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Blending Lime with Sugarcane Bagasse Ash for Stabilizing Expansive Clay Soils in Subgrade

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Highlights:

- The chemical analysis of the bagasse ash used in this study indicated that the main elements were silica (64.89%), alumina (5.66%), and iron (3.39%).
- The California bearing ratio (CBR) increased from 34% to 48% with SCBA partially replacing hydrated lime.
- Lime replacement of 6% SCBA of the 5% lime was obtained as the optimum treatment. This produced a CBR of 48%, an optimum moisture content of 25%, a maximum dry density (MDD) of 1.7 Mg/m3, linear shrinkage of 10%, and a plasticity index of 20%.

Abstract. Expansive soils constitute one of the most frequently encountered and challenging soils to geotechnical engineers. This study assessed the possibility of utilizing sugarcane bagasse ash (SCBA) by partially replacing slaked lime to stabilize expansive clay soils. The soil samples were picked from Muduuma area, Mpigi district, Central Uganda. Experimental tests of linear shrinkage (LS), plasticity index (PI), and California Bearing Ratio (CBR) were conducted on both unstabilized soil and SCBA-lime treated samples. The SCBA-lime mixture was prepared by partially replacing 5% lime with SCBA at 2, 4, 6, 8, and 10% by weight. Hence, SCBA was used in proportions of 0.1, 0.2, 0.3, 0.4, and 0.5% by dry weight of the soil. The addition of lime greatly lowered the PI and LS, which later increased with the addition of the SCBA. The maximum dry density was generally lowered with the addition of lime and SCBA, from 1.87 g/cm^3 to 1.58%. The CBR increased with SCBA-lime addition from 12% for unstabilized soil up to 48% at 6% SCBA replacement. The optimum lime replacement was established as 6% SCBA lime replacement based on CBR criteria. At the 6% optimum, the optimum moisture content (OMC) was 1.7 Mg/m^3, LS was 10%, and PI was 20%. This study demonstrated the potentiality of SCBA as a novel construction material, specifically by partially reducing the usage of the unsustainable, non-environmentally friendly lime. It is also expected to enable using currently unsuitable clays from the region.

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1 Introduction

Expansive soils continue to be one of the most extremely difficult soils to deal with during construction due to their very poor strength and low bearing capacity [1-4]. They are prone to cycles of drying and wetting, making them highly risky. This behavior induces shrinkage and swelling under the road pavement, resulting in the development of cracks within structural and non-structural elements [1]. Problems are also highly related to their unfavorable physical and mechanical properties, which include very fine particles of montmorillonite minerals, high natural moisture content causing huge volume changes, high void ratio, high optimum moisture content, low California bearing ratio, low compressive strength, among others. They tend to be unsaturated and to attract monovalent cations by the dominant minerals within their microstructure. To overcome these problems, scholars have tried out a number of different approaches, such as the sand cushion technique, granular piles, and chemical stabilization. Chemical stabilization of clay soils stands out as one of the most popular and efficient methods to improve the physical and mechanical properties of these problematic soils. Engineering requirements such as strength, bearing capacity and durability are said to improve greatly with this technique [5].

Traditionally, chemical stabilizers such as lime and cement so far have been the most commonly used in soil modification [6,7]. These materials have good pozzolanic and binding properties. The chemical stabilization mainly takes place either by modification, which is due to the lime giving away its cations of calcium hydroxide or calcium oxide under a high alkaline medium, or by stabilization [8,9]. Stabilization is quite a long-duration effect, mainly due to the pozzolanic reaction [10].

Researches on traditional stabilizers of cement have shown an increase in unconfined compressive strength (UCS) of clays under varying surcharges of cement for example in [5]; reduction in shrinkage in [6]; and an increase in dry density of the soil and a decrease in OMC as established in [11]. Meanwhile, lime has attracted most of the interest as a soil stabilizer, mainly due its richness in cations of $Ca(OH)_2$ and (CaO), or lime slurry. Dissolution of the minerals from the clay, i.e. SiO_2 and Al_2O_3, leads to reaction with calcium generated from the lime, leading to formulation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). This pozzolanic reaction is said to be the source of strength improvement of expansive clays under lime stabilization [10-15].

Industrial and agricultural wastes mainly constitute alternative stabilizers under investigation [2]. These waste materials have been studied as auxiliary or partial supporting materials to cement and lime [12]. Auxiliary materials that have been studied to partially support lime include fly ash [6,16,17], rice husk ash [18,19], and sugarcane bagasse ash [10,15,20,21].

SCBA studies have established it as being notably a more favored auxiliary material under lime stabilization. This is mainly due to being abundantly available agricultural waste even in developing countries. For example, 5 million tonnes in Uganda in 2018 [22] as compared to others like fly ash and rice husk. Secondly, it comprises a very high percentages of oxides of silica and alumina and sometimes calcium [15]. This facilitates the pozzolanic chemical reaction enabled by the silica and alumina donated by SCBA, with the calcium hydroxide or calcium oxide coming from lime forming CAH and CSH compounds [10,12,13]. This pozzolanic activity increases its potential for improving the engineering properties of subgrade road pavement layers [23,24]. Additionally, SCBA stabilizer once blended with lime has been reported to increase the efficacy of the stabilization process by fastening the chemical reaction by disintegrating the montmorillonite into reactive products [25]. This expansion potential is greatly influenced by the mineralogical constituents of expansive soil, hence influencing the index properties of unstabilized soil [25].

