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Henri Haggai Y. Cua
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University

Julianne Carissa C. Ferrer
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University

Kyle Vincent T. Go
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University

Eddryck Benjamin C. Yao
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University

他

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Strength Development Assessment of Banana Leaf Ash and Lime Mixture in Clayey Sand Soils

Henri Haggai Y. Cua[1], Julianne Carissa C. Ferrer[1], Kyle Vincent T. Go[1], Eddryck Benjamin C. Yao[1]
Irene Olivia Ubay-Anongphouth[1]
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University.
Corresponding author email: irene.ubay@dlsu.edu.ph

Abstract: *High clay-content soils exhibit suboptimal geotechnical characteristics, including low shear strength, potentially leading to structural failure. This study investigates Banana Leaf Ash (BLA) as a sustainable alternative pozzolan to carbon-intensive cement, utilizing lime as an activator. The shear strength and geotechnical index characteristics of clayey sand altered with 5%, 10%, and 15% BLA (with 8% lime) were assessed. Reduced specific gravity, a coarser grain size distribution, higher optimal moisture content, and a lower maximum dry density were all associated with higher BLA content. The lowest Plasticity Index value was obtained at 5% BLA. Shear strength measures rose with curing time (7 and 28 days).*

Keywords: Banana Leaf Ash; Pozzolanic Compounds; Shear Strength

1. INTRODUCTION

Soil stabilization is the process of altering the geotechnical properties of soil in order to increase its mechanical strength. Conventional techniques include adding chemical admixtures, like cement and lime, which create pozzolanic reactions in the soil matrix to produce cementitious compounds. However, the manufacturing of cement is linked to the release of pollutants into the atmosphere, particularly greenhouse gases. As a result, studies are concentrating more on assessing different soil stabilization agents, such as bio-based pozzolans, as more ecologically friendly additives [1]

In the Philippines, banana is a significant cash crop and is commonly found in the country [2]. This generates an abundance of banana leaves which is an easily accessible resource to produce banana leaf ash (BLA). Leveraging locally sourced, high-volume recyclable and waste streams in infrastructure development, coupled with suitable processing methodologies for economic valorization of waste materials, would significantly promote sustainable development [3, 4]. These leaves, which are regarded as agricultural waste, offer a promising potential as a pozzolan for long-term soil stabilization applications [5]. Previous studies have demonstrated that BLA has pozzolanic potential in lateritic soils [6]. According to their findings, optimum moisture content (OMC) was directly correlated with the BLA mixture, whereas maximum dry density (MDD) declined as the percentage of BLA increased. With the introduction of BLA their soil mix resulted with increased California bearing ratio and unconfined compressive strength values which peaked at 4% BLA. The increase in strength is attributed to BLA having 48.7% silicon dioxide (SiO_2) content reacts with the calcium hydroxide ($Ca(OH)_2$) found in the soil to generate cementitious calcium silicate ($CaSiO_3$). Daramola [7] conducted more research to determine the ideal BLA % for clay soils. He experimented with 2%, 4%, and 6% BLA concentrations by burning banana leaves at 550°C to create BLA, and he found that 4% BLA produced the largest increase in the California Bearing Ratio (CBR).

When BLA, a pozzolan, and the calcium in the soil combine to form cementitious compounds, the pozzolanic reaction takes place [8]. The possibility of starting a pozzolanic reaction with a larger sand percentage is unclear, though, because the study uses clayey sand. If the soil's calcium content is insufficient for adequate binding, lime should be added as a calcium supplement. Research has indicated that lime works well for stabilizing clayey soils [3]. Quicklime works better at stabilizing soil than hydrated lime [9].

According to previous studies, BLA is an effective pozzolanic material, but it has not been thoroughly investigated, particularly when combined with lime. The study examined BLA utilizing various burning techniques, temperatures, and time to determine the ideal BLA burning parameters for the soil mixture that contained varying percentages of lime. This study improves the understanding of how BLA and lime can be used to increase the shear strength and index properties of soil. Future investigations on BLA soil stabilization and other geotechnical applications may benefit from this study as well.

