Mechanical and Structural Correlation of Lateritic Soil Road Base Stabilized with Cement and Selected Biochars

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ABSTRACT

The study considers the strength and structural characterization of lateritic soil road base in order to increase the strength of low-volume sealed road construction. Sugar Cane Bagasse Ash (SCBA) and Saw Dust Ash (SDA), mixed with soil and in combination with different percentages of Ordinary Portland Cement (OPC), were utilized in the current study. Structural and mechanical characterization of the investigated samples was performed by X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Standard Proctor Test (SPT), Unconfined Compression Strength (UCS) Test, and California Bearing Ratio (CBR) Test. The observed increase in strength may be due to the reduction of mica, quartz, and calcite in the investigated samples. CaO and SiO_2 contribute to the development of strength in cement, while SCBA, and SDA-stabilized lateritic soils. The microstructural study revealed that the mica, quartz, and calcite phases play a very important role in maintaining the strength and stability of the investigated samples.

Keywords-strength and structural characterization; X-Ray diffraction; X-Ray fluorescence; sugar cane bagasse ash; saw dust ash

I. INTRODUCTION

Lateritic soils are very common in sub-Saharan Africa. They are easy to extract and have a relatively low operating cost, hence, they are commonly used in road construction. However, the application of these materials is subjected to meeting certain criteria defined by existing technical specifications [1-2]. Soil stabilization is a technique almost as common as road construction itself. It refers to the mixing of a foreign element in the construction material for the enhancement of the engineering properties of the construction project. Another important advantage is the conservation of natural construction material and controlling of waste materials from polluting the environment [3]. A common antecedent for pavement failure of most roads is the poor quality of the lateritic soil used in its construction. This soil type is mainly differentiated by its poor workability, low shear strength, high compressibility and poor bearing capacity. Stabilization with an additive will help ameliorate this type of soil for use in pavement construction rather than replace them with good quality soil which is uneconomical [4]. Cement and lime stabilization are the most commonly used techniques for stabilization of expansive soils. Nowadays, the concentration is on the use of industrial and agricultural waste materials along with cement or lime to achieve improved strength and waste management [5-9].

Bagasse is a fibrous material that remains upon crushing sugarcane to extract its juice. Bagasse ash contains a high percentage of silica (SiO_2), and is regarded as a sensitive pozzolanic material with non-reactive actions that has the possibility to be used in road subgrade stabilization [10]. Saw dust ash consists of loose particles or burned wood chippings obtained by sawing hard wood into standard useable sizes. Clean saw dust without a large amount of bark has proved to be satisfactory due to its low organic content [11]. Researchers are focusing on ways of using either industrial or agricultural waste, along with other additives, as alternative materials for improving the engineering performance of the soil. The utilization of these waste materials from the industry is economical and protects the environment [12].

Authors in [13] observed that the increase in strength is due to the reduction of mica in the soil and, therefore, increase of the silica in the soil increases strength and stability. A microstructural study revealed that mica phase may play very important role in maintaining the strength and stability of the soil. Authors in [5] concluded that mineralogical investigation on optimum lime content stabilized soil amended with 0.5% bagasse ash indicated reduction in peaks of quartz and montmorillonite and development of new peaks corresponding to reaction products of the pozzolanic reactions. Authors in [14] confirmed from XRD results that rice husk ash and pond ash both have pozzolanic behavior. Therefore, both can be used as partial replacement materials for cement. Authors in [15] studied the assessment of the geotechnical and microstructural characteristics of lime-stabilized expansive soil with bagasse ash and concluded that the formation of cementitious products as a result of the time-dependent pozzolanic reactions between clay and bagasse ash particles along with hydrated lime plays a key role in the improvement in the strength and stiffness of the treated soils. Authors in [16] studied the role of industrial precursors in the stabilization of weak soils with geopolymers. They observed that since there were no new minerals formed after stabilization, the binding effect of the geopolymer gels likely improved the mechanical properties of the soil.