Much research has been done to establish the potentiality of blending lime with an auxiliary stabilizer of SCBA. The approach in these studies was mainly to add different percentages of SCBA to the lime. For example, Ref. [10] found improvement of the CBR and significant improvement of linear shrinkage when SCBA was added in dosages from 0% to 25% of dry weight of soil. Unsoaked CBR increased up to 60% at 25% SCBA addition. In Ref. [26], addition of lime or SCBA at 4%, 5% and 6% reduced plasticity. The CBR increased with lime but reduced with SCBA. As for the use of lime or SCBA individually, both reduced linear shrinkage but lime performed better. As for blending the two, a combination ratio of 4:1 showed the best results, with a CBR of 36%, linear shrinkage of 9.0 and a PI of 20. In Ref. [1], using SCBA and lime in a ratio of 3:1 was studied, with the two added to soil in percentages from 0% to 25% of dried soil sample. They established an improvement in free swell ratio, CBR and UCS of the stabilized soil.

All this notwithstanding, continued usage of traditional stabilizers of cement and lime has disadvantages. This is mainly because it is expensive for some poor developing countries and has negative side effects on the environment associated with CO_2 emissions during their manufacture [27,28]. As seen in many studies, researches have not tried to reduce their usage, hence, this study tried to fill the research gap needed to reduce their utilization. This was done by approaching the problem from a different perspective from previous studies. Lime stabilization at 5% was considered, which was amended by partially replacing it with SCBA in proportions of 2% to 10% of the 5% proportion of hydrated lime. This solves the problem of unsuitable expansive soils and at the same time reduces the amount of environmentally unfriendly lime used for stabilization.

Following the merits of SCBA, this study aimed to modify the use of lime stabilizer in line with the suggestion in [29]. Relevant parameters of the Atterberg limits and mechanical properties of expansive soil stabilized with lime partially replaced with SCBA were studied.

2 Materials and Methods

2.1 Materials

2.1.1 Sugarcane Bagasse Ash (SCBA)

The sugarcane bagasse ash used in this study was obtained from Kakira Sugar Factory Limited, which is located in Kakira town, Jinja district, Eastern Uganda. This bagasse ash is produced during electric co-generation, where it is left behind as a by-product after burning in boilers up to about 530 °C. The collected ash was sun-dried (Figure 1b) to remove the water content and then standardized by sieving it through a 300µm BIS sieve to obtain fine particles that contain high amounts of silica [30]. This sieving also facilitates the reaction with lime and clay soil [29]. Chemical analysis of the sugarcane bagasse ash was performed using a X-ray fluorescence spectrometer machine (XRF) from the X-5000 series at the College of Geology and Petroleum Studies Laboratory of Makerere University. This characterization was done as adopted in [31]. The results were as tabulated in Table 1.

Table 1 Chemical composition of SCBA and lime.

Parameter	% Pozzolan) SCBA (primary data)	Hydrated Lime [32]
Al_2O_3	5.66	0.66
Fe_2O_3	3.39	0.43
SiO_2	63.59	2.55
SiO_3	1.3	-
CaO	3.19	61.62
MgO	0.75	3.82
NaO	0.62	-

The chemical analysis showed that the SCBA contained very high components of amorphous silica at 63.59% and alumina at 5.66%, which are needed to facilitate the chemical reaction with calcium oxide from hydrated lime to facilitate a pozzolanic reaction, as identified by [33]. In line with that, hydrated lime also contains the essential ingredient CaO, which is highly needed to produce hydrates in the pozzolanic reaction [31].

2.1.2 Expansive Clay Soil

The expansive clay soil sample (Figure 1(a)) for the research was collected from two trial pits in the Muduuma area located at 0°20'39.246" south latitude, 320°18'34.67" longitude, Mpigi district in central Uganda. The area selection followed referral from the Uganda National Roads Authority. The sample was picked along the soil profile at the depth of 1.5 m to avoid the inclusion of organic matter. The unstabilized soil sample was tested for its physical and mechanical properties to ascertain conformity with the criteria for expansive soil. The results are as shown in Table 2. Then particle size distribution of the soil sample was also determined, as shown in Figure 2.

(a) (b)

Figure 1 (a) Greyish expansive clay soil ready for sieving, (b) Sugarcane bagasse ash.

The grain size distribution of the expansive soil showed that 67% of the soil particles were fine-grained material (silt/clay), because more than 50% passed through a 75 micron sieve.

Only 3% of the grains were in the range of gravel and 30% were in the range of sand according to [34]. The soil had high values of linear shrinkage (16%) and a plasticity index of 33%.

Table 2 Physical and mechanical properties of the expansive clay soil.