2. MATERIALS AND METHODOLOGY

2.1 Material Preparation

Based on the positive relationship between leaf age and silica concentration, mature banana leaves, typically those up to 1 to 4m in length and 1 m in width were chosen. After being picked and cleaned to remove any surface impurities, 80 leaves were desiccated by air drying for a week. To make crucible loading easier, the dried leaves were ground up with the use of a blender. In a homemade furnace, 50-gram samples were burned under controlled conditions. The temperature was raised linearly by 100°C every 7.5 minutes, reaching the desired temperature of 400°C over a 30-minute ramp and was burned for a total of 2 hours the result of which is seen on Figure 1. To increase its specific surface area and potential pozzolanic reactivity with substances like lime and water, the resulting BLA was grounded using a blender. The lime that was obtained was crushed and sieved using No. 40 sieve to increase surface area, The detailed methodology and results of how the temperature and burning time was determined is discussed in a separate paper.

Fig. 1. BLA burned for 2 hours at 400°C

2.2 Index Property Tests

This study utilized specific gravity, Atterberg limits, sieve analysis, hydrometer analysis, and standard proctor to determine the index properties of the soil and mixed soil. The soil was then added and mixed with 5%, 10%, and 15% BLA and a constant 8% lime based on their volume.

2.2.1 Specific Gravity Test

The test began by preparing the soil through sieve washing using sieve No. 200 to separate the fines and the coarse particles. It was then oven dried for a minimum of one day, pulverized separately, and combined for testing. A volumetric flask with 500 mL of distilled water was weighed and its uniform temperature recorded. Half of the water was transferred to a beaker. Based on varying percentages of BLA and constant 8% lime, different soil mass was required for the test and transferred to the volumetric flask for agitation. A vacuum machine was used to remove air bubbles for an interval of 5 minutes, each with 2 minutes rest, until air bubbles have been minimized/removed. The remaining de-aired water was placed back until the 500 mL mark and reweighed. The mixture was transferred to the pan and a squeeze bottle was then used to remove small particles in the flask into the pan then the entire mixture was weighed. Finally, the soil mixture was placed in the oven at 110°C for drying. After the soil has dried it will be weighed again for computation. This was repeated three times per set of BLA percentage.

2.2.2 Atterberg Limits

Two tests were done regarding the Atterberg Limits, namely: Liquid and the Plastic limit test. For the liquid limit, the soil sample was mixed with water to form clay-like texture, this is then placed on the brass cup of the Casagrande apparatus for grooving, evenly spreading it to a depth of 10 mm and the surface smoothed. The groove is made at the middle of the soil with edge facing the cup. The cup is rotated at rate of 2 drops per second starting from zero until the grooved portion has closed at the middle. A sample was taken at the grooved portion, and its water content was determined. The procedure was repeated until a range of blows was obtained: 15-25, 20-30, and 25-35 blows. For the plastic limit, the soil was rolled between the palm and fingers against a glass plate until it had a uniform diameter of 3.2 mm; should it break, it will be repeated and broken down into smaller pieces. The sample should reach a total of 6 grams before drying in the oven for moisture content computation. This process was repeated three times.

2.2.3 Sieve Analysis

The sample made use of the sieve washing to obtain the fines and coarse particles separately. This was oven dried for a minimum of a day to remove moisture. The process of segregation before pulverizing was done to preserve the fine and coarse particles so that the Particle Size Analysis will not be affected by the pulverizing process. 500g of soil sample was used and each sieve was weighed in descending order before the test. A pan was placed under Sieve No. 200 and weighed, then the soils sample was placed on topmost sieve and the stack of sieve was clamped on the sieve shaker. The sieve shaker shook the sieve for about 10 to 15 minutes; following this, the percentage of mass retained, and percentage of mass passing were recorded.

2.2.4 Hydrometer Analysis

From the fines obtained on the sieve wash, 50g of fines of soil was used for the hydrometer analysis. It was then combined with 250 mL of water, soaked for 10 minutes, and stirred to form a slurry. The slurry was then transferred to a cylindrical vessel, adding water to bring the slurry to a total volume of 1000 mL. The cylinder was then sealed with a red rubber stopper and then agitated for 1 minute. Afterwards the Cylinder was then placed in a water bath and the hydrometer readings and temperatures were taken at 2, 5, 15, 30, 60, 120, 240, and 1440 minutes. The need for the hygroscopic moisture content was disregarded for the soil sample was oven dried.