II. ENVIRONMENTAL IMPACT

Most developing nations face problems from weak waste management regulation processes, therefore impacting negatively on the environment and the air quality in these countries. The lack of a framework in dealing with the waste originated from sugarcane harvest and saw mills, produces a huge volume of residues which are often burned. Burning sugarcane bagasse and saw dust leads to the degradation of the air quality and the emission of harmful combustion products such as Volatile Organic Carbons (VOCs) and carbon monoxide (CO). In addition, sugarcane and fertilizer waste turn into nitrate reducing water oxygen content thus negatively impacting marine life [16-24]. Agricultural pollution is a main source of air and water pollution. The combustion of bagasse and saw dust produces many harmful emissions. Moreover, chemicals from fertilizers and pesticides leaking into groundwater cause many health-related problems [17]. The application of these wastes in construction can reduce the negative environmental effects.

III. MATERIALS AND METHODS

The materials used in this investigation were Lateritic Soil (LS), Ordinary Portland Cement (OPC), Sugar Cane Bagasse Ash (SCBA), and Saw Dust Ash (SDA). The LS used was obtained from Kamiti Prisons ground in the county of Kiambu, Kenya. The sampling location was located at 1°09’00.4"S, 36°53’00.2"E. The sampled soil was dried for two days to become completely dry. The OPC used was CEM I 42.5N, which was produced by the Bamburi Cement Company in Kenya and obtained from Thika cement yards in Kiambu County. The SDA was obtained from Timber Processing yards, Kiambu Town, Kenya. After collection, the clean saw dust was air dried and burnt in a furnace at a temperature of 800^0C. This burning, which is different from that done by sawmills, was done in a closed furnace so that the ash produced did not escape into the atmosphere and thereby yielded large quantities of ash with minimized environmental pollution [25]. The SDA was then sieved through 600-micron sieves to remove lumps, gravels, unburnt particles, and other materials deleterious to the soil. The remaining SDA was used for this study. The used sugar cane bagasse was collected from SONY Sugar, Awendo, Migori County, Kenya. The air-dried bagasse was burnt in a locally constructed incinerator at a controlled temperature range between 600°C and 700°C to acquire the bagasse ash [26] and the obtained SCBA was passed through BS No. 200 sieve. The LS used in this study was A-2-7 according to AASHTO classification, with a specific gravity of 1.97 and a pH of 6.78.

The engineering properties of the soil were investigated in the laboratory in accordance with BIS specifications which included Optimum Moisture Content (OMC), Maximum Dry Density (MDD), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). The soil was initially stabilized with the addition of varying proportions of cement (0%, 3%, 5%, 7%, and 9% by weight). Previous studies adopted comparably the same proportions for soil stabilization for possible use in road construction [27-31]. The specified dosages for use in road construction are 5-7% OPC for clayey soils and 5-8% OPC for plastic gravels [32]. Against this background, this research adopted the proportions of 0-9% OPC for stabilization of LS. Various tests were performed on the soil-cement samples in order to obtain the optimum cement content (P%). The conducted tests included compaction characteristics and CBR in accordance to BS 1377: Part 4: 1990 and UCS in accordance to BS 1924:Part 2: 1990. The UCS tests were carried out on samples compacted at their OMCs in the standard Proctor mold with an internal diameter of 100mm and an internal height of 115mm. After establishing the optimum cement content, the other tests to determine the optimum content of cement, SDA and SCBA were conducted as illustrated in Table I and compaction characteristics and CBR in accordance to BS 1377: Part 4: 1990, UCS in accordance to BS 1924:Part 2: 1990 were carried out for B1, B2, B3, B4, and B5 samples. The UCS samples at 28 days for B1, B2, B3, B,4 and B5, after testing, were packed in sealable polythene bags for XRD test and the procedure adopted in [5] was used in the preparation for the samples. Crystal phase evolution in the LS, cement, SCBA, SDA, and the investigated UCS stabilized samples was done through a Shimadzu XRD 6000 Diffractometer at the Kenya Electricity Generating Company (KENGEN) in Kenya. The elemental analysis of the LS, OPC, SDA, and SCBA of the investigated samples was conducted with X-Ray Fluorescence (XRF) through the Shimadzu EDX-800HS, Energy Dispersive X-Ray

Spectrometer at the Materials Testing and Research Centre of the Kenyan Ministry of Roads and Transport.