Property	Value
Color	Greyish
Percentage passing 75 micron test sieve	67%
Liquid limit	55%
Plastic limit	22%
Plasticity index	33%
Linear shrinkage	16%
Maximum dry density	1.87 Mg/m^3
Optimum moisture content	16%
California bearing ratio	12%
USCS classification of the soil	CH

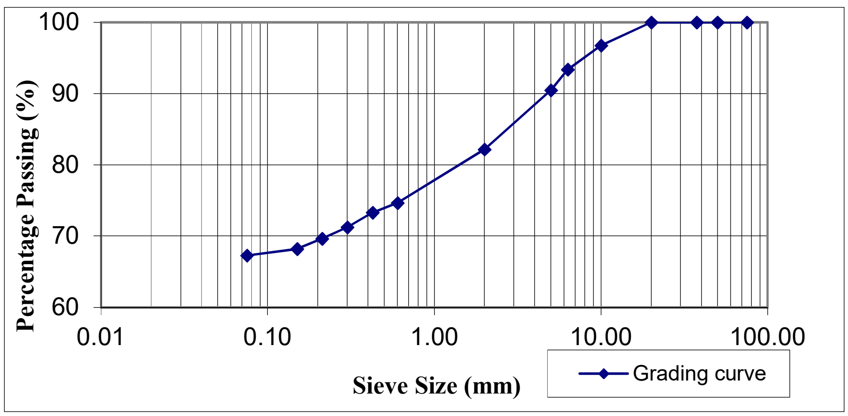

Figure 2 Particle size distribution of the expansive clay soil.

The soil had a low bearing capacity of 12% when soaked and a high plasticity index. This is an indicator that it falls below the standard recommendations for most geotechnical construction works, especially highway construction. Therefore, the soil would require initial modification and stabilization to improve its workability and engineering properties for it to be used in pavement construction. Based on these properties, this soil was classified as high plasticity clay (CH) soil according to the Unified Soil Classification System (USCS) ASTM D 2487 [35].

2.1.3 Lime

The lime used in this study was hydrated calcium hydroxide, commonly known as slaked lime or road lime. It was purchased from Cheap General Hardware, located in Kasubi town, Kampala district. Some of the chemical properties of lime are shown in Table 2. Hydrated lime was preferred due to its suitability in terms of being relatively less reactive compared to quick lime. This lowers the difficulties in its application compared to highly reactive quick lime [36].

2.2 Methods

2.2.1 Mix Proportions of SCBA-Lime Blended Soil

The lime content used for the control sample was 5% by dry weight of soil, which was amended with SCBA. The SCBA-lime mixture was prepared by partially replacing the 5% hydrated lime with different amounts of SCBA, at 0, 2, 4, 6, 8, and 10% by weight. Hence, the lime decreased from 5% to 4.5% by weight of dry soil, while the SCBA increased from 0% to 0.5% by dry weight of soil as shown in Table 3.

Table 3 Mix proportions of SCBA and lime use to stabilize expansive clay soil.

Mix No.	(%) weight of SCBA by dry weight of sample soil	Hydrated lime (%) by dry weight of sample soil
1	0	0
2	0 (0% of 5% lime)	5
3	0.1 (2% of 5% lime)	4.9
4	0.2 (4% of 5% lime)	4.8
5	0.3 (6% of 5% lime)	4.7
6	0.4 (8% of 5% lime)	4.6
7	0.5 (10% of 5% lime)	4.5

2.3 Physical Properties of Expansive Clay Soil

The expansive clay soil was treated with lime and later modified with injection of additional SCBA and investigated on a number of physical properties. After curing, the samples were prepared and tested with the following tests:

1. Atterberg limits tests were conducted to establish the liquid limits, plastic limits and the plasticity indexes for the unstabilized, lime stabilized and SCBA-lime stabilized mixtures. The tests were conducted after 3 days of curing and four (4) days of soaking, following the BS 1377 1990 testing procedures [37]. Three specimens were prepared for different soil treatments, i.e. for unstabilized, stabilized with lime only, and for different SCBA injections of 0, 2, 4, 6, 8, and 10% partially replacing 5% lime (Table 3). For each treatment 3 specimens were used of which the mean was obtained, giving a total of 42 specimens for the Atterberg limits. The plasticity index of the samples, as the difference between the liquid limits and their corresponding plastic limits, was calculated using Eq. (1) for all samples.

$$PI = LL - PL \tag{1}$$

2. Linear shrinkage was conducted in reference to BS 1377 1990. The equipment used was a flat glass plate, a palette knife, a drying oven, clean water, a brass mold, silicone grease, and a Vernier caliper. Three specimens were prepared for each soil treatment, including the unstabilized sample, giving a total of 21 specimens. The mold was oven-dried at about 105 °C. After about 24 hours, the mold was taken from the oven and cooled. The soil bar was measured for its mean length and the percentage for linear shrinkage was computed using Eq. (2).

$$\mathrm{LS} = 100((\mathrm{Lo} - \mathrm{LD})/\mathrm{Lo}) \tag{2}$$

2.4 Mechanical Tests

Mechanical tests were conducted to establish the mechanical properties of the compaction test and the California bearing ratio (CBR) for the expansive soil, both unstabilized and after stabilizing with lime alone, and with the SCBA-lime mixture. The tests were conducted after 3 days curing and 4 days soaking of the samples following standard BS 1377: 1990.

