bamboo leaf ash (BLA) was added, the LL and PL slightly decreased to 38.20% and 32.28%, respectively, while the PI remained relatively stable at 5.92%. Although BLA does not chemically react like cement, it can improve the soil's physical structure by absorbing water and filling micro voids, thus promoting interparticle friction and reducing water film thickness—

mechanisms also reported [1]. This suggests that BLA enhances soil behavior primarily through physical modification rather than chemical reaction.

In contrast, the addition of 5% cement significantly increased the LL to 61.85%, the PL to 44.88%, and the PI to 16.97%, shifting the soil into the high plasticity CL region on the plasticity chart. This increase reflects the initial hydration reactions of cement, which form cementitious gels that bond soil particles and increase plasticity, as supported [7]. These gels enhance the cohesive structure of the soil and expand its capacity for plastic deformation before failure.

From the last stabilization variation, which is soil added with 10% BLA and 5% cement, the PI increases to 20.18%, the LL decreases to 47.70% and the PL decreases to 27.52%. In table 2, the addition of 10% BLA and 5% cement was seen to increase the PI into the highest value. Although the decrease of LL and PL and increase of PI seems contradictory, the behavior indicates that the initial reaction between cement and ash began to form a cohesive structure. However, the structure was not yet fully stable due to insufficient curing time. The phenomenon found in this study aligns with the findings, which reported that the reduction in PI due to the addition of BLA only occurred after a curing process of at least 21 days. Similar findings were reported by Wijaya (2021), which stated that the combination of cement and BLA is effective in reducing soil plasticity and swelling if supported by sufficient curing time.

Additionally, [7] noted that BLA can absorb free water and improve the distribution of soil micropores. However, its stabilizing effect becomes significantly noticeable only after a specific reaction time. Also demonstrated that combining ash and cement can increase soil CBR and reduce expansion potential, although PI values may temporarily increase during the structural transition process. Based on the previous studies, it can be concluded that the increase in PI values in this study is still in an initial stage, and it is not an indication of failure, but rather a part of the chemical reaction process.

Standard Proctor Compaction

The standard compaction test is a critical procedure used to determine the optimum moisture content (OMC) and maximum dry density (γ dry) of soil. Table 3 presents the results of standard compaction tests conducted on the soil sample and soil samples treated with BLA and cement.

Table 3. Results of Optimum moisture content and maximum dry density (γ dry)

Sample Code	OMC	γ dry (g/cm^3)
Sample 1 (0% BLA, 0% Cement)	32,12%	1,39
Sample 2 (Soil+ 10% BLA)	24,43%	1,48
Sample 3 (Soil+ 5 % Cement)	29,75%	1,7
Sample 4 (Soil+10% BLA+5 Cement)	34,02%	2,17

From Table 3, the natural soil without stabilizers have OMC of 32.12% and γ dry of 1.39 grams/cm^3. Adding 10% BLA to the soil decreases the OMC to 24.435%, while the γ dry increases to 1.48 grams/cm^3. On another hand, adding 5% cement decreases the OMC to 29.75% and increases the γ dry to 1.749 grams/cm^3. Lastly, mixtures of 10% BLA and 5% cement increases the OMC to 34.02% and the γ dry to 2.17 grams/cm^3. The results of adding stabilizers such as BLA and cement steadily increases the γ dry with the found when adding 10% BLA + 5% cement. The increase is attributed to the synergy between bamboo leaf ash and cement, where the silica released from BLA and calcium oxide from cement fill the voids and bind the particles together. This study aligns [10], which showed that a mixture of 14% cement and 20% BLA produced an optimum option of cement and BLA mixture from their soil. Showed that BLA exhibits optimum results in clay soils, especially soft clay, which has a high specific surface area and large cation exchange capacity, enabling it to bind with active compounds in ash [7], [11].

pISSN 2302-4240
eISSN 2655-2086
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However, the ML soil used in this study has a silt-dominated composition, which is generally more inert and lacks the mineral surface reactivity found in clay. Through XRD and XRF analysis, BLA's pozzolanic reactions depend on interaction with fine-grained, chemically active substrates. In silt soils, the coarser and less reactive particles limit the formation of effective cementitious bonds [12]. Therefore, while BLA alone can aid in densification through physical modification, it cannot serve as a standalone stabilizer for silt soils. The results confirm that cement is required to chemically bond and solidify ML soils, while BLA acts as a beneficial supplement rather than a primary stabilizing agent.

