An Evaluation of the Performance of Lateritic Soil Stabilized with Cement and Biochars to be Used in Road Bases of Low-Volume Sealed Roads

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ABSTRACT

The study investigated the effects of adding Saw Dust Ash (SDA) and Sugar Cane Bagasse Ash (SCBA) on the strength of cement with stabilized lateritic soil. The experiments carried out in both the lateritic soil and stabilized lateritic soil considered Atterberg limits, sieve/hydrometer analysis, compaction, soaked California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) at various curing periods. Ordinary Portland Cement (OPC) was introduced into the soil with varying content (0%, 3%, 5%, 7%, and 9%) by weight of the soil sample. The results showed that CBR and UCS increased to 175.7% and 1.999 MPa, respectively, as the OPC content increased to 7%. The optimal OPC content to meet the 1.5MPa UCS requirement for road bases on low-volume sealed roads in Kenya was 7%. The next treatment involved partially replacing the OPC content with SDA and SCBA in different doses (7-0-0%, 5-1-1%, 3-2-2%, 1-3-3%, and 0-3.5-3.5%, respectively) for various curing periods. The results showed that CBR and UCS decreased as the OPC content decreased and SCBA and SDA increased. At a content of 5% OPC, 1% SDA, and 1% SCBA, UCS and CBR were 1.877 MPa and 149%, respectively, suggesting that it was the optimal dosage to meet the 1.5MPa UCS requirement for road bases on low-volume sealed roads in Kenya. The durability test indicated that the specimens treated with 5% OPC, 1% SDA, and 1% SCBA met the 80% durability index mark, as recommended for cement-stabilized soils. Previous studies used SDA and SCBA separately with cement or lime to stabilize the subgrade or subbase of roads, but this study focused on using these materials together as a partial OPC replacement to stabilize lateritic road bases for use in low-volume sealed roads. The goal was to use local agricultural and industrial waste materials in road construction and improve the strength characteristics of road bases while preserving the environment through waste utilization.

Keywords-low volume sealed roads; saw dust ash; sugarcane bagasse ash

I. INTRODUCTION

Cement has a considerably high carbon dioxide (CO2) footprint that contributes significantly to global anthropogenic emissions. Climate change is considered a cumulative phenomenon that can increase global temperatures due to the presence of CO_2 in the atmosphere. The burning of fossil fuels for the production of cement contributes to the greenhouse effect, which is a major cause of climate change [1]. Therefore, it is important to explore alternatives to reduce the overreliance on conventional materials in concrete production, such as using agricultural and industrial waste such as Sugar Cane Bagasse Ash (SCBA) and Saw Dust Ash (SDA).

Transport infrastructure is a key point in long-term economic development. Developing countries face challenges related to their fragile transportation system, which does not facilitate transport. In these countries, the growing trade exchange, the increase in the number of vehicles, and the concentration of administrative services in county centers increase the deterioration of roads. Therefore, sustainable road construction materials with superior mechanical properties are needed [2]. The increase in population in urban areas in most developing countries has resulted in the need to expand the transportation infrastructure to enable upcountry communities to travel and carry their goods conveniently [3-4].

Roads and railway embankments and beds become vulnerable when the soil has a considerable proportion of clay minerals, as this type of soil has low engineering properties. The high proportion of fine-grained soil particles in the majority of residual tropical lateritic soils contributes to their low engineering characteristics [4-5]. However, the construction of gravel roads has become more expensive due to the increasing demand, variations in land use, high rate of gravel loss, environmental degradation, and considerable high frequency of re-graveling. Lateritic soil, which is widespread in tropical countries, including Kenya, could replace gravel in low-volume roads. Low-volume roads have an Average Daily Traffic (ADT) below 250 vehicles per day [6]. Materials in their natural state are sometimes not strong enough to meet the demands of modern-day road infrastructure. In civil engineering, for projects such as roads, building foundations, and dams, among others, soil stabilization is essential, as most lateritic soils typically have low bearing capacity and low strength due to the high clay content [7]. Most lateritic gravels are not suitable for road bases, due to their poor nodule hardness (incomplete lateralization) and high plasticity [8].