1. The compaction test was carried out to determine the maximum dry density and the optimum moisture contents for both the natural unstabilized soil and the stabilized soil. The test followed the procedures laid out in [38]. For each soil treatment, i.e. the unstabilized and the lime-only stabilized samples, three specimens were prepared, giving a total of 21 specimens. The results of the dry densities were plotted against the moisture contents to get the optimum moisture contents that corresponded to the maximum dry densities of the different samples.
2. The California bearing ratio test was conducted in accordance with the BS 1377 Part 4 [38] testing procedures. The CBR value was obtained to determine the resistance to penetration of 2.5 mm of a standard cylindrical plunger of 50 mm diameter. For the unstabilized soil sample the mold was immediately soaked in a soaking tank for 4 days and then penetrated. As for the stabilized samples, they were cured for 3 days while sealed in an airtight bag and then soaked for 4 days before testing them with the penetration plunger. The force applied to the plunger was calculated from each reading of the loading ring observed during the penetration test using Eq. (3). This soaked CBR at 95% MDD:OMC was obtained for 3 samples for each soil stabilization, i.e. unstabilized, 5% lime and 2 to 10% SCBA replacement of lime (Table 3). In total 21 specimens were prepared.

$$\mathrm{Force} = \text{penetration of plunger x } 0.113\mathrm{kN} \tag{3}$$

where 0.113kN is the ring constant.

3. Each value of force was plotted as ordinate against the corresponding penetration and a smooth curve was drawn through the points. This soaked CBR at 95% MDD:OMC was obtained for 3 samples for each soil stabilization mix sample and the average CBR value was obtained, i.e. unstabilized, 5% lime, and 2 to 10% (Table 3) SCBA replacement of lime. In total 21 specimens were prepared.

3 Results and Discussion

3.1 Physical Properties of Soil After Stabilization

3.1.1 Plasticity Index and Linear Shrinkage

The addition of lime and SCBA had a remarkable effect on the plasticity and linear shrinkage of the cohesive soils, as can be seen in Figures 3 and 4.

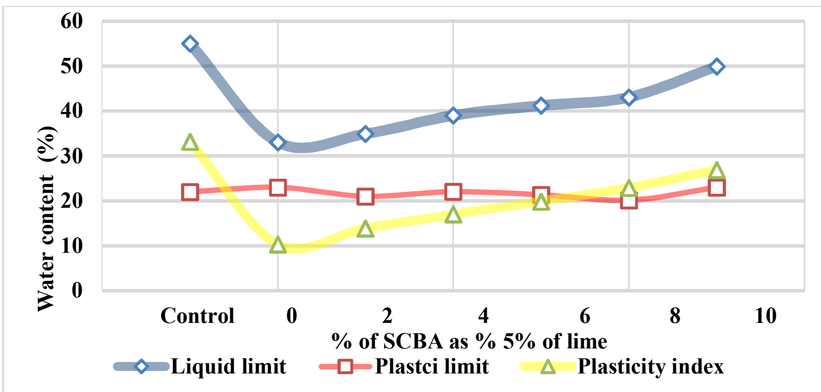

Figure 3 Atterberg limits for both the unstabilized and the SCBA-lime stabilized expansive soil.

The addition of SCBA-lime lowered the liquid limit from 55% to 39% at 4% lime replacement and later increased it back to 50% at 10% SCBA of lime replacement (Figure 3). The decrease in the liquid limit can be attributed to aggregation and flocculation [39]. Meanwhile, there was a slight increase in the plastic limit with partial replacement of lime with SCBA; a similar trend as was obtained by [40]. In general, it can be stated that the plasticity index decreased with the addition of lime and bagasse ash. In more detail, the PI of the control unstabilized sample soil dropped significantly from 33% to 10% when 5% of lime was added. When lime was partially replaced with dosages of SCBA, the PI increased from 10% to 27% for 0% to 10% of 5% lime. This indicates that the lime had a greater decreasing effect on the plasticity of the soil than when it was mixed with SCBA. This is in agreement with previous findings such as those reported in Ref. [26]. The effect on the plasticity can be attributed to the replacement of much of the plastic particles in the clay with less plastic ones in the SCBA-lime mixture and, again, the calcium for iron exchange and hence flocculation-aggregation occurs [12,31, 40]. Therefore, it can be stated that the SCBA richness in SiO_2 facilitated pozzolanic reactions, hence the expansive soil structure change and the resultant plasticity alteration [15].

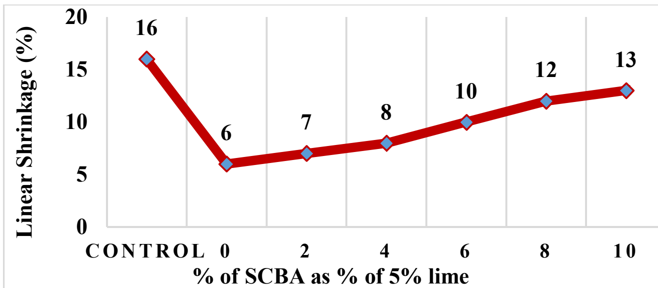

Figure 4 Linear shrinkage against lime placement.

Linear shrinkage of the natural unstabilized soil was reduced by around 63% when 5% of lime was introduced. It increased gradually with the addition of SCBA from 6% at 0% SCBA to 13% at 10% SCBA, representing a 53% improvement at 10% SCBA replacement of 5% lime (Figure 4). This indicates that the use of SCBA-lime stabilization improved linear shrinkage, but using lime alone performed better than the SCBA-lime mixture. The improvement in linear shrinkage can be attributed to flocculation plus aggregation phenomena caused by free CaO in the lime, which reduces the surface of finer clay particles. This reduction results in coarser particles of clay from the original finer particles [1]. LS decreased with partial replacement of lime by SCBA, however, it stayed lower than with unstabilized soil. Hence, the SCBA also lowered the LS of the clay particles less considerable than the lime. Thus, it was found that the SCBA-lime mixture also has the potential to reduce the LS, hence reducing shrinkage and cracking that cause a lot of damage to roads built on expansive clay soils.