2.2.5 Standard Proctor test

During the sample preparation of the soil, the soil was air-dried, in accordance with ASTM D698-12, for a week; this is because the soil was highly saturated for the test to undergo. The soil was broken into finer pieces and sieved through Sieve No. 4, until 3 kg of soil has passed. This was spread into a large pan and subjected to small amounts of water until the desired moisture content is reached. The Proctor Mold and base plates were weighed. Approximately half of the mold sample was the first layer and compacted with 25 uniform blows. This was repeated for three layers in total. The extension collar was removed, and a steel edge was used to trim excess soil from the mold's surface. The mold and soil were weighed without the extension collar. The sample was broken midway in order to collect the samples from the middle top and the middle bottom layer. This was placed in moisture cans and weighed. The soil samples were then oven-dried and the corresponding moisture contents were determined. The process was repeated with increasing moisture contents for the purpose of plotting the compaction curve of the soil sample.

2.2.6 Direct Shear Test

The soil sample was prepared initially by Sieve wash and oven until fully dried. This was then pulverized and sieved into a No. 40 sieve in order to remove the shells. It was placed in a customized 60 x 60 x 30 mm acrylic mold then letting it cure for 0, 7, and 28 days. These were tested in the Direct Shear Apparatus using loads 50, 100, and 150 KPa; with 95% relative compaction, as a simulation for embankment situations; porous stones, and the use of strain rates 1mm/min and 0.25mm/min for a testing time of 18 minutes. The 1 mm/min strain rate was used because the soil was identified to be a clayey sand soil; even in the presence of clay particles in the soil sample, the findings in sieve analysis show that less than 50% passed sieve #200. The 0.25mm/min strain rate, in accordance with ASTM D2080 was used to test if the strain rate of 1 mm/min is sufficient for the testing duration.

2.2.7 Scanning Electron Microscopy Testing

The Scanning electron microscopy (SEM) was employed on the 28 days cured soil sample mixes to characterize the microstructure of cementitious compounds, specifically C-S-H and C-A-H. The appearance of these compounds in the cured soil would prove the occurrence of the pozzolanic reaction and the effectiveness of the reactions of BLA and lime within the soil matrix.

3. RESULTS AND DISCUSSION

3.1 Index Properties

3.1.1 Specific Gravity

The results of the specific gravity tests show an inverse relationship between the specific gravity of the soil matrix and the volumetric incorporation of BLA additive seen in Table 1. This can be attributed to the inherent lower specific gravity of the BLA constituent which would decrease the specific gravity of mixed soil [6]. A decrease in specific gravity would mean that the overall density of the soil decreases.

Table 1. Soil Specific Gravity with varying percentages of BLA

Lime	BLA	Specific Gravity
0%	0%	2.60
8%	5%	2.58
8%	10%	2.32
8%	15%	2.29

3.1.2 Grain Size Distribution

Grain size distribution curves (GSDCs) are a vital tool in soil analysis and geotechnical engineering because they shed light on the characteristics and behavior of soil. By showing the relative amounts of different particle sizes in a soil sample, the GSDC makes soil classification easier. According to the results, 74.7% of the soil was retained above the sieve, indicating the coarser materials, such sand, in the soil, while 25.3% of the soil passed the No. 200 sieve, representing the clay in the soil. The determined values for D10, D30, and D60 were 0.0305 mm, 0.0885 mm, and 0.2079 mm, in that order. These numbers indicate a well-graded sand soil, with a Coefficient of uniformity (Cu) of 6.824 and a coefficient of curvature (Cc) of 1.238.

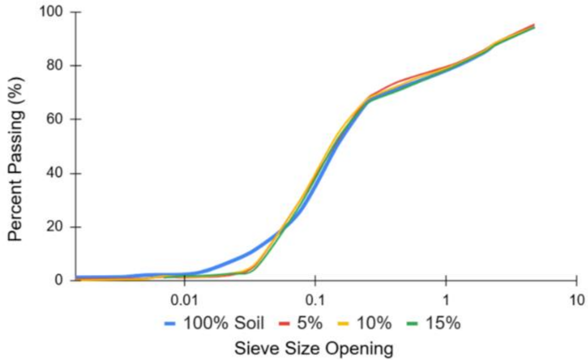

Fig. 2. GSDC for all BLA percentages

For the mixed soils, particle size analysis yielded values of D10 0.0431-0.0461 mm, D30 0.0770-0.0822 mm, and D60 0.1892-0.2027 mm. Cu ranged from 4.393 to 4.527, and Cc ranged from 0.6853 to 0.7283. GSDC indicates well-graded sand with a slight coarse particle bias with increasing BLA content as shown in Figure 2. According to ASTM D4609 and Zada, et al. [10, 11]), coarser particle distribution suggests improved soil stability and strength.