As roads use aggregates, the contribution of the aggregate cost to the total cost of road construction is significant. In India, the use of recycled building waste aggregates was explored to reduce material costs [9]. There are many reasons for using lateritic soil cement, such as the lack of crushed rock, the reduction in the use of crushed rock for environmental reasons, the difficulty to access and the depletion of quarry sites, transportation costs, and the considerable amount of energy demands in mining, transportation, and burning, which also contribute to the total CO_2 emissions. Cost reduction and environmentally friendly characteristics are the added benefit of stabilizing locally available soils for road construction [4, 11-13].

Kenya's road network is 161,451 Km and is valued at over Ksh 3.5 trillion. This constitutes one of the country's largest public investments. The government has invested in Low-Volume Sealed Roads (LVSR) across the country to open up rural areas, and so far about 4,500 Km of LVSR projects have been completed with a further 3,800 Km under construction. In total, there is over 5,900 Km of ongoing national road development programs across the country approximated at Ksh 658 billion [14].

In [15], optimal results were achieved by adding 6% SDA by weight to lateritic soils, showing that SDA acts satisfactorily as a cheap stabilizing agent for subgrade and subbase purposes in lateritic soils. In [16], the maximum compressive strength of stabilized soil was obtained using 5% lime and 8% SDA, while in [17] it was concluded that SDA can be considered a cheap and acceptable stabilizing agent in road construction to improve most geotechnical properties of soft clay soils. In [18], the maximum Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) values of 698 KN/m^2 and 43% were recorded for soil treated with 8% lime and 6% bagasse ash, but although the properties of the natural soil improved, it did not meet the criterion of 1710 KN/m^2 specified by the Transport and Road Research Laboratory (TRRL) (1977) for adequate stabilization using Ordinary Portland Cement (OPC). The use of a hydrated lime-bagasse ash mixture to stabilize expansive soil could meet CBR requirements for most specifications for subgrade or even subbase course materials for road and highway construction purposes [19].

In [4, 20], MDD and OMC of treated soil generally showed decrease and increase trends, respectively, with a higher bagasse ash content. Soil samples stabilized with bagasse ash recorded some gain in UCS but did not meet the 7-day 1,700 KN/m^2 strength criterion recommended by TRRL (1977) for base course materials. In [21], the maximum CBR value was 16% for soil treated with 2% bagasse ash and did not meet the requirement of the Nigerian General Specifications (1997) of 180% for the laboratory-tested cement-stabilized material mix-in-place method, concluding that bagasse ash cannot be used as a standalone stabilizer in road construction.

II. RESEARCH GAP

Previous studies used SDA and SCBA separately with cement or lime to stabilize the subgrade or subbase. This study focuses on the use of these two materials together as partial replacements of cement to stabilize lateritic road bases for possible use in low-volume sealed roads. This study aims to use local agricultural and industrial waste materials in road construction to improve the strength characteristics of road bases while at the same time preserving the environment through waste utilization. The results of this study promote rural mobility, enhance trade activities with a reduction in travel time, can provide beneficial income to woodworkers and sugar industries through the utilization of waste, and finally protect the environment.

III. MATERIALS AND METHODS

This study used Lateritic Soil (LS), OPC 42.5N, SDA, and SCBA. The LS used was collected from Kiambu County, Kenya. The OPC used was CEM I 42.5 N, produced by Bamburi Cement Company in Kenya. OPC CEM I was chosen because it had 95-100% clinker compared to 65-94% for CEM II, which means that CEM I had higher strength [4, 22]. In addition, using a higher percentage of clinker, the targeted strength could be achieved faster [3]. The SDA was obtained from the Kiambu Town Timber Factory in Kenya. SCBA was obtained from Sony Sugar Company in Awendo, Migori County, Kenya. Figures 1, 2, and 3 show the respective materials.

Fig. 1. Lateritic soil.

Fig. 2. Sugar cane bagasse ash.

Fig. 3. Saw dust ash.

