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Clay Soil Stabilization Using Sugarcane Ash and Lime

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Abstract –This study investigates the effectiveness of sugarcane bagasse ash (SBA) and lime as chemical stabilizers for clay soil subbase improvement. The research investigates clay soil from Taxila Pakistan which received stabilization treatment by SBA and lime along with their combination at different mixing ratios. A series of geotechnical tests, including Atterberg limits, compaction tests, and California Bearing Ratio (CBR) tests, were conducted on both untreated and stabilized soil samples. SBA and lime were used in concentrations of 2.5%, 5%, and 7.5% by dry soil weight, while their mixtures were applied in ratios of 1:1, 2:1, 3:1, 1:2, and 1:3 at 5%, 7.5%, and 10% of dry soil weight. The results indicate that soil mixed with 7.5% SBA exhibited a 28% increase in the liquid limit, while the combination of 2.5% lime and 7.5% SBA resulted in a 40% increase in the plastic limit. The plasticity index improved by 42% with 7.5% SBA, and a mixture of 2.5% lime and 2.5% SBA significantly reduced soil plasticity, classifying it as low-plasticity soil. Moreover, the highest improvement (69%) in the CBR value was observed at 2.5% SBA and 5% lime mixture, which indicates the significant enhancement of the strength enhancements of the pavement soil. The cost analysis of the treated pavement shows that this method serves as an environmentally friendly practice that lowers roadway costs while prolonging service span and solving disposal issues through waste material conversion to SBA. The research findings confirm SBA alongside lime as an affordable sustainable stabilizer suitable for road construction projects that require clay soil improvement.

Keywords**:** sugarcane bagasse ash (SBA), agro-industrial waste, clay soil, lime, CBR, pavement subgrade, soil improvement

1. Introduction

Soil stabilization methods have evolved through the last fifty years using different stabilization techniques. The implementation of chemical stabilization employs binders which include lime and cement as well as fly ash and sugarcane bagasse ash (SBA). Koukouzas et al.[1] thoroughly examined soil stabilization methods by studying numerous binders combined with various mixing approaches. The self-cementing properties of fly ash binders with high calcium oxide content (CaO: 10–35%) help strengthen soil structures. Exponential agricultural growth has rapidly increased the production of agricultural residuals and ashes. Brazil's sugarcane production was projected to rise from 570 million tons in 2008 to 1000 million tons by 2020[6], while Australia expected production of 10 million tons of grace by 2020 [2]. This expansion raised serious concerns regarding effective disposal methods for sugarcane bagasse which results from sugar extraction. The improper disposal of bagasse could cause environmental threats and health problems which may develop into the respiratory illness known as bagassosis caused by breathing airborne particles.[3]. To mitigate these effects bagasse is normally used as fuel in cogeneration boilers following specific combustion procedures at 700–900°C that convert it into bagasse ash. The ash material contains substantial amorphous silica and a large surface area which makes it suitable for sustainable soil stabilization applications. [4].

Numerous studies have demonstrated that SBA can work as an eco-friendly and effective stabilizing agent for the weak subgrade clay soil in road construction. A study by Osinubi [5] investigated that adding 2% SBA results in the enhancement of soil strength and bearing capacity, though SBA alone is insufficient as a stabilizer, and it requires an activating agent. A similar study by Anupam et al. [6] observed that adding 25% SBA, improved the shrinkage limit and California Bearing Ratio (CBR), and the corresponding dry density of the sample reduced. Further studies by Dang et al. [7] and Hassan et al. [8] confirmed the effectiveness of the SBA and lime and reported that the mixture of SBA and lime contributes largely to the enhancement of the soil strength and reduction in the shrinkage limits of the clay soil.