The UnconsolidatedUndrained (UU) Triaxial

To determine the mechanical properties of the stabilized soil, the triaxial test method is used to understand the effect of BLA and Cement as stabilizers to the shear strength parameters. The results can be seen in Figure .

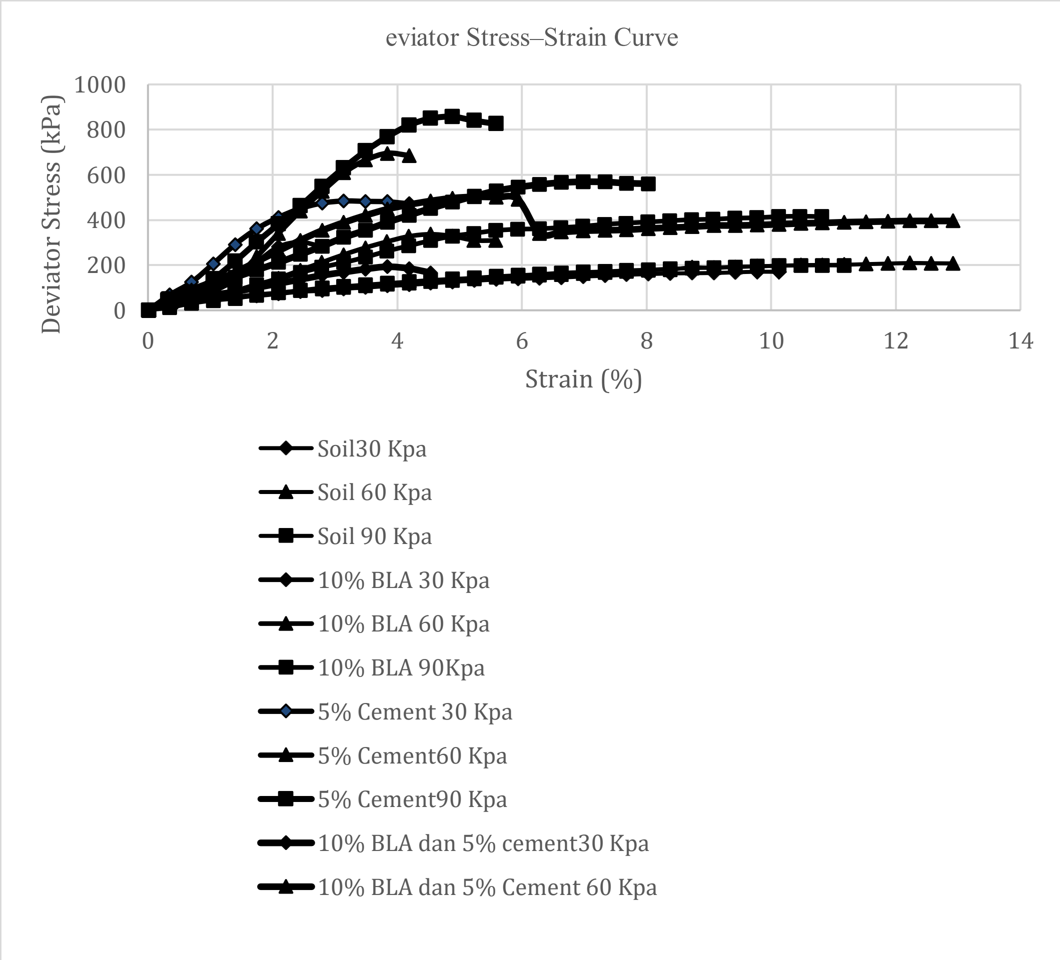

Figure 2. Deviator Stress and Strain Graph

Figure 2 presents the stress–strain behavior of untreated and stabilized soft soil samples under unconsolidated undrained (UU) triaxial compression conditions at confining pressures of 50, 100, and 150 kPa. The objective of this test is to evaluate short-term shear strength performance, particularly under saturated and undrained conditions representative of embankment or foundation loading scenarios in soft soil environments.