3.2 Mechanical Properties

3.2.1 Compaction Characteristics

The maximum dry density (MDD) of the soil was reduced greatly, from 1.87 to 1.81 g/cm^3 by the addition of 5% of lime alone (Figure 5). The MDD continued to drop gradually with a reduction in the quantity of lime and an increase in the amount of SCBA from 2% to 10% partially replacing 5% lime. It was observed that the optimum moisture content (OMC) increased when the expansive clay was modified with the SCBA-lime mixture. The OMC of the control unstabilized sample was originally 16% at 5% lime stabilization. This value increased and continued to increase up to 30% at 10% SCBA partially replacing 5% of lime.

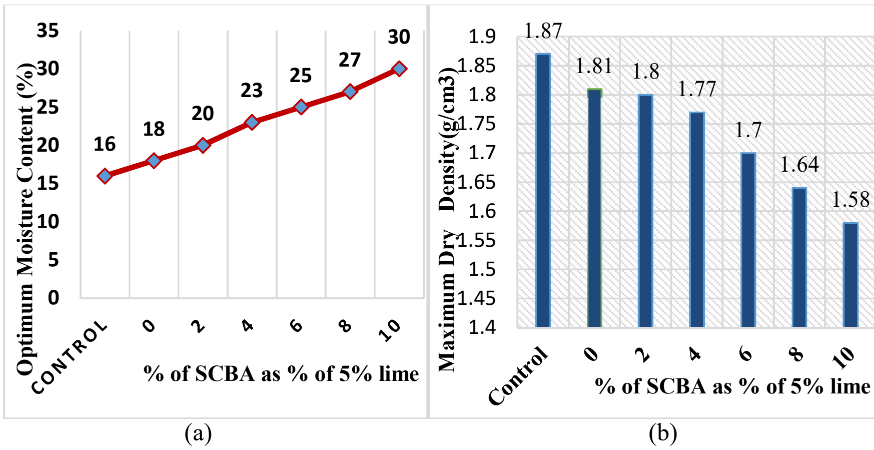

Figure 5 (a) Optimum moisture content, (b) maximum dry density.

The reason for the drop in dry density can be attributed to the introduction of lime, which has low specific gravity. The continuous drop as SCBA was introduced was because SCBA is also a much lower-density material compared to unstabilized soil [1]. Meanwhile, the increase in OMC could be due to the pozzolanic reaction between the lime in SCBA and the clay, as identified by [41]. The addition of SCBA-lime mixtures caused a decrease in the quantities of free silt and clay particles, resulting in the formation of coarser materials with a larger surface area. This important effect of SCBA-lime stabilization by lowering the MDD and raising the OMC improves compaction when the soil is wet [41].

3.2.2 California Bearing Ratio

Soaked CBR tests were performed on both the untreated and treated expansive soil to examine the strength and bearing capacity of the expansive soil as subgrade material in support of road and highway systems.

The CBR of all treated soil samples generally increased with the addition of lime and SCBA-lime mixture (Figure 6). This indicates that the load-bearing capacity of the samples was increased considerably by the bagasse ash and lime treatment. The CBR of the unstabilized sample of the soil was initially 12% and it rose to 34% when 5% of lime stabilizer was added. This means a raise of almost 183% in comparison with the CBR of unstabilized soil. This improvement in CBR indicates that lime is a strong stabilizer for expansive clay soil. This is consistent with what has been established by other studies, for example Refs. [10,26,27]. The CBR property improvement can be attributed to the pozzolanic reaction enabled by the calcium oxide from the lime causing cementation [1].

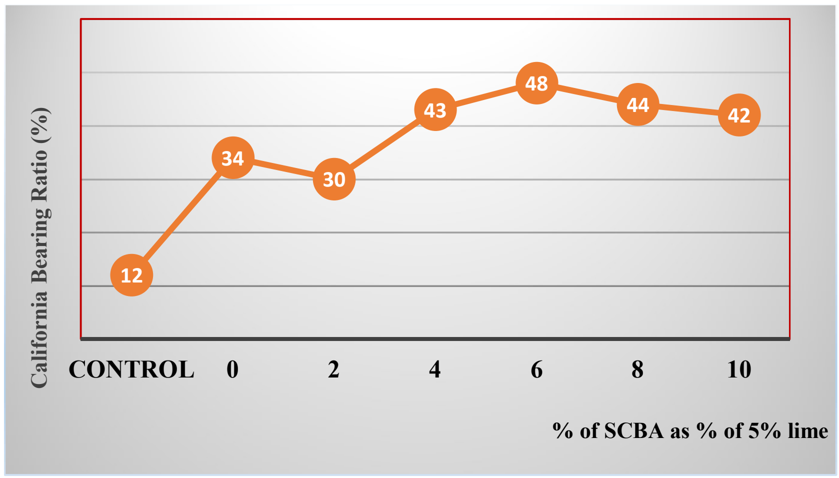

Figure 6 Soaked CBR after 7 days of curing against SCBA as % of lime.