The physical and mechanical properties of the soil were determined according to [23], including Liquid Limit (LL), Plastic Limit (PL), Plastic Index (PI), Shrinkage Limit (SL), Specific Gravity (SG), Particle Size Distribution (PSD), Optimum Moisture Content (OMC), Maximum Dry Density (MDD), CBR, and UCS, followed by classification. The elemental properties of LS, cement, SDA, and SCBA were investigated according to [23], using X-Ray Fluorescence (XRF) through a Shimadzu EDX-800HS energy dispersive X-ray spectrometer in the Materials Testing and Research Division (MTRD) of the Ministry of Roads and Transport (MORT) in Kenya. The soil was first stabilized by adding varying proportions of cement, ranging from 0, 3, 5, 7, and 9% by weight of the soil. The soil component was 100, 97, 95, 93, and 91%, respectively. Previous studies adopted comparable proportions for soil stabilization for possible use in road construction [3-4, 25-29]. Significant tests were carried out on the soil-cement samples to obtain the optimal cement content (M%). The tests included Atterberg limits, OMC, MDD, and CBR according to [23], and UCS according to [24].

UCS tests were carried out on samples compacted at their OMC in a standard Proctor mold with internal diameter and height of 100 and 115 mm, respectively. Samples were cured for 7, 14, and 28 days under controlled conditions. Then, they were subjected to a uniaxial compression test at a rate of 0.2 m/s, using a compression machine. It is worth noting that trial speeds above 0.2 m/s produced lower values than expected [4, 26]. The maximum load and compressive strength were recorded at the time of failure. The second study involved the partial replacement of OPC with equal amounts of SDA and SCBA, as shown in Table I, to produce soil-cement-SDA-SCBA samples [20]. Figures 4, 5, and 6 show some tested samples, the soaking process of the CBR samples, and the UCS samples testing setup, respectively.

Fig. 4. UCS samples to be tested

Fig. 5. CBR sample soaking.

Fig. 6. UCS sample testing.

Soil-cement-SDA-SCBA samples were subjected to durability tests according to [23]. Durability was expressed in terms of the resistance of the samples to loss of strength. This was achieved by dividing the UCS value obtained from stabilized samples cured for 7 days and soaked in water for another 7 days by the UCS value obtained from another set of stabilized samples cured for 14 days under controlled conditions. This test method was preferred to the wet and dry and freeze-thaw tests specified in the ASTM standard because it better represents field conditions in the study area. The same testing method was adopted in [30] to assess the durability of LS stabilized with eggshell and cement, and in [31] to assess the durability of cement-stabilized LS for use as a flexible pavement construction material.

After establishing the optimal OPC content, the other tests were performed to determine the optimal OPC, SDA, and SCBA content, as shown in Table I, according to [23-24]. M represents the optimal OPC content obtained in the initial experimental investigation and replaced by equal proportions of SDA and SCBA in the second study.

TABLE I. EXPERIMENTAL DESIGN

S/N	Soil (%)	Cement (%)	SCBA(%)	SDA (%)
B1	100-M	M-0.0-0.0	0.0	0.0
B2	100-M	M-1.0-1.0	1.0	1.0
B3	100-M	M-2.0-2.0	2.0	2.0
B4	100-M	M-3.0-3.0	3.0	3.0
B5	100-M	M-3.5-3.5	3.5	3.5

IV. RESULTS AND DISCUSSION

A. *Characterization of LS, SDA, and SCBA*

1) *Particle Size Distribution*

Figure 7 shows the particle size distribution curve of LS with contents of 17.8% clay, 24.7% sand, 52.6% gravel, and 4.9% silt. The soil was classified as A-2-7: silty, clay gravel sand, according to the AASHTO classification, and GC with USCS, which is clay gravel with sand. This implies that it cannot be used as a road base construction material, therefore, it must be stabilized [2, 4, 26].