TABLE I. STRENGTH AND MICROSTRUCTURAL EXPERIMENTAL DESIGN

Experimental design						
1st investigation		**2nd investigation**				
LS	CEM	S/n	LS	CEM	SDA	SCBA
100	0	B1	100-P	P	0	0
97	3	B2	100-P	P-1-1	1	1
95	5	B3	100-P	P-2-2	2	2
93	7	B4	100-P	P-3-3	3	3
91	9	B5	100-P	P-3.5-3.5	3.5	3.5

IV. RESULTS AND DISCUSSION

A. Mechanical Properties

1) OMC, MDD, CBR and UCS for Cement-Stabilized LS

Table II presents the OMC, MDD, CBR, and UCS of the cement stabilized LS. The results show that the OMC, MDD, and UCS increased with the increase in cement content. The CBR increased for cement content up to 7% to the maximum of 175.7% and then decreased to 102.6% at 9% cement content. The increase of OMC may be due to the flocculation and agglomeration of clay-sized particles because the cat-ion exchange causes increase in volume. With increase in cement content, the OMC increased as well, maybe due to the increase in fines content or to the increased amount of water required for the hydration of the cement [33, 34]. The increase in OMC may be caused by the stabilizing binder requiring more moisture for the dissociation of the calcium ions and subsequent hydration process [4]. The increase in MDD may be due to the greater affinity of water for the hydration process. The increase in CBR can be attributed to the chemical reaction between the stabilizing binder and the soil particles which is complemented by the compaction process. The increase in the UCS values is probably caused by the cementitious properties of the stabilizing binder which aids in the solidification of the soil matrix, thereby increasing strength [4]. The reduction in CBR value at 9% may be due to the excess cement that was not mobilized in the reaction, therefore reducing the bond in the cement-soil matrix [35, 36]. The strength gain due to cement is attributed to decreased soil porosity [28, 29].

TABLE II. VARIATION OF OMC, MDD, CBR, AND UCS WITH CEMENT CONTENT

Cement content %	OMC (%)	MDD (g/cm^3)	CBR (%)	UCS at 28 days (MPa)
0	18.0	1.72	30.9	0.275
3	21.5	1.76	67.5	0.472
5	21.5	1.76	119.5	0.688
7	24.5	1.77	175.7	2.258
9	24.7	1.79	102.6	2.729

2) OMC,MDD, CBR, UCS of Cement, SCBA, and SDA-Stabilized LS

From Table II, it is observed that the OMC of the LS is 18.0, but when cement is added at 7%, which is the optimum cement content in this research, it increased to 24.5%. With the reduction in cement content and increase in SCBA and SDA content, there is a slight increase in the OMC as shown in Table III. Table II shows that the MDD of the LS is 1.72. When 7% cement was added, the MDD increased to 1.77. With the decrease in cement content and the addition of SCBA and SDA, the MDD depicts an increasing and decreasing trend as shown in Table III. This agrees with the results of [37]. The minimal changes may be attributed to the addition of small amounts of SDA-SCBA in the soil-cement mixture [38]. From Table II, it is observed that the CBR of the lateritic soil is 30.9%. With the addition of 7% cement the CBR increased to 175.7% and thereafter decreased to 102.6% at 9%. The increase in values of CBR is consistent with the findings of [39-41]. The increase in the values of CBR upon the addition of cement may be attributed to the presence of adequate amounts of calcium required for the formation of Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which are the major compounds responsible for strength gain [42]. The reduction in CBR value at 9% may be due to the excess cement that was not mobilized in the reaction, therefore reducing the bond in the cement-soil matrix [35, 36]. The UCS at 28 days increased from 0.275 MPa to 2.729 MPa with the increase in cement content as shown in Table II. The increase in UCS is consistent with the findings in [43]. The strength gain due to cement is attributed to decreased soil porosity when adding cement [29] and to the compaction and hydration of cement [44]. From Table III, it is observed that with further reduction in the cement content and increase in the SCBA and SDA content, the CBR value decreases. The gradual decrease in the CBR may be due to the excess SDA-SCBA that was not mobilized in the reaction, which consequently occupies space within the samples and therefore reduces bond strength in the soil-cement-SDA-SCBA mixtures [45]. The chemical reaction between the stabilizers and the soil, complimented by compaction, may be responsible for the increase of the CBR.