An experimental study by Silvani et al. [9] Conducted one-dimensional swelling tests to assess the swell potential of the clay soil treated with sand-bentonite blends (S-B blends) compacted at different densities at varying SBA content. The results indicated that the S-B blend with more than 12.5% SBA content produced a swell factor lower than 0.5%. Mora-Ruiz et al. [10] Investigated the physical and mechanical properties of the unsaturated compacted mixture of clay soil and SBA and reported that adding 8% SBA to the soil reduced the plasticity index (PI) by 20% while the unconfined compressive strength of the soil increased by 15%. Similarly, Dang et al. [11] Studied the effect of SBA, lime, and a mixture of both (SBA-L) on the mechanical properties of expensive soil. Results showed that increasing the content of SBA and lime maximum compressive strength increased by 800% and CBR by nine times. Moreover, it reduced the swell potential by 100% and improved the soil compressibility by 83%. Another experimental investigation by Pardeep et al. [12] found that addition of the 20% bagasse ash (SBA) reduced the plasticity index by 38.5%, however when it was combined with 5% lime, a significant reduction (81%) of plasticity index was achieved along with minimized swelling. This improvement was attributed to the cementitious bonding between clay, lime, and SBA. Teddy et al. [13] Studied the Atterberg limits and mechanical properties of the expensive soil and reported that a combination of SBA with lime improved expansive soil properties by decreasing the Maximum Dry Density (MDD) by 16% while increasing the Optimum Moisture Content (OMC) by 90% which enhanced soil compaction performance in wet conditions. The research demonstrates that SBA–lime successfully enhances the performance characteristics of expansive soils.

Finally, it can be concluded that the use of sugarcane bagasse ash (SBA), either alone or in combination with cement or lime, has been shown to enhance the strength and consistency of weak soils. However, limited research exists on its impact on expansive soils when used with hydrated lime. SBA not only offers an eco-friendly solution for subgrade stabilization but also acts as a pozzolanic and alumina-silicate binder, making it a viable alternative to cement and lime in highway construction. Its high non-crystalline silica content promotes pozzolanic reactions, enabling effective bonding with hydrated lime and triggering beneficial chemical processes such as cation exchange, cementation, and soil stabilization. This study evaluates SBA effectiveness for silty clay soil improvement both individually and with hydrated lime addition. The research analyses two aspects: (1) how do SBA and lime affect Atterberg limits and soil classification as well as compaction properties? (2) how do these stabilizers influence CBR values by varying additive quantities? A cost analysis of the flexible pavement section was performed to evaluate the economic benefits of the stabilization for the treated and untreated pavement subgrade.

2. Material Properties and Sample Preparation

The soil sample was collected from a road construction site in Taxila, Pakistan, and was processed in the geotechnical laboratory at the University of Engineering and Technology, Taxila. The collected soil was crushed and sieved to remove organic matter before testing as shown in Figure 1a. The soil classification was performed, and it identified it as high-plasticity silt (MH) according to the Unified Soil Classification System (USCS) and A-5 soil under the AASHTO classification. These results show that the soil is prone to moisture-related changes, requiring stabilization for use in pavement applications. Laboratory tests showed that the soil contained 88.97% silt and clay, with a liquid limit of 65%, a plastic limit of 38%, and a plasticity index of 27. The specific gravity was measured at 2.64, and the soil exhibited a natural water content of 30.76% and a linear shrinkage of 21.67%.

The chemical composition of the soil and SBA was compared to get insight into their compatibility to get the desired chemical bonding. The soil was primarily composed of 61.8% silicon dioxide (SiO_2), 23% aluminum oxide (Al_2O_3), and 8.5% iron oxide (Fe_2O_3). SBA, which was obtained from a local sugar industry, was subjected to controlled burning at 600–700°C to enhance its pozzolanic activity. The SBA sample contained 77.5% (SiO_2), 5.96% (Al_2O_3), and 5.3% (Fe_2O_3), making it a suitable material for soil stabilization due to its high silica content. The ash was sieved through No. 40 and No. 200 sieves to remove unburnt particles and ensure uniformity as shown in Figure 1b. The local supplier provided hydrated lime (calcium hydroxide, $Ca(OH)_2$) to be used as a stabilizing agent along with SBA as shown in Figure 1c. The mixture of lime with SBA was expected to modify soil characteristics through pozzolanic processes which would lead to enhanced strength along with decreased plasticity and extended durability.

(a) 3000 gm silty clay soil (b) Sugarcane bagasse ash (c) Hydrated lime

Fig. 1: (a) Soil sample, (b) sugarcane bagasse ash (SBA), and (c) hydrated lime, used in this study.

The following sub-section explains the procedures needed to prepare soil samples for the testing program. Soil and both sugarcane bagasse ash (SBA) and lime were combined manually and mixed until they blended into a uniformly distributed mixture. The mixing ratios followed predefined percentages based on the type of test being conducted, such as Atterberg limits, compaction, and California Bearing Ratio (CBR) tests. A detailed test matrix is presented in Table 1. The required moisture content was achieved by adding filtered tap water to the mixtures afterward the mixtures were kept in sealed plastic bags for 24 hours for uniform moisture distribution. All prepared samples received were weighed with a precision level of 0.01g before they underwent main tests the next day. A small sample extraction was performed to confirm the moulded moisture content. Following the mixing process, samples underwent geotechnical tests, including index tests, compaction, and CBR tests. These tests were performed to assess the key parameters of the admixtures including plasticity, optimum moisture content, maximum dry density, and CBR values. The process ensured consistency in sample preparation for reliable test results.