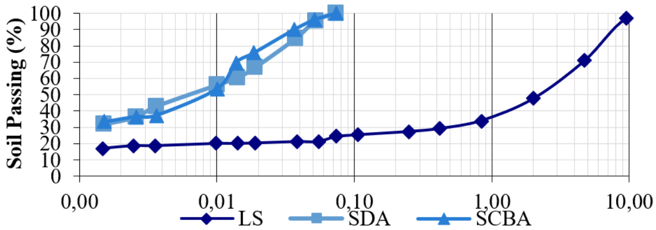

Fig. 7. PSD curve of the LS-SCBA-SDA.

2) *Chemical Composition of LS, SDA, and SCBA*

The prominent oxides found in LS were silica, iron, and aluminum oxides, which accounted for 42.94% SiO_2, 28.47% Fe_2O_3, and 18.29% Al_2O_3, respectively. The silica to sesquioxide ratio $(SiO_2)/(Al_2O_3+Fe_2O_3)$ was used as an indication of the extent of laterization. The ratio was found to be 0.92, which is less than 1.33, indicating that the LS used was true laterite [2, 32]. The sum of the silica and sesquioxide content in SCBA was 78.59% (59.92% SiO_2, 11.58% Fe_2O_3, and 7.09% Al_2O_3,), which is greater than the required 70% minimum [33], showing that the sample is a pozzolanic material (Table II). The SDA did not exhibit pozzolanic characteristics given the sum of 3.54% silica and sesquioxide content (0% SiO_2, 2.58% Fe_2O_3, and 0.96% Al_2O_3,). The results obtained for LS were consistent with those of [5, 34-35].

TABLE II. ELEMENT PROPERTIES OF LS, OPC, SCBA, SDA

Elements	SDA	OPC	SCBA	LS
Fe %	2.580	4.080	11.580	28.470
MgO %	4.030	0.490	-	-
Al_2O_3, %	0.960	6.020	7.090	18.290
SiO_2, %	-	25.300	59.920	42.940
K_2O, %	15.710	-	5.130	1.280
CaO, %	66.070	59.500	10.390	0.460
TiO_2, %	0.410	-	1.930	2.360
P_2O_5, %	3.690	-	1.500	0.210
S, %	3.750	2.630	1.110	0.140
Cl, %	1.150	0.0010	0.210	0.040
Insoluble residue, %	-	4.410	-	-
Loss on ignition @750^{0}C	-	4.390	-	-

B. *Stabilization of Laterite Soil with Cement*

1) *Effects of Cement on Atterberg Limits and Compaction*

Figure 8 shows that PI was reduced, which implies that the soil plasticity improved as the higher the PI, the more clayey the soil [4, 20, 36]. Figures 9 and 10 show the influence of cement on the compaction properties of LS. MDD and OMC for untreated soil were obtained at 1.72 g/cm^3 and 18.0%, respectively. After adding cement to 3, 5, 7, and 9%, MDD increased to 1.76, 1.76, 1.77, and 1.79 g/cm^3, respectively. Similarly, the OMC increased to 18.0, 21.5, 21.5, 24.5, and 24.7% by adding 3, 5, 7, and 9% cement, respectively. The increase in OMC may be due to the flocculation and agglomeration of clay-sized particles resulting from cat-ion exchange, which also causes an increase in volume. When the cement content increases, the increase in OMC may be due to the increase in fine content and the greater amounts of water required for cement hydration [4, 20, 37-38]. The increase in OMC may be due to the stabilizing binder that requires more moisture for the dissociation of calcium ions and the subsequent hydration process [4, 20, 30, 39]. The increase in MDD may be due to the greater affinity of water for the hydration process.

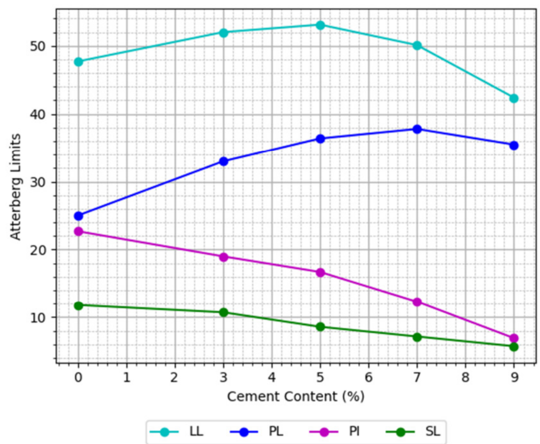

Fig. 8. Atterberg limits with cement content.