The untreated soft soil (exhibits a relatively ductile behaviour with limited deviatoric stress across all confining pressures, reaching peak strengths of approximately 140 kPa, 220 kPa, and 300 kPa at

50, 100, and 150 kPa, respectively. This reflects the inherently low strength of ML-classified silt under undrained loading, as expected for low plasticity soils.

Upon stabilization with 10% BLA, the deviator stress increases modestly across all confining pressures, indicating slight improvement in interparticle bonding and cohesion due to the physical filler effect of BLA. However, the stress–strain curves remain relatively flat post-peak, with visible strain softening and early yielding. This confirms that BLA alone does not significantly improve the undrained shear strength, which aligns with prior findings that BLA requires reactive clay minerals or cementitious binders to achieve chemical bonding [7].

In contrast, samples treated with 5% cement show a pronounced improvement in both peak strength and stiffness. At 150 kPa confinement, the cement-treated sample reaches nearly 600 kPa in deviatoric stress, exhibiting more brittle behavior with clear peak strength and reduced strain softening. This suggests successful hydration reactions and early-stage formation of cementitious gels (C–S–H), which enhance particle interlock and internal friction.

The most significant improvement is observed in the composite mix of 10% BLA and 5% cement. At 150 kPa confining pressure, this mixture achieves a peak deviatoric stress of over 800 kPa, demonstrating the highest strength and most rigid response of all tested samples. The curve shows strong initial stiffness, rapid stress build-up, and clear failure peak, confirming synergistic pozzolanic activity. The silica-rich BLA appears to react with calcium hydroxide from cement hydration, forming additional cementitious products and contributing to matrix densification and enhanced cohesion.

Overall, these results confirm that BLA alone offers limited improvement in undrained shear strength for ML soils. Cement alone performs significantly better due to hydration bonding. However, combining BLA with cement provides the most effective stabilization strategy—achieving both environmental sustainability (through partial cement replacement) and mechanical performance—making it a viable solution for soft silt stabilization under undrained condition.

The Mohr–Coulomb failure envelopes derived from the UU triaxial test results illustrated the progression of shear strength parameters—namely cohesion (c) and internal friction angle (φ)—as the soil is treated with bamboo leaf ash (BLA), cement, and their combination. The untreated soil, classified as low-plasticity silt (ML), displays small Mohr circles with a low envelope intercept and shallow slope, indicating low cohesion and poor frictional resistance.

With the addition of 10% BLA, the Mohr circles expand modestly and the failure envelope becomes slightly steeper. This minor improvement is attributed to the physical effect of BLA particles, which fill voids and enhance particle contact, resulting in limited increases in strength. However, due to the absence of reactive clay minerals and calcium hydroxide, the pozzolanic potential of BLA remains underutilized in ML soils [1]. In contrast, the sample treated with 5% cement exhibits significantly larger Mohr circles and a noticeably steeper envelope, reflecting increased cohesion and friction angle. The formation of cementitious products such as calcium silicate hydrate (C–S–H) through early hydration strengthens interparticle bonding and improves resistance to deformation [7], [10].

The most substantial enhancement is observed in the sample stabilized with a combination of 10% BLA and 5% cement. The resulting Mohr circles are larger and the failure envelope exhibits both high intercept and steep slope, indicating a significant gain in both c and φ. This confirms a synergistic interaction between the reactive silica in BLA and the calcium in cement, facilitating the formation of additional C–S–H compounds. These compounds densify the soil structure, improve cohesion, and enhance shear strength beyond the levels achievable by BLA or cement alone [11], [13]. In conclusion, while BLA contributes mainly through physical mechanisms in silty soils, its effectiveness is substantially amplified when used in conjunction with cement. The combination markedly enhances undrained shear strength parameters, offering a promising stabilization strategy for low-plasticity fine-grained soils.