TABLE III. VARIATION OF OMC, MDD, UCS, AND CBR WITH CEMENT, SCBA, AND SDA CONTENT

Sample name	OMC (%)	MDD (g/cm^3)	UCS (MPa)	CBR% (soaked)
B1	24.5	1.77	2.258	175.7
B2	24.5	1.78	1.913	149.0
B3	25.2	1.76	1.139	66.1
B4	25.7	1.76	0.841	53.4
B5	26.4	1.74	0.287	32.3
B0 (soil)	18.0	1.72	0.275	30.9

In Table III, it is shown that the UCS of the LS is 0.275 MPa. With the addition of 7% cement, the UCS increased to 2.258 MPa. As the cement content decreased and the SCBA and SDA increased, the UCS decreased as well. The decrease of the UCS is due to the soil-SCBA reactions and soil-SDA reactions which result in the formation of cementitious compounds that bind soil aggregates and the availability of sufficient water that enhances the hydration reaction of cement which reacts with silica and alumina in the LS to produce secondary cementation compounds [46-48] and calcium ions that combined with reactive silica and aluminum, or both, to form insoluble calcium silicates or aluminates and other pozzolanic products and the agglomeration of the heterogenous materials of the SDA-stabilized LS and SCBA-stabilized LS [37, 38]. The value of UCS at B2 satisfied the Kenya Pavement guideline requirement for Low Volume Sealed Roads of 1.5 MPa for road base. For stabilized materials that are rigid or semi rigid, the CBR is meaningless [32]. The most convenient strength criterion for such materials is the UCS.

B. Structural Properties

1) Semi-Quantitative Elemental Analysis of the Studied Samples from XRF Spectrums

Tables IV-V show the semi-quantitative elemental analysis of the investigated samples from XRF which included LS, CEM (Cement), SCBA, SDA, B1, B2, B3, B4, and B5. CaO/SiO_2 and $CaO/(SiO_2 + Al_2O_3)$ ratios are important factors for pozzolanic reaction in the stabilization process especially at longer curing times [48]. Higher strengths are achieved when the ratios are in the range of 2 to 2.5. It was further observed that stabilizer's constituents, especially CaO, play a critical role in the strength gain characteristics of stabilized soils' early strength. Other oxides (SiO_2 and Al_2O_3) play a significant role at longer curing times, suggesting that there could be a higher strength realized at curing periods beyond 28 days. CaO and SiO_2 were noted to be the dominant composition of the investigated samples. This explains why there is significant decrease in UCS and CBR values with decreasing ratios as shown in Table V.

TABLE IV. ELEMENTAL ANALYSIS OF LS, CEM, SCBA, AND SDA

Component	SCBA	SDA	CEM	LS
Fe %	11.58	2.58	4.08	28.47
MgO %	-	4.03	0.49	-
Al_2O_3 %	7.09	0.96	6.02	18.29
SiO_2 %	59.92	-	25.30	42.94
K_2O %	5.13	15.71	-	1.28
CaO %	10.39	66.07	59.50	0.46
TiO_2 %	1.93	0.41	-	2.36
P_2O_5 %	1.50	3.69	-	0.21
S %	1.11	3.75	2.63	0.14
Cl %	0.21	1.15	0.001	0.004
Insoluble residue %	-	-	4.41	-
Loss on ignition at 750°C	-	-	4.39	-