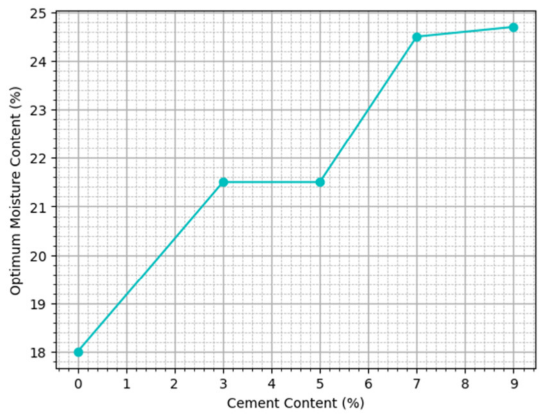

Fig. 9. OMC with cement content.

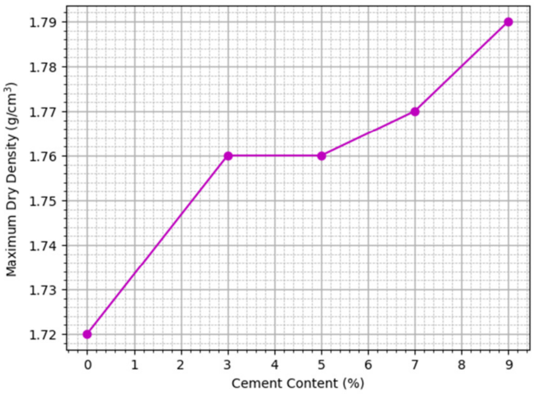

Fig. 10. MDD with cement content.

2) *Effect of Cement on California Bearing Ratio*

Figure 11 shows the summary of CBR for varying cement content of 0, 3, 5, 7, and 9% in LS. CBR increased from 30.9 to 175.7% with increasing cement content, where the maximum value was achieved with 7% cement and then decreased to 102.6% with 9% cement content. The increase in CBR agrees with [4, 20, 29, 39-41]. The increase in CBR with cement addition may be due to the availability of large quantities of calcium necessary for the formation of Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which are the main compounds responsible for strength gain [42]. The decrease in CBR at 9% may be due to large amounts of cement that were not mobilized in the reaction, thus reducing the bond in the cement-soil matrix [4, 20, 39, 43-44].

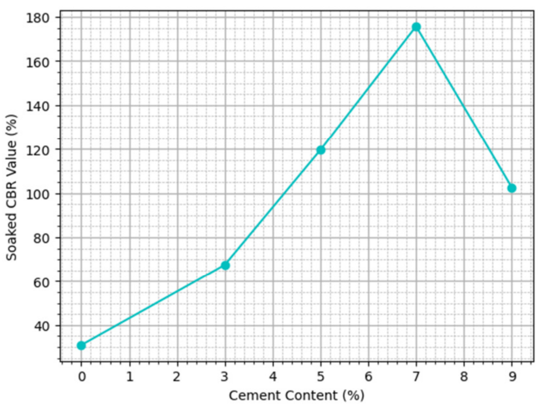

Fig. 11. Variation of soaked CBR with cement content.