ASTONJADRO
pISSN 2302-4240
eISSN 2655-2086
Volume 15, Issue 1, March 2026, pp.0151-0160
DOI: http://dx.doi.org/10.32832/astonjadro.v15i1.20727 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

Table 4. Cohesion and Friction Angle

Sample Code	Cohesion (Kpa)	ϕ
Sample 1 (0% BLA, 0% Cement)	64,49	11,03°
Sample 2 (Soil+ 10% BLA)	46,12	38,84°
Sample 3 (Soil+ 5 % Cement)	55,38	49,16°
Sample 4 (Soil+10% BLA+5 Cement)	102,59	31,79°

The soil sample displayed moderate cohesion (64.49 kPa) but a low friction angle (11.03°), characteristic of ML-classified silt under undrained loading, which tends to exhibit weak interparticle friction and cohesion due to limited bonding capacity.

When 10% bamboo leaf ash (BLA) was added), cohesion decreased to 46.12 kPa while the friction angle rose sharply to 38.84°. This increase in ϕ indicates that BLA improves soil friction by physically altering the soil structure—filling voids and promoting particle interlocking—rather than through chemical bonding. Similar findings were reported [1], [14], who observed that BLA alone enhanced friction angle in fine-grained soils but offered limited cohesion improvement. Soil treated with 5% cement, showed increases in both cohesion (55.38 kPa) and friction angle (49.16°), confirming that cement hydration products—particularly calcium silicate hydrate (C–S–H)—improve both bonding and internal friction. This is consistent with the results [7], [15], who demonstrated that cement significantly improves both shear parameters in soft subgrade soils. The highest cohesion value was observed in the 10% BLA + 5% cement mixture (Sample 4), at 102.59 kPa. This reflects a synergistic effect, where reactive silica in BLA interacts with calcium hydroxide from cement to form secondary cementitious products. Although the friction angle (31.79°) is lower than that in the cement-only sample, the significant gain in cohesion more than compensates for the decrease. Combinations are particularly effective in soft fine-grained soils where pozzolanic reactivity and binder dispersion must work in tandem to improve mechanical strength.BLA contributes to improved frictional resistance through physical means, while cement increases both cohesion and friction due to chemical bonding. Their combination yields the most substantial improvement in shear strength, particularly in cohesion, making it a favorable strategy for stabilizing ML-type silts under undrained conditions [10], [16].

CONCLUSION

Based on laboratory test results conducted on sandy loam soil stabilized with bamboo leaf ash (BLA) and cement, it can be concluded that the addition of these materials significantly influences the soil's index properties, density, and shear strength parameters. Specifically, incorporating 10% BLA and 5% cement resulted in the highest increase in maximum dry bulk density at 2.17 g/cm³. This increase indicates enhanced density due to the filling effect and the bonding of particles, facilitated by silica from the BLA and calcium from the cement. Although the optimum moisture content increased to 34.02%, it remains within an acceptable range for compaction processes involving reactive additives. Regarding Atterberg limits, the combination of BLA and cement raised the plasticity index (PI) to 20.18%, which indicates improved cohesion and the potential for the initial formation of new soil structures. However, stability has not yet been fully achieved without a curing process. UU triaxial testing yielded notable results for the mixture of BLA and cement, with the cohesion value reaching 102.59 kPa—this was the highest among all tested mixtures. However, there was a decrease in the internal friction angle to 31.79°. This suggests that the formation of a homogeneous rigid structure due to pozzolanic reactions reduces friction between particles of varying sizes. On the other hand, BLA alone effectively increases the internal friction angle to 38.84° but reduces cohesion. Cement demonstrates a more balanced effect, as it enhances both cohesion and the friction angle. Therefore, the effectiveness of stabilization is heavily reliant on the mineral characteristics of the soil, with clay soils being more reactive to BLA. It also depends on technical conditions such as curing processes and mixing ratios. Overall, while the combination of BLA and cement shows great potential for improving the mechanical properties of soil, it is crucial to tailor these approaches to field conditions and the specific type of soil being used.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to the Soil Mechanics Laboratory, Department of Civil Engineering, Universitas Indonesia, for providing the facilities and technical support required for the experimental work in this study.

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