Soil stabilization can be achieved by the pozzolanic reaction between the CaO present in the stabilizers and the soil particles. When SCBA and SDA are added to the LS and mixed with water, the $Ca(OH)_2$ dissociates into Ca^{2+} and OH^- ions. These ions cause the silica and alumina contained in the LS to dissolve and combine with Ca^{2+} ions to form CSH and CAH which are the main products of the hydration of OPC and are responsible for the strength in cement-based materials. The amorphous gel (CSH and CAH) binds the soil matrix and it is principally responsible for the increase in strength [50-52]. But for this particular study, there was a decrease in UCS with the addition of SCBA and SDA at 1:1 ratio. Authors in [53] observed that the main constituents of SCBA are silicon oxide (SiO_2) and lower contents of Calcium Oxide (CaO), Potassium Oxide (K_2O), and Magnesium Oxide (MgO), which agrees with this investigation as shown in Table IV. Authors in [54] found that SDA contains calcite and silica while this study shows no traces of silica in the used SDA, as indicated in Table IV.

TABLE V. SEMI-QUANTITATIVE ELEMENTAL ANALYSIS OF THE INVESTIGATED SAMPLES FROM XRF SPECTRUMS

Component	B1	B2	B3	B4	B5
Fe %	20.6	20.7	24.8	25.1	22.1
MgO %	-	-	-	-	-
Al_2O_3 %	6.8	7.9	9.4	11.0	10.1
SiO_2 %	26.2	31.5	34.9	39.1	39.8
K_2O %	1.0	1.6	2.8	2.6	4.1
CaO %	39.5	31.9	20.1	14.6	16.5
TiO_2 %	1.5	1.9	2.1	2.3	2.1
P_2O_5 %	0.5	0.4	0.7	0.2	0.9
S %	1.5	1.3	1.6	0.6	0.9
Cl %	0.09	0.03	0.15	0.29	0.09
Insoluble residue, %	-	-	-	-	-
Loss on Ignition at 750°C	-	-	-	-	-
$[CaO/SiO_2]$	1.5	1.01	0.57	0.37	0.41
$[CaO/(SiO_2 + Al_2O_3)]$	1.19	0.81	0.45	0.29	0.33

2) Structural Properties of Cement, SCBA, and SDA Stabilized LS from XRD Analysis

In Figure 1 and Table VI, the XRD patterns of SCBA show that, it contains crystalline quartz and gismondine, amorphous mica, clinochlore, chlorite, and calcite. Figure 2 and Table VI show that the SDA contains crystalline mica, chlorite, muscovite, amorphous clinochlore, calcite, and quartz. Figure 3 and Table VI present the XRD pattern of cement. They show that cement contains crystalline calcite ($CaCO_3$) and amorphous mica, clinochlore, cristabolite, quartz, and gismondine.

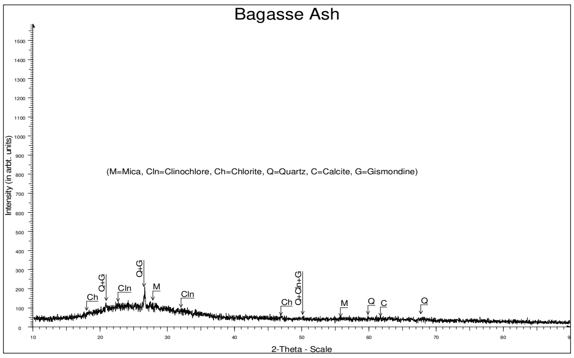

Fig. 1. XRD pattern of SCBA.