3) *Effect of Cement on Unconfined Compressive Strength*

Figure 12 shows that UCS increased with cement content. At 7 days of curing, the UCS of LS of 0.226 MPa improved to 0.483, 0.775, 1.99, and 2.769 MPa for cement content of 3, 5, 7, and 9%, respectively. This increase is consistent with [29, 45]. Strength gain due to cement was attributed to decreased soil porosity when cement is added, as well as to the compaction and hydration of cement [25, 46]. The UCS at 7 days of curing is the most important strength criterion used for cement-stabilized materials for road purposes. In [47], it was concluded that the UCS test should be used to determine the strength of the cement-stabilized soil base. Since UCS at 7 days of curing increased with cement content and all soil-cement mixes above 7% cement content meet the requirements of the Kenya Pavement Design Guideline for LVSR [48], which recommends a minimum of 1.5 MPa for road bases, the 7% cement content was identified as optimal. This is nearly in agreement with [49], where 2 and 6% cement were proposed to stabilize Colombian LS for use in the construction of low- to medium-volume roads. In [50], the use of 9.23% OPC was recommended to meet the requirement of 80% CBR, which can achieve a strength of 1428.09 KPa. There was no significant change in UCS with curing periods of 14 and 28 days, respectively. The slightly higher values obtained at 14 days could be due to swelling as a result of comparably longer curing periods [4, 20].

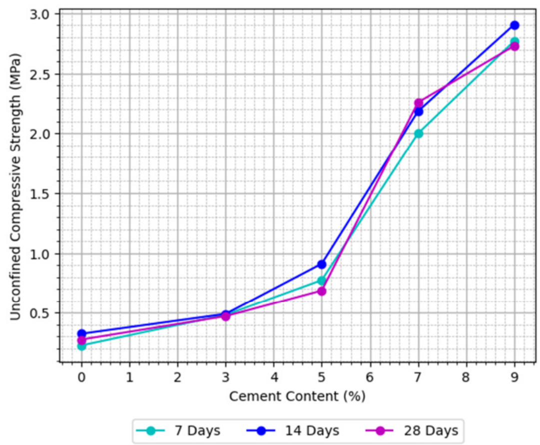

Fig. 12. Variation of UCS with cement content.

C. *Stabilization of LS with OPC, SDA, and SCBA*

1) *Effect on Atterberg Limits and Compaction*

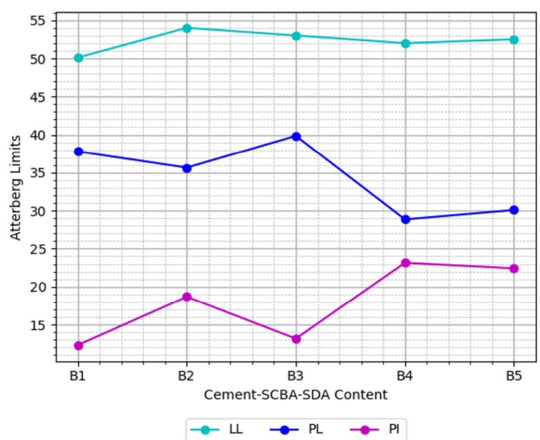

Fig. 13. Atterberg limits with cement, SCBA, and SDA.

LS was stabilized with SDA and SCBA as a replacement for cement for the optimal content of 7%. Figure 13 shows that PI increased from 12.3 to 22.42%. The increase in PI may be attributed to the addition of SDA and SCBA, which have higher water absorption affinity [2, 7, 51]. According to [36], the higher the PI, the more clayey the soil. Figure 14 shows that an increase in SDA-SCBA content from 0 to 3.5% along with a decrease in cement content from 7 to 0% showed a slight increase in OMC from 24.5% (B1) to 26.4% (B5).

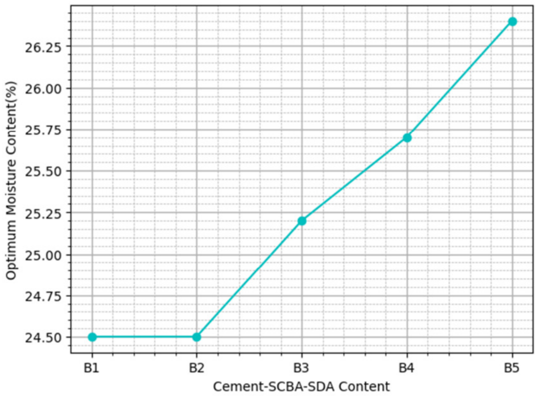

Fig. 14. OMC with cement, SCBA, and SDA.