3.1.3 Atterberg Limits

The untreated soil exhibited an average Liquid Limit (LL) of 36%. Incorporation of BLA resulted in LL values of 31%, 33%, and 39% for 5%, 10%, and 15% BLA content, respectively. The initial reduction in LL at 5% BLA, attributed to the hydrophilic nature of the additives and the elevated CaO content inducing colloidal structure formation via increased ionic concentration and pH suggests a modification of the soil's water retention characteristics [12]

The soil's Plasticity Index (PI) was 12%. PI dropped to 7% at 5% BLA after BLA was added and then rose to 8% and 9% at 10% and 15% BLA, respectively as shown in Figure 3. The clumping of soil particles and decreased empty spaces caused by lime and the hydroxyl ion-mediated alteration of clay surface attraction to water are both compatible with the first PI reduction at 5% BLA [13, 14]. The most advantageous PI reduction was obtained with the 5% BLA admixture because, according to ASTM D4609, a drop in PI indicates improved soil stability. A decrease in PI would also indicate that the soil would be less susceptible to swelling and shrinkage [15].

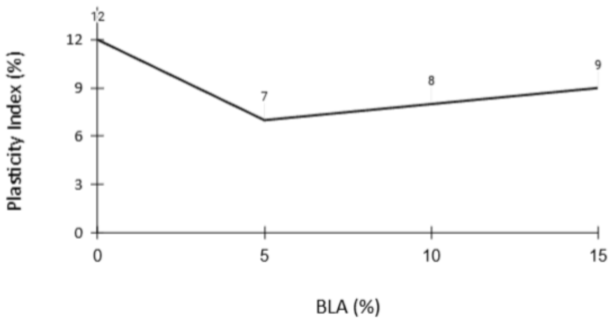

Fig. 3. Plasticity Index variation across BLA percentages

3.1.4 Optimum Moisture and Maximum Dry

Density

The results of the standard proctor test showed that the natural soil's average OMC was 24.23%, and its MDD was 14.07 kN/m. A positive association between BLA percentage and OMC was found through analysis of the soil-BLA-lime mixes; this correlation peaked at 28.77% with 15% BLA and 8% lime as shown on Table 2. The introduction of finer particles that require a higher water content and the hydration requirements of pozzolanic processes are the reasons for this OMC increase, which is consistent with findings by Alrubaye et al [16] for lime-mixed clay. The higher OMC, which is caused by absorption for pozzolanic action, is not in line with ASTM D4609 recommendations for soil stabilizing admixtures, which advocate for lower OMC to decrease the logistical and economical water requirements.

At 15% BLA, MDD decreased from 14.07 kN/m³ for the natural soil to 12.8 kN/m³, demonstrating an inverse relationship with BLA content as shown on Figure 4. This decrease is explained by the lower specific gravity of BLA in comparison to the soil, which causes void filling with a less dense substance [6]. ASTM D4609 guidelines for soil admixtures state that an increase in MDD is a sign of improved strength and less compaction effort, which contrasts with this trend. Utilizing the results of the soil's Atterberg Limits and particle size distribution the natural soil was determined to be Clayey Sand (SC), based on the Unified Soil Classification System (USCS) ASTM D 2487.

Table 2. Standard Proctor Testing for OMC (%) and MDD (kN/m3)

Lime	BLA	OMC	MDD
0%	0%	24.23	14.07
8%	5%	24.56	13.34
8%	10%	27.33	13.10
8%	15%	28.77	12.80