Figure 4 and Table VI present the XRD pattern of LS. It is observed that it contains crystalline quartz, mica, clinochlore, and gismondine. Authors in [17] report that LS is composed mainly of quartz, iron-magnesium-manganese, and kaolinite. This is comparable with the results obtained in this study. The XRD patterns indicated that quartz is the predominant mineral present in the LS sample. Quartz is silicon dioxide (SiO_2) having a Moh's hardness of 7. It is a durable material and it is highly resistant to both chemical and mechanical weathering. The presence of quartz in LS adds to its durability and will aid the formation of cementitious material (CSH) when mixed with SCBA and SDA in the presence of water. Other minerals present in the LS are kaolinite, moganite (SiO_2), gismondine, sanidine, muscovite, and dickite [52], which partly agrees with the results found in this investigation.

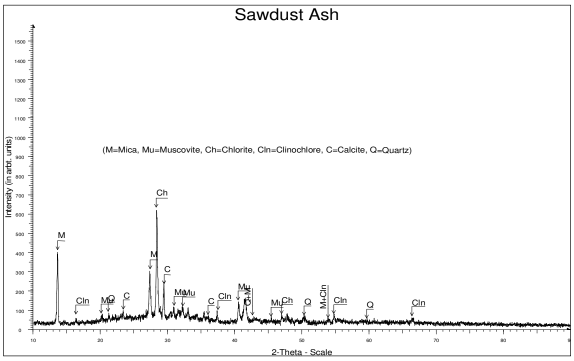

Fig. 2. XRD pattern of SDA.

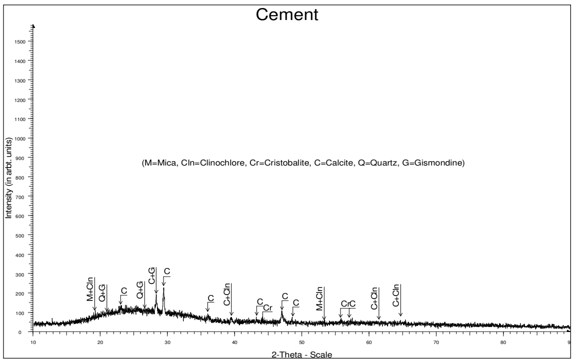

Fig. 3. XRD pattern of cement.

TABLE VI. CHEMICAL COMPOSITION OF THE INVESTIGATED SAMPLES FROM XRD ANALYSIS

Sample marks	Phases identified from XRD
Cement	Mica, clinochlore, cristabolite, calcite, quartz, gismondine
SCBA	Mica, clinochlore, chlorite, quartz, calcite, gismondine
SDA	Mica, muscovite, chlorite, clinochlore, calcite, quartz
B0 (LS)	Mica, clinochlore, quartz, gismondine, calcite, cristobalite
B1	Mica, clinochlore, quartz, gismondine, calcite
B2	Mica, clinochlore, calcite, cristobalite, quartz, gismondine
B3	Mica, clinochlore, cristobalite, quartz calcite, gismondine
B4	Mica, clinochlore, cristobalite, calcite, quartz, gismondine
B5	Mica, clinochlore, cristobalite, calcite, quartz, gismondine

3) Structural Properties of the Investigated Samples B1-B5

Figure 5 shows the XRD pattern of B1, which is composed of 93% LS and 7% cement, contains mica, clinochlore, quartz, gismondine, and calcite. It is observed that the UCS at B1 is at the optimum value of 2.258MPa with CBR of 175.7. It is also observed from Table IV that both CaO/SiO_2 and $CaO/(SiO_2 + Al_2O_3)$ are the highest for this combination, with values of 1.5 and 1.19, respectively. Authors in [49] observed that stabilizer's constituents, especially CaO, play the most vital role in the strength gain characteristics of stabilized soil's early strength. Increases in the amount of (quartz) silica, lead to increase in strength and stability [13]. The XRD scatter pattern gives a clear indication of the presence of crystalline and amorphous phases in the investigation samples. Crystalline phases induce sharper peaks, whereas amorphous phases result in the formation of a broad hump [5]. Figure 5 shows the mineralogy of B1, i.e. 7% cement stabilized LS. It shows both crystalline and amorphous phases of quartz, mica, clinochlore, calcite, and gismondine. The stabilization process results in the complete disappearance of the cristobalite peak of the mineral phase and a reduction in the intensity of the peaks, especially gismondine [5, 56].