Figure 15 shows that MDD had a slight decrease from 1.77 g/cm^3 to 1.74 g/cm^3 at B5. This is consistent with [2, 31]. The minimal changes can be attributed to the addition of small amounts of SDA-SCBA in the soil-cement mixture [26, 39].

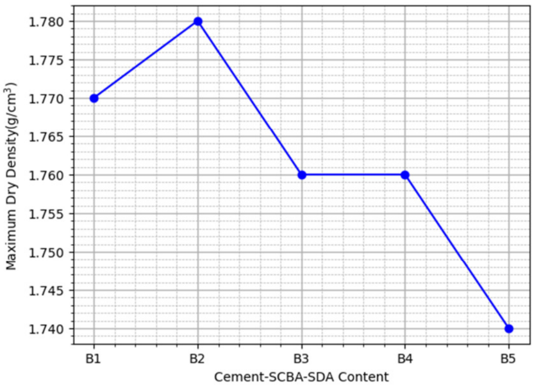

Fig. 15. MDD with cement, SCBA, and SDA.

2) *Effect of OPC-SDA-SCBA on California Bearing Ratio*

Figure 16 shows that CBR decreased from 175.7% (B1) to 32.3% (B5) [2, 7]. The gradual decrease in CBR may be due to the high amount of SDA-SCBA that was not mobilized in the reaction, which therefore occupied more space in the sample and thus reduced bonding in soil-cement-SDA-SCBA mixtures [39, 52]. The chemical reaction induced by stabilizers and soil and catalyzed by compaction may be responsible for the decrease in CBR, but in [47] it was stated that the UCS test should be used to determine the strength of cement-stabilized soil base. As stabilized materials are rigid or semi-rigid, CBR is meaningless, and the most convenient strength criterion for such materials is UCS [8].

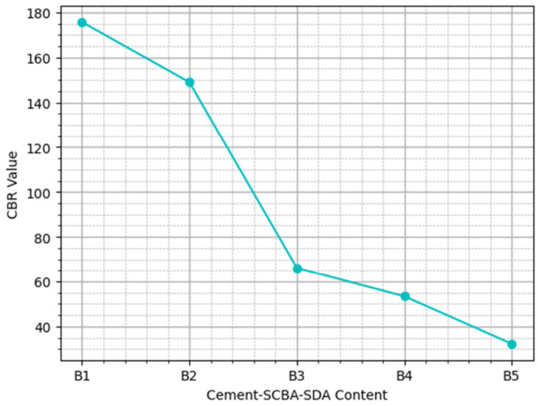

Fig. 16. CBR with cement-SCBA-SDA content.

3) *Effect of OPC-SDA-SCBA on Unconfined Compressive Strength*

Figure 17 shows that UCS decreased from 1.999 to 0.305 MPa, from 2.184 to 0.246 MPa, and 2.258 to 0.287 MPa for 7, 14, and 28 days of curing, respectively, with an increase in SDA, SCBA content from 0 to 3.5% and a decrease in cement content from 7% to 0 [2, 7]. The lower specific gravity of SDA and SCBA replacing those of the soil and cement may contribute to the decrease of UCS. The UCS value at 7 days curing for 5% OPC, 1% SDA, and 1% SCBA was 1.877 MPa, which is within the range specified in the Kenya pavement design guideline for LVSR of above 1.5 MPa for road bases. According to [8], CBR is meaningless for rigid or semi-rigid stabilized materials, the most convenient strength criterion for such materials is UCS, and a minimum UCS of 1800 KN/m^2 is required on the laboratory mix compacted at 95% MDD after 7 days cure plus 7 days soak, which is economically justified for traffic classes T1 to T3. In this study, the results for 7 days cure and 7 days soak were 1.539 MPa (B2), which was the optimal combination.