After adjustment of the lime stabilizer with 2% of SCBA, the CBR value dropped a little by 2%. This drop in CBR can be attributed to the fact that the lime was reduced but the amendment was insignificant. Hence, this did not trigger a significant chemical reaction between the calcium hydroxide in the lime with the silica and alumina in the SCBA. The 2% of SCBA could not provide enough silica and alumina for the excess calcium hydroxide in the lime. Therefore, the CBR value dropped instead, as the amendment only decreased the $Ca(OH)_2$ that had earlier improved the CBR in the lime-only stabilization without any significant donation of free silica from SCBA. On the continuous addition of SCBA dosages, the CBR started increasing up to 48% at 6% lime replacement with SCBA. This means about 41% CBR improvement compared to the 5% lime-only stabilization. The improvement in the geotechnical property in terms of CBR as the SCBA proportion was increased indicates that expansive clay soil can be enhanced with SCBA-lime blending. The finding agrees with what was discovered in Refs. [13,32,41] and can be attributed to cementation together with the pozzolanic reactions triggered by SCBA injection.

Beyond 6% lime replacement, the CBR values dropped gradually from 48% to 44% and then 42% at 8% and 10% replacement respectively. This could be due to the fact that as the quantity of SCBA increases and the lime reduces, it reaches a point whereby continuous SCBA addition yields more silica and alumina compared to the available calcium hydroxide. Therefore, less CAH and CSH are produced, reducing the strength of the soil with 8% and 10% replacement of lime compared to the optimum (6% replacement). The SCBA played a role in enhancing the pozzolanic reaction. This occurs through speeding up the stabilizing process by quickening the breakdown of the structure plus the creation of new reaction products [1,15,42]. The microstructural analysis as reported previously also confirms this role of SCBA [15,31,43]. In these findings, this SCBA stabilization process enhancement was also indicated by a reduction of unreacted soil zones. This soil structure modification results in compact and denser matrices compared with soil stabilized by lime only, in the form of well-developed floccules. Finally, SCBA also reduces the voids within the stabilized soil compared to stabilization with lime only.

This study was generally successful in finding an alternative way of stabilizing soil besides using traditional stabilizers such as cement and lime. The partial replacement of lime with SCBA at 2 to 10% of 5% hydrated lime greatly improved the CBR property of the expansive clay soil: it improved from 34% at lime-only stabilization to 48% at 6% SCBA replacing 5% lime by weight. This achieved a 41% CBR improvement, which is a sign of better aggregation of the expansive soil and hence improvement of the CBR [15,31].

4 Conclusions

The study produced some promising results on the utilization of SCBA-lime in a form where SCBA is not just added and the lime proportion maintained but SCBA partially replaces the hydrated lime. The following conclusions can be drawn from the results of this study:

1. The effect of SCBA utilization to partially replace lime demonstrated high improvement of the Atterberg limits. The liquid limit was generally well improved by lime-only stabilization as compared with using an SCBA-lime mixture. However, SCBA-lime mixture stabilization attained a lower liquid limit compared to unstabilized soil. The liquid limit was slightly increased with SCBA-lime mixture stabilization. The PI for lime-only stabilization was better, as it gave about 69% improvement. This PI increased by about 62% with 10% SCBA addition. Hence, the lime-only treatment gave better results than the SCBA-lime mixture treatment.
2. Linear shrinkage of the expansive soil reduced when lime and SCBA were used. The effect of lime-only stabilization was more pronounced than that of SCBA-lime stabilization. As a result, the use of the SCBA-lime treatment gave promising results as a ground improvement solution for expansive soils.

3. The SCBA-lime stabilization also produced an improvement of MDD from 1.87 to 1.58 g/cm^3 and an increase of OMC from 16% to 30%. This provides potential benefits to expansive soil stablization as it improves compaction when the soil is wet.
4. The findings obtained significant results on CBR improvement, as all SCBA-lime mixtures gave results that satisfy most specification requirements for subgrade. At 6%, SCBA replacement of 5% lime stabilization gave an optimum replacement of 48% with a plasticity index of 20%. This optimum gave acceptable Atterberg limits as per Road Design Manual Part III for sub-base roads, as applied in East Africa [44].
5. This study showed partial replacement of hydrated lime with SCBA to stabilize expansive clay soil and enhance its geo-technical engineering properties. Hence, blending SCBA and lime while partially reducing the usage of non-environmentally friendly lime can have potential benefits. It can help to reduce the negative effects on the environment of waste by-product SCBA and greenhouse gases emitted during lime manufacture, thus having potential as a novel construction material for sustainable development. Finally, it gives a large amount of cost savings based on the fact that the amount of traditional stabilizers used such as lime and cement can be decreased considerably.

Nomenclature

LS = linear shrinkage
L_O = initial length of the sample on the mold
L_D = oven-dried length of the sample
PI = plasticity index
LL = liquid limit
PL = plastic Limit
SCBA = sugarcane bagasse ash
CBR = California bearing ratio

References

[1] Hasan, H., Dang, L., Khabbaz, H., Fatahi, B. & Terzaghi, S., *Remediation of Expansive Soils Using Agricultural Waste Bagasse Ash*, Procedia Engineering, **143**, pp. 1368-1375, 2016. DOI: 10.1016/j.proeng.2016.06.161.

[2] James, J. & Pandian, P.K., *Soil Stabilization as an Avenue for Reuse of Solid Wastes: A Review*. Acta Technica Napocensis: Civil Engineering & Architecture, **58**(1), pp. 50-76, 2015.