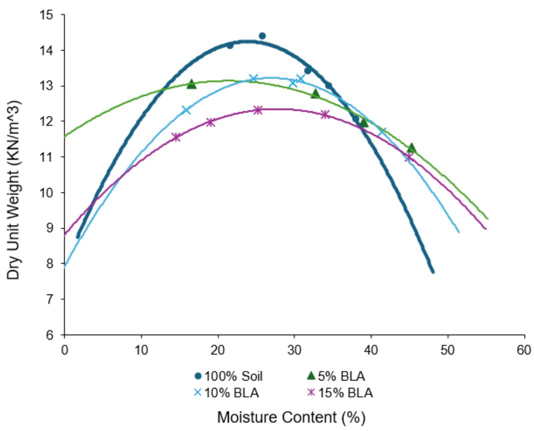

Fig. 4. Compaction Curve of Soil Mixture

3.2 Shear Strength Properties

3.2.1 Cohesion

The shear strength results showed that cohesion grows as the curing day goes on, according to an analysis of the correlations between cohesion and curing day. By the 28th curing day, the cohesiveness of the 5% BLA mixture had tripled, rising from 30.93 kPa to 96.08 kPa. The 10% BLA mixture's cohesiveness rose from 69.44 kPa to 118.43 kPa, nearly double its original value. Finally, 15% BLA increased from 28.24 kPa to 112.84 kPa, nearly quadrupling its growth, shown on Table 3.

Table 3. Soil Cohesion at different BLA percent and Curing Days

Days	5% BLA	10% BLA	15% BLA
	C' (kPa)	C’ (kPa)	C' (kPa)
0	30.93	69.44	28.24
7	78.29	93.73	89.81
28	96.08	118.43	112.84

Cohesion peaked at 10% BLA during all curing days and greatly surpassed the untreated soil. The pozzolanic reactions between BLA and clay particles is responsible for this rise [8]. According to Harichane et al [17], the addition of lime improves soil cohesiveness over time by hardening and forming strong interparticle bonds. The minor decrease in cohesiveness at 15% BLA as opposed to 10% BLA might be the result of not having enough calcium hydroxide to fully react with the higher BLA concentration. Additionally, too much BLA may decrease interparticle interaction by dislodging finer, more cohesive soil components [6].

3.2.2 Angle of Internal Friction

The results of the angle of internal friction are seen on Table 4 and show how the friction angle progressively increased with the curing days. This caused the BLA to nearly double from 34.86° to 53.64° for the 5% BLA, from 28.57° to 54.04° for the 10% BLA, and from 42.55° to 60.77° for the 15% BLA on the 28 days of curing.

The addition of BLA may have caused the soil particles' angularity to alter and clump together. Furthermore, the incorporation of BLA into the soil matrix may cause particle aggregation, thereby augmenting intergranular frictional resistance and interparticle cohesive forces, resulting in an elevated angle of internal friction [8]. This observation aligns with the findings of Alshawmar [18], whose experimental investigation demonstrated a positive correlation between plantain ash content and the angle of internal friction, reaching an apex at a 15% ash inclusion rate. Simila research indicated that incremental lime additions significantly enhanced the soil's angle of internal friction [19].

Table 4. Soil Friction Angle at different BLA percentage and Curing Days

Days	5% BLA	10% BLA	15% BLA
	ϕ (°)	ϕ (°)	ϕ (°)
0	34.86	28.57	42.55
7	40.55	33.25	42.51
28	53.64	54.04	60.77

Because of an increased angle of internal friction the overall shear strength increased despite this slight drop in cohesiveness at 15% BLA. These findings, visualized in Figure 5, along with cohesiveness and angle of internal friction, show how successful the pozzolanic reaction is by showing that shear stress rises as the curing duration increases from no curing to 28 days.