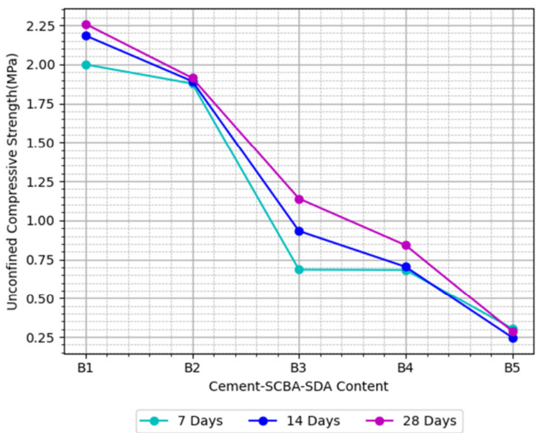

Fig. 17. UCS with cement-SCBA-SDA content.

4) *Effect of OPC-SDA-SCBA on Durability*

Figure 18 shows the durability results of the optimal soil-cement-SDA-SCBA admixtures under simulated tropical conditions, determined from the resistance of the samples to strength loss. UCS decreased to 94.71% (B1), 82.03% (B2), 75.61% (B3), 61.35% (B4), and 47.64% (B5). The durability of the soil-cement-SDA-SCBA content in B2 was found to be satisfactory, as the values were above the recommended minimum of 80% [31]. The decreasing trend of UCS against wetting-drying cycles was ascribed to the degradation of cement bonding [53]. Furthermore, in [54], it was stated that strength reduction against wetting-drying is due to the back pressure caused by the absorbed pore water and the softening of the specimens due to water immersion.

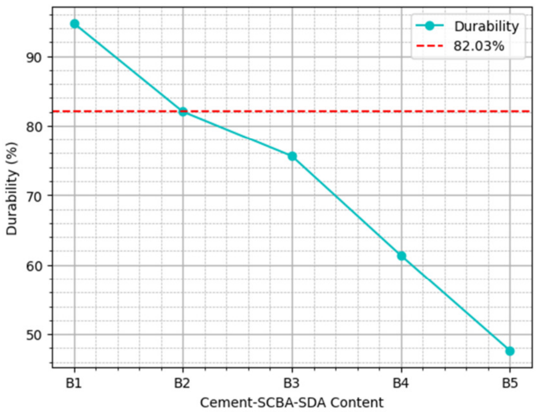

Fig. 18. Durability with OPC-SCBA-SDA content.

V. CONCLUSIONS

This study evaluated the effects of adding SDA and SCBA on cement-stabilized LS by selecting five different cement proportions to determine the optimal cement content. This optimal cement content was partially replaced by SDA and SCBA to determine the optimal cement-SDA-SCBA content for the stabilization of LS road bases in LVSR. The results of this study shed light on the following issues:

- The grain size distribution curve of LS indicates the high content of gravel (52.6%), sand (24.7%), silt (4.9%), and clay (17.8%). The soil was classified as A-2-7 silty, clay gravel sand according to AASHTO classification and GC according to USCS, which is clayey gravel with sand. The sum of the silica and sesquioxide contents in SCBA was 78.59%, which was greater than the minimum 70% required by ASTM C 618-05 (2005) [33], indicating that it was pozzolanic, while the SDA sample did not exhibit pozzolanic characteristics.
- There was a strength gain from 0 to 9% with cement addition in LS at a curing period of 7 days, but the corresponding strength gain at curing periods of 14 and 28 days was minimal. The optimal dose for the stabilization of LS was 7%, with a UCS of 1.999 MPa at 7 days of curing. This meets the Kenya Pavement Design Guideline for LVSR, which recommends a UCS of 1.5 MPa.
- There was a significant decrease in strength with the addition of SDA and SCBA to cement-stabilized LS. The optimal cement-SDA-SCBA content was 5, 1, and 1%, respectively, which had a strength of 1.877 MPa. This strength was found sufficient to obtain a UCS of more than 1.5 MPa for LVSR, as specified in the Kenya Pavement Design Guideline.
- There was a decrease in durability with the addition of SDA and SCBA to cement-stabilized LS. The durability of the cement-SDA-SCBA content at 5% cement, 1% SDA, and 1% SCBA was 82.03%, which was satisfactory as the values were above the recommended minimum of 80%.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding this study.

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