Table 1: Summary of the Admixtures used in the study

Mix No.	Bagasse Ash (SBA) (%)	Hydrated Lime (%)	Mixture Ratio (SBA: L)	Total Additive Content (%)	Notes
1	0	0	0:0	0	Natural soil
2	0	2.5	0:2.5	2.5	Lime
3	0	5.0	0:5.0	5.0	
4	0	7.5	0:7.5	7.5	
5	2.5	0	2.5:0	2.5	SBA
6	5.0	0	5.0:0	5.0	
7	7.5	0	7.5:0	7.5	
8	2.5	2.5	1:1	5.0	Lime + SBA
9	2.5	5.0	1:2	7.5	
10	2.5	7.5	1:3	10	
11	5.0	2.5	2:1	7.5	
12	7.5	2.5	3:1	10	

3. Testing Program

Atterberg limits use soil moisture content to establish standard ranges for classifying fine-grained materials into different stability states ranging from solid through semisolid and plastic to liquid. The engineering properties including the strength and deformation behavior of soil are influenced by each state. The liquid limit defines the precise water content when soil transitions from a stiff to a flowing state under low-stress conditions. Soils containing low LL exhibit brittleness leading to cracking but soils containing high LL demonstrate ductility which resists cracking. Plastic limit test determines the minimal water content which allows the soil to mold without breaking. Soil becomes more prone to deformation when moisture content decreases below the plasticity limit. The plasticity index (PI) is calculated as the difference between LL and PL, determining the soil's plasticity range. The testing was performed according to ASTM D4318 (2018a) [14] Standards by using Casagrande's liquid limit apparatus.

The modified compaction test (ASTM D698-78) [15] was performed using 3 kg of oven-dried soil mixed with different proportions of sugarcane bagasse ash (SBA), lime, or their combination, as specified in the study. Water was added to achieve the target moisture content, and the mixture was compacted in a 4-inch mold in five layers, each receiving 25 evenly distributed blows. The compaction tests were used to determine the optimum moisture content (OMC) and maximum dry unit weight of the virgin soil and different stabilized mixtures as specified in the study. The results were used in subsequent geotechnical evaluations. However, swelling potential and volumetric changes post-compaction were not measured, as they were beyond the scope of this study.

California Bearing Ratio (CBR) test was conducted to assess the suitability of soil as a road subgrade material and determine its bearing capacity. The CBR value is derived from the relationship between applied force and penetration depth when a plunger penetrates the soil at a standard rate. The testing process utilized a standard mold shape (7 inches in height and 6 inches in diameter) for both treated and untreated soil samples. The samples were compacted at optimum moisture content (OMC) and maximum dry unit weight (MDUW) following ASTM D1883-21 standards. [16]. To prevent moisture loss, the specimens were wrapped in plastic and stored under controlled conditions. A 2.5 kPa annular surcharge was applied to simulate field loading conditions before conducting the CBR test without soaking. Load-penetration data were recorded and corrected according to standard procedures. The CBR values were then calculated based on the higher stress values at 0.1-inch (2.5 mm) or 0.2-inch (5 mm) penetration depths, indicating the soil's bearing strength.

4. Results and discussion

4.1 Effect on Index Properties and Classification

The untreated soil sample exhibited a Liquid Limit value of 64.5%. The addition of lime at 5% to 7.5% decreased the LL by 21% which made the soil less plastic and more stable. When the content of SBA exceeded 7.5% the plastic limit increased which resulted in a more ductile soil that could readily expand. A mixture of 2.5% lime with 2.5% SBA showed the most optimal results by effectively decreasing the LL. It is noted that the addition of lime caused LL reduction, yet SBA led to a substantial increase in LL. Lime reduced the Liquid Limit through pozzolanic reactions which modified soil consistency, but SBA increased the Liquid Limit because its high silica content influenced water absorption and soil structure. The Plastic Limit (PL) increased with lime, SBA, or a combination of both. The highest increase in PL was observed at 7.5% SBA, while 2.5% lime + 7.5% SBA showed greater improvement. The effect of SBA on raising PL was more significant than that of lime. The PL increase suggests that stabilized soil becomes more resistant to deformation under load, particularly when lime and SBA are used together.