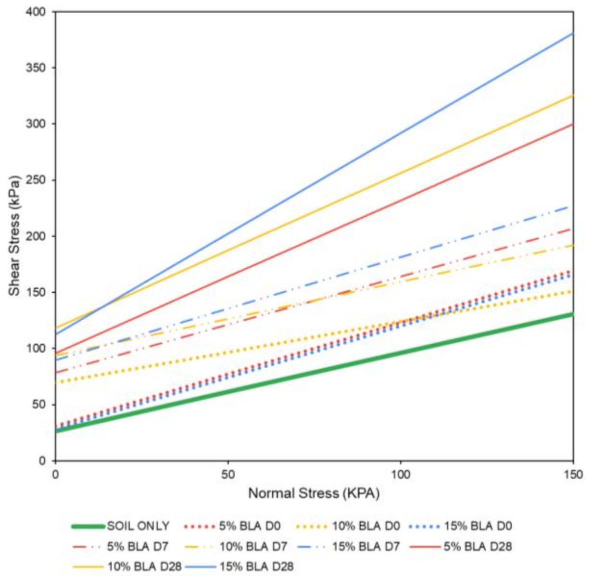

Fig. 5. Shear Failure Envelope of Soil Mixtures with curing day

3.2.3 Shear Strength

The incorporation of BLA at 5%, 10%, and 15% by dry solid volume demonstrably enhances shear strength compared to unamended soil, with increases reaching approximately 200% at 15% BLA. Comparative analysis between BLA percentages reveals a substantial strength gain of roughly 30% between 5% and 15% BLA, indicating BLA's effectiveness as a supplementary pozzolanic material that contributes to strength development in conjunction with lime and soil. Direct shear test results underscore the necessity of curing BLA-lime-soil mixtures to optimize cohesion, angle of internal friction, and overall shear strength through pozzolanic reaction-induced cementation. Based on the experimental data, the 15% BLA admixture is recommended due to its capacity to yield the highest angle of internal friction while maintaining elevated cohesion levels after a 28-day curing period, ultimately resulting in the maximum observed shear strength as evidenced by the shear failure envelope.

3.2.4 Microstructure

Through SEM testing the BLA-lime soil mixes at 28 days curing showed an effective pozzolanic reaction through the appearance of crystalline or shard-like structures, in comparison to the natural soil's granular appearance as shown in Figures 6 and 7. The crystalline shape of C-S-H was clearly visible in the acquired SEM. A stronger and more resilient substance resulted from these reactions, which encouraged the binding of soil particles.

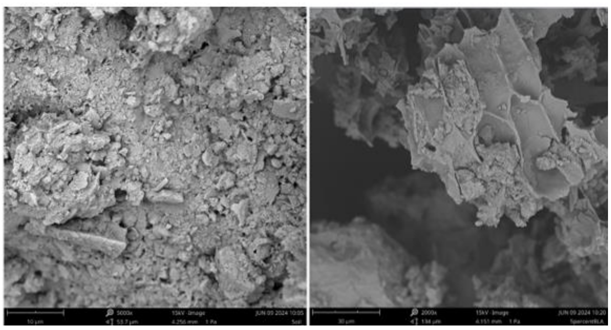

Fig. 6. SEM Micrographs of Soil and 5% BLA mixture at 10 µm from left to right

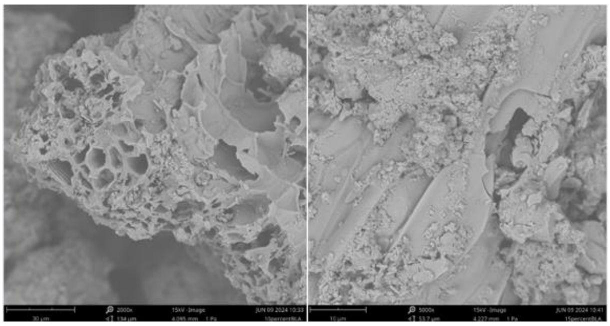

Fig. 7. SEM Micrographs 10% and 15% BLA mixture at 10 µm from left to right

4 CONCLUSION

A geotechnical investigation characterized the index and strength properties of soil containing 5%, 10%, and 15% BLA and 8% lime by dry solid volume, compared to the natural clayey sand soil. The soil exhibited a specific gravity of 2.6, decreasing with increasing BLA due to BLA's lower specific gravity. Particle size distribution indicated a well-graded soil, shifting towards coarser fractions with BLA and lime addition. Standard Proctor testing showed the soil additives increased OMC and decreased MDD. Direct shear tests on cured 0, 7, and 28 days revealed increased cohesion, friction angle, and shear strength with curing duration, confirming pozzolanic activity. The 15% BLA exhibited the highest shear strength post-curing. SEM results confirmed the formation of cementitious compounds. Based on ASTM D4609 the BLA mixtures met some requirements including GSDC, 5% BLA Atterberg, and direct shear results indicate significant strength enhancement. The study recommends BLA and lime as a pozzolanic stabilizer for structural fill, with 15% BLA and 8% lime identified as the optimal additive ratio based on shear strength, SEM analysis, and statistical evaluation. The direct shear test results indicated a statistically significant increase in the shear strength of the treated soil samples. Based on these findings, the combined application of BLA and lime is proposed as a viable alternative pozzolanic stabilizer for structural fill applications.

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