[3] Yilmaz, F. & Fidan, D., *Effect of Wetting-Drying Cycles on Volumetric Stability of Clayey Soil Stabilized with Lime and Perlite*, European Journal of Technique, **7**(2), 207-218, 2017.

[4] Sridharan, A. & Prakash, K., *Classification Procedures for Expansive Soils*, Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, **143**(4), pp. 235-240, 2000. DOI: 10.1680/geng.2000.143.4.235

[5] Fatahi, B., Engelbert, D., Mujic, S. & Khabbaz, H., *Assessment of Surcharging on Strength and Stiffness of Cement Treated Clays*, Grouting and Deep Mixing, 2012, USA, pp. 272-280. DOI: 10.1061/9780784412350.0013

[6] Fatahi, B. & Khabbaz, H., *Predicting Settlement of Chemically Stabilised Landfills*, International Journal of Geomate, **5**(2 SERL 10), pp. 700-706, 2013.

[7] Kharade, A.S., Suryavanshi, V.V., Gujar, B.S. & Deshmukh, R.R., *Waste Product Bagasse Ash from Sugar Industry Can Be Used as Stabilizing Material for Expansive Soils*, International Journal of Research in Engineering and Technology, **3**(3), pp. 506-512, 2014.

[8] Little, D.N., *Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates*. National Lime Association, 1998.

[9] Bell, F.G., *Lime Stabilization of Clay Minerals and Soils.* Engineering geology, **42**(4), pp. 223-237, 1996. DOI: 10.1016/0013-7952(96)00028-2.

[10] Dang, L.C., Hasan, H., Fatahi, B., Jones, R. & Khabbaz, H., *Enhancing the Engineering Properties of Expansive Soil Using Bagasse Ash and Hydrated Lime*, International Journal of Geomate, **11**(25), pp. 2447-2454, 2016.

[11] Patel, H., Singh, L., Dewangan, P. K., Kumar, S. & Pal, A., *Stabilization of Soil with Cement*, International Journal of Innovations in Engineering and Science, **5**(2), pp. 16-19, 2020.

[12] Wubshet, M., *Bagasse Ash as a Sub-grade Soil Stabilizing Material*, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, 2013.

[13] Wubshet, M. & Tadesse, S., *Stabilization of Expansive Soil Using Bagasse Ash & Lime*, Zede Journal, **32**, pp. 21-26, 2014.

[14] Sadeeq, J.A., Ochepo, J., Salahudeen, A.B. & Tijjani, S.T., *Effect of Bagasse Ash on Lime Stabilized Lateritic Soil,* Jordan Journal of Civil Engineering, **159**(3091), pp. 1-11, 2015.

[15] James, J. & Pandian, P.K., *Bagasse Ash as an Auxiliary Additive to Lime Stabilization of an Expansive Soil: Strength and Microstructural Investigation*, Advances in Civil Engineering, **2018a**, 9658639, 2018. DOI: 10.1155/2018/9658639.

[16] Zha, F., Liu, S. & Du, Y., *Behavior of Expansive Soils Stabilized with Fly Ash*, Nat Hazards, **47**, pp. 509-523, 2008. DOI: 10.1007/s11069-008-9236-4.

[17] Ji-ru, Z. & Xing, C., *Stabilization of Expansive Soil by Lime and Fly Ash.* J. Wuhan Univ. Technol.-Mat. Sci. Edit. **17**, pp. 73-77, 2002. DOI: 10.1007/BF02838423.

[18] Jha, J.N. & Gill, K.S., *Effect of Rice Husk ash on Lime Stabilization of soil.* Journal of the Institution of Engineers (India), Part CV, Civil Engineering Division, **87**, pp. 33-39, 2006.
[19] Choobbasti, A.J., Ghodrat, H. & Vahdatirad, M.J., *Influence of Using Rice Husk Ash in Soil Stabilization Method with Lime,* Front. Earth Sci. China, **4**, pp. 471-480, 2010. DOI: 10.1007/s11707-010-0138-x
[20] Kharade, A.S., Suryavanshi, V.V., Gujar, B.S. & Deshmukh, R.R., *Waste Product Bagasse Ash from Sugar Industry Can Be Used as Stabilizing Material for Expansive Soils*, International Journal of Research in Engineering and Technology, **3**(3), pp. 506-512, 2014.
[21] Manikandan, A.T. & Moganraj, M., *Consolidation and Rebound Characteristics of Expansive Soil by Using Lime and Bagasse Ash,* International Journal of Research in Engineering and Technology, **3**(4), pp. 403-411, 2014.
[22] Food and Agricultural Organization (FAO), *Production/Yield Quantities of Sugar Cane + (Total) 1994-2018, 2018*. Retrieved from: http://www.fao.org/faostat/en/#data/QC/visualize.
[23] Ganesan, K., Rajagopal, K. & Thangavel, K., *Evaluation of Bagasse Ash as Supplementary Cementitious Material,* Cement and concrete composites, **29**(6), pp. 515-524, 2007. DOI: 10.1016/j.cemconcomp. 2007.03.001.
[24] Cordeiro, G.C., Toledo Filho, R.D., Fairbairn, E.M., Tavares, L.M. & Oliveira, C.H., *Influence of Mechanical Grinding on the Pozzolanic Activity of Residual Sugarcane Bagasse Ash*, Proceedings of International RILEM Conference on the Use of Recycled Materials in Building and Structures, Barcelona, Spain, pp. 731-40, 2004.
[25] Richardson, I.G., *The Calcium Silicate Hydrates*, Cement and Concrete Research, **38**(2), pp. 137-158, 2008. DOI: 10.1016/j.cemconres. 2007.11.005.
[26] Barasa, P.K., Too, D., Jonah, K. & Mulei, S.M., *Stabilization of Expansive Clay Using Lime and Sugarcane Bagasse Ash.* Int. J. Sci. Res. (IJSR), **4**(4), pp. 2112-2117, 2015.
[27] Barasa, P.K., *Stabilization of Expansive Clay Soil Using Bagasse Ash and Lime,* Doctoral dissertation, COETEC, Jomo Kenyatta University of Agriculture and Technology, Kenya, 2017.
[28] Rehan, R. & Nehdi, M., *Carbon Dioxide Emissions and Climate Change: Policy Implications for the Cement Industry*, Environmental Science & Policy **8**(2), pp. 105-114, 2005. DOI: 10.1016/j.envsci.2004.12.006
[29] Metelková, Z., Boháč, J., Přikryl, R. & Sedlářová, I., *Maturation of Loess Treated with Variable Lime Admixture: Pore Space Textural Evolution and Related Phase Changes*, Applied Clay Science, **61**, pp. 37-43, 2012.