Using Unified Soil Classification System (USCS) in **Figure 2**, the untreated soil was classified as high plastic silt (MH) because of its high LL (64.5%) and PI (26.5%) which indicated significant sensitivity to volume fluctuations due to moisture changes. Adding sugarcane bagasse ash to the soil resulted in higher LL and PI levels which moved the soil classification deeper into the high plasticity zone. SBA by itself provides no effective stabilization because it creates soil moisture sensitivity which leads to increased softness and susceptibility to deformation under wet conditions. The addition of lime caused LL and PI to decrease substantially thus reclassifying the soil towards lower plasticity due to natural pozzolanic reactions that enhance soil consistency and reduce its shrink-swell potential. **Figure 2** shows the effect of SBA & lime on the classification of the soil. The addition of 2.5% lime and 2.5% SBA generated the best results by reducing PI 54% to 76% and transforming high plasticity MH soil to ML low plasticity silt. The classification shift reflects reduced compressibility improved strength and lower expansion capacity, so the lime-SBA mixture works effectively for subgrade stabilization.

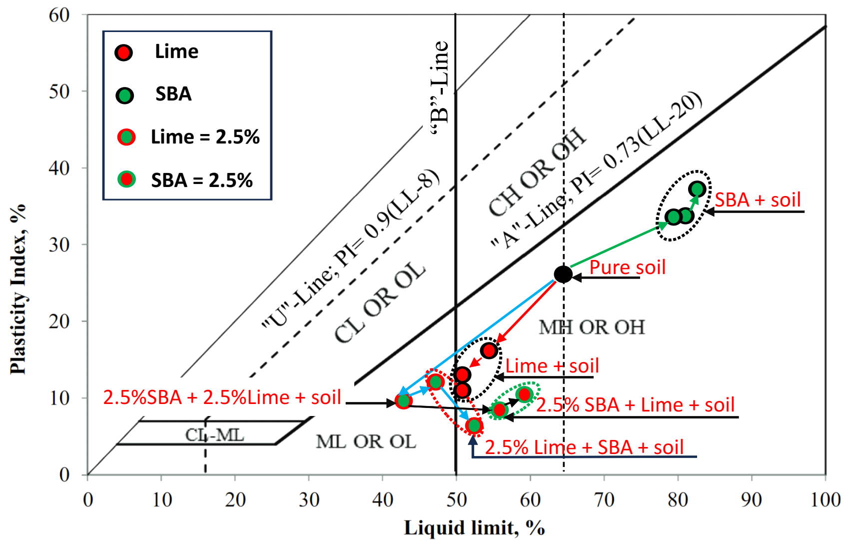
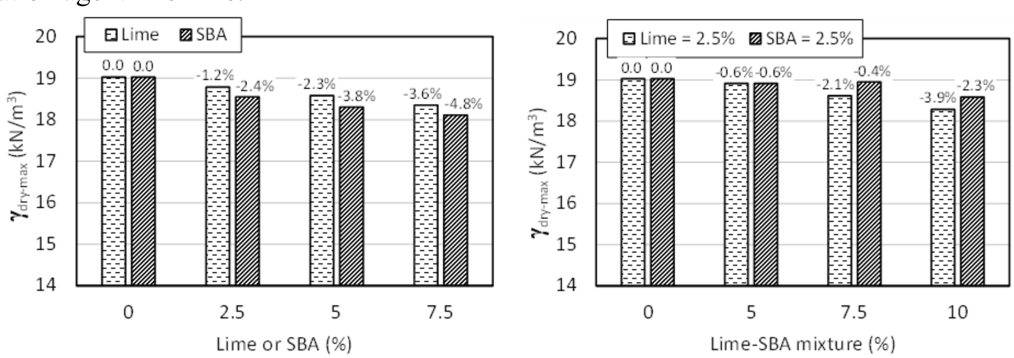


Fig. 2: Effect of SBA and lime of soil classification

4.2 Compaction Properties

The compaction properties of the treated and untreated soil were analysed to determine the optimum moisture content (OMC) and maximum dry unit weight (MDUW). The addition of lime and SBA to the mix led to OMC growth because these materials possess high surface areas which require more water to activate hydration and pozzolanic actions. The lime reacts with clay minerals which result in flocculation and agglomeration allowing water absorption to increase. However, SBA alone caused a slight decrease in OMC, likely due to its impact on soil structure and the limited reaction of its silica content without an activation agent like lime.