[30] James, J. & Pandian, P.K., *Industrial Wastes as Auxiliary Additives to Cement/Lime Stabilization of Soils,* Advances in Civil Engineering, **2016**, 1267391, pp. 1-17, 2016. DOI: 10.1155/2016/1267391.

[31] James, J. & Pandian, P.K., *Select Geotechnical Properties of a Lime Stabilized Expansive Soil Amended with Bagasse Ash and Coconut Shell Powder*, Selected Scientific Papers-Journal of Civil Engineering, **13**(s1), 45-60, 2018b. DOI: 10.1515/sspjce-2018-0005.

[32] Norouzian, K., Abbasi, N., & Koupai, J.A., *Use Of Sewage Sludge Ash and Hydrated Lime to Improve the Engineering Properties of Clayey Soils*, Geotechnical and Geological Engineering, **36**(3), pp. 1575-1586, 2018.

[33] Goyal, A., Anwar, A.M., Kunio, H. & Hidehiko, O., *Properties of Sugarcane Bagasse Ash and Its Potential as Cement-Pozzolana Binder*, Proceedings in Twelfth International Colloquium on Structural and Geotechnical Engineering, pp. 10-12, 2007.

[34] Bureau of Indian Standards (BIS), I 2720. *Methods of Test for Soils: Part 4 Grain Size Analysis*, Bureau of Indian Standards, New Delhi, India, pp. 1-38, 1985.

[35] ASTM D 2487, *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System),* ASTM International, West Conshohocken, PA, USA, 2011.

[36] Cherian, C., Bandipally, S., Arnepalli, D.N., Dhulipala, V.R. & Korupolu, R.N., *Reappraisal of Optimum Lime Content Determination for Lime Stabilization of Fine-Grained Soils,* Proceedings of 6th Asian Regional Conference on Geosynthetics-Geosynthetics for Infrastructure Development, pp. 8-11, November, 2016.

[37] British Standard, *BS 1377-2: Methods of Test for Soils for Civil Engineering Purposes, Part 2, Classification Tests*, British Standard Institution, London, UK, 1990.

[38] British Standard, *BS 1377-4: Methods of Test for Soils for Civil Engineering Purposes, Part 4: Compaction-related Tests,* London: UK, British Standard Institute, 1990.

[39] Muazu, M.A., *Evaluation of Plasticity and Particle Size Distribution Characteristics of Bagasse Ash on Cement Treated Lateritic Soil*, Leonardo Journal of Sciences, **10**(1), pp. 137-152, 2007.

[40] Yadav, A.K., Gaurav, K., Kishor, R. & Suman, S.K., *Stabilization of Alluvial Soil for Subgrade Using Rice Husk Ash, Sugarcane Bagasse ash and Cow dung ash for rural roads.* International Journal of Pavement Research and Technology, **10**(3), pp. 254-261, 2017. DOI: 10.1016/j.ijprt.2017.02.001.

[41] Osinubi, K.J., Bafyau, V. & Eberemu, A.O., *Bagasse Ash Stabilization of Lateritic Soil,* Appropriate Technologies for Environmental Protection in

the Developing World, pp. 271-280, Springer, Dordrecht, 2009. DOI: 10.1007/978-1-4020-9139-1_26.

[42] Hasan, H., Khabbaz, H. & Fatahi, B., *Strength Property of Expansive Soils Treated with Bagasse Ash and Lime*, Proceedings of International Congress and Exhibition Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology, pp. 24-35, Springer, Cham, 2017. DOI: 10.1007/978-3-319-61931-6_3.

[43] Al-Mukhtar, M., Khattab, S. & Alcover, J.F., *Microstructure and Geotechnical Properties of Lime-Treated Expansive Clayey Soil*, Engineering Geology, **139**, pp. 17-27, 2012. DOI: 10.1016/j.enggeo.2012.04.004.

[44] Ministry of Transport and Communication Road Department, *Road Design Manual Part III*, 1981.