(**a**) Percentage of Lime or SBA by weight of soil (**b**) Mixture percentage of lime–SBA by weight of soil.

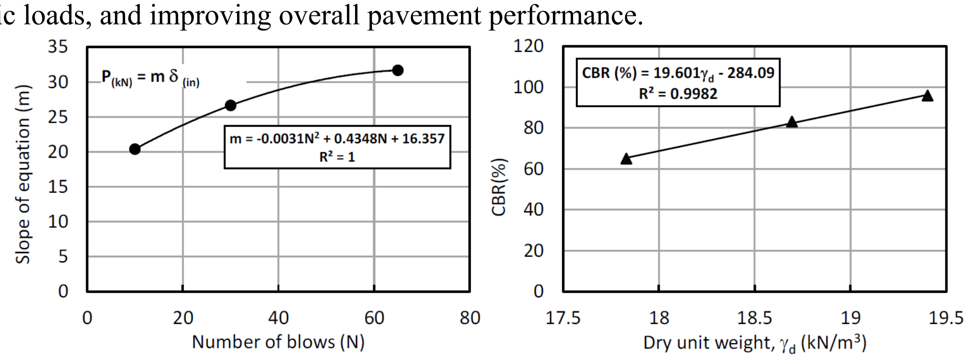
Fig. 3. Effect of Lime or SBA, and the mixture of lime–SBA on the maximum dry unit weight.

Figures 3 shows the effect of SBA, lime, and their combination on MDUW. The MDUW decreased as the percentage of lime, SBA, or their combination increased. Additions of lime and SBA create a lightweight mixture with increased volume due to their reduced specific gravity as compared to natural soil. The greatest reduction (4.8%) in MDUW occurred at 7.5% SBA because SBA particles remain lighter than soil grains which causes them to form less dense structures during mixing operations. The addition of lime to the mixture lowered MDUW values although this effect was less significant than of SBA. When lime and SBA were combined, the presence of higher lime content counteracted the extreme weight reduction seen with SBA alone, resulting in a more stable compaction profile.

Figures 3 shows that the addition of lime and SBA within stabilized soil creates material that becomes less dense but results in better workability. A lower MDUW value indicates compacted stabilized soil density becomes lower thus affecting its strength and load-bearing ability. However, Pozzolanic reactions produced by lime work to counter this compaction challenge by creating better soil bonding that leads to enhanced long-term stability alone does not improve compaction characteristics as effectively as lime, but when used in a lime-SBA mixture, it provides a more balanced stabilization approach, making it a viable option for pavement subgrade improvement.

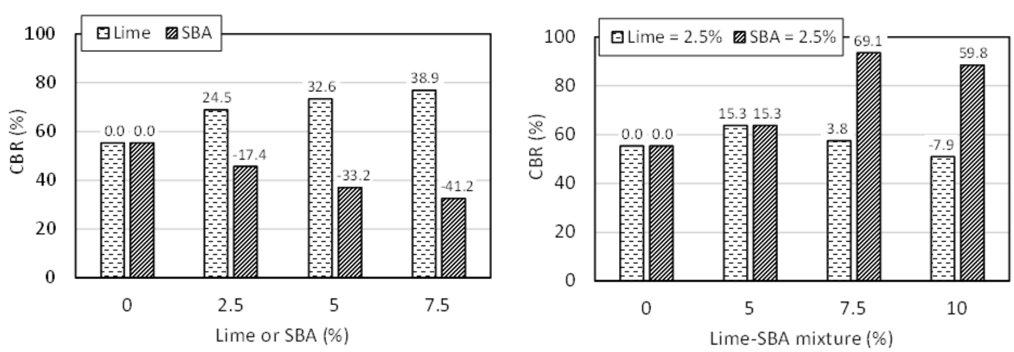
4.3 California Bearing Ratio (CBR)

CBR values were obtained under different compaction efforts, using varying numbers of hammer blows per layer to achieve different dry unit weights. The experimental data shown in **Figure 4** revealed that increasing the compaction efforts resulted in higher CBR values because they enhanced soil density and strength. The resistance to penetration increased with higher soil density which resulted in improved CBR values. Figures 5 demonstrates the effect of SBA and lime on the CBR value. **Figure 5a** indicates that the application of lime produced significant CBR enhancements while pure SBA application caused noticeable CBR reductions in fine-grained soils. The application of lime at 7.5% resulted in maximum CBR improvement (39%) whereas SBA treatment at 7.5% led to the largest CBR reduction (41%). The single use of SBA does not display effectiveness in improving soil strength. Using a combined mixture of 5% lime and 2.5% SBA, **Figure 5b** resulted in the best performance by producing 69% increase in CBR value compared to untreated soil. The development of cement-like compounds such as calcium silicate hydrates and calcium aluminate hydrates from pozzolanic reactions leads to enhanced soil cohesion and strength. The findings of the CBR test confirm that lime is more effective in improving soil strength, while SBA alone reduces soil-bearing capacity due to its influence on soil plasticity. The lime-SBA mixture provides the best stabilization, with 5% lime + 2.5% SBA yielding the highest CBR improvement. It is expected that this combination enhances load resistance, making it suitable for road subgrade applications by increasing soil stiffness, reducing deformation under traffic loads, and improving overall pavement performance.



(a) (b)

Fig. 4. Effect of compaction effort and dry unit weight on CBR values (samples with 7.5% lime).
(a) Slope (m) vs. number of below (N). (b) CBR vs. dry unit weight.



(**a**) Percentage of Lime or SBA by weight of soil (**b**) Mixture percentage of lime–SBA by weight of soil

Fig. 4: Effect of lime or SBA, and mixture of lime–SBA on CBR values.

4.4 Cost analysis

This section reviews the economic advantages of soil stabilization by comparing flexible pavement cost and service lives between untreated and stabilized subgrades prepared with lime and SBA mixtures. This analysis employs the government construction rates established by NHA (CSR 2014 of NHA, Pakistan) together with AASHTO 1993 [17] Pavement design standards. Cost analysis encompassed material expenses in addition to labour costs, equipment costs, overhead costs and pavement rehabilitation costs for the entire project lifetime. Heukelom and Klomp's (1962) [18] The equation was used to transform CBR data into subgrade resilient modulus (MR) values.

$$M_R = 1500\ x\ CBR \qquad (1)$$

The untreated soil showed an M_R value of 33,206 psi at its initial status whereas the combination of 5% lime with 2.5% SBA treatment yielded an M_R value of 46,475 psi. Table 7 illustrates how the enhanced pavement layer thickness decreased due to this increase in material strength. Subgrade stabilization extended the pavement lifetime from 12 **years** for untreated subgrade to 25 years for treated subgrade soil while simultaneously resulting in a 16% reduction in overall construction and maintenance costs.

Table 2: Thickness of Pavement layers for treated and untreated Soil

Pavement Layer	Material	Layer Coeff.	Thicknesses, in (cm)	
			Untreated Soil	**Treated Soil**
Wearing course	Hot mix asphalt	$\alpha_1 = 0.44$	D_1 = 2.0 in (5.08)	D_1 = 1.7 in (4.318)
Base course	Aggregate-Bituminous	$\alpha_2 = 0.30$	D_2 = 5.0 in (12.7)	D_2 = 4.5 in (11.43)
Sub-base	Crushed stone	$\alpha_3 = 0.11$	D_3 = 7.0 in (17.78)	D_3 = 6.0 in (15.24)

5. Conclusion

This study examined whether sugarcane bagasse ash (SBA) in combination with lime (L) could enhance the engineering properties of weak fine-grained subgrade soil. A series of laboratory tests were conducted to examine the effect of the SBA, lime, and their controlled mixture on the index properties, compaction properties, and strength of the natural soil. Soil plasticity increased with the addition of SBA, but strength decreased whereas lime application enhances soil strength. The plastic limit (PL) increased with all stabilizers, with the best improvement observed at 7.5% SBA and 2.5% lime + 7.5% SBA mixtures. The plasticity index (PI) significantly decreased with lime or SBA-lime mixtures, which improved soil consistency and classification. The compaction results showed that stabilization increased the optimum moisture content (OMC) but reduced the maximum dry unit weight (MDUW), making the soil less dense but more workable. The CBR test results confirmed that lime greatly enhances soil strength, while SBA alone reduces CBR values. The highest improvement (69%) in CBR was achieved with 5% lime + 2.5% SBA, due to the formation of cementitious compounds that enhance soil bonding and load-bearing capacity. Cost analysis showed that pavement thickness was reduced, cutting construction costs by 16% and doubling pavement lifespan from 12 to 25 years. These findings confirm that lime-SBA stabilization is a cost-effective and sustainable method for improving weak subgrade soils, offering both engineering and environmental benefits.

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