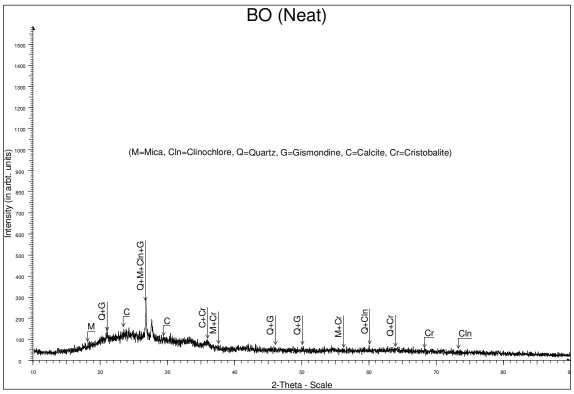

Fig. 4. XRD pattern of LS.

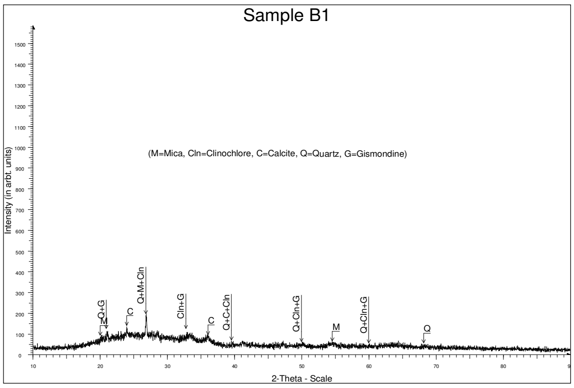

Fig. 5. XRD pattern of B1.

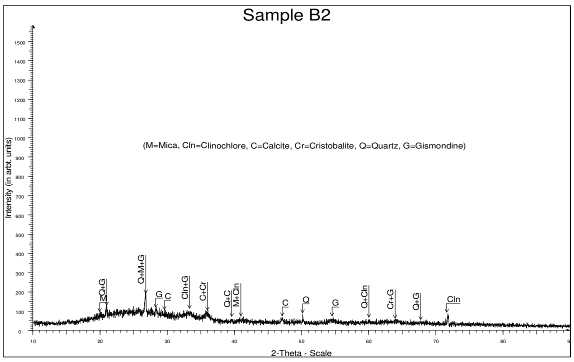

Fig. 6. XRD pattern of B2.

Figure 6 and Table VI present the mineralogy of B2, which consists of 5.0% cement, 1.0% SCBA, and 1.0% SDA stabilized LS. The results show both crystalline and amorphous phases of quartz, mica, clinochlore, calcite, gismondine, and cristobalite. The stabilization process does not cause a complete disappearance of the existing peaks of mineral phases, but a reduction in the intensity of the peaks, especially clinochlore. This observation is similar with the results in B3 (Figure 7) which consist of 3.0% cement, 2.0% SCBA, and 2.0% SDA, B4 (Figure 8) which contains 1.0% cement, 3.0% SCBA, and 3.0% SDA, and B5 (Figure 9), which contains 0% cement, 3.5% SCBA, and 3.5% SDA.

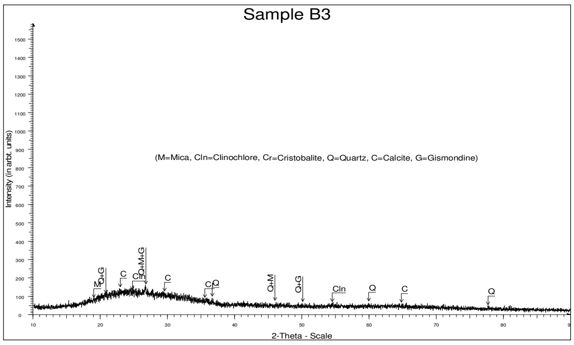

Fig. 7. XRD pattern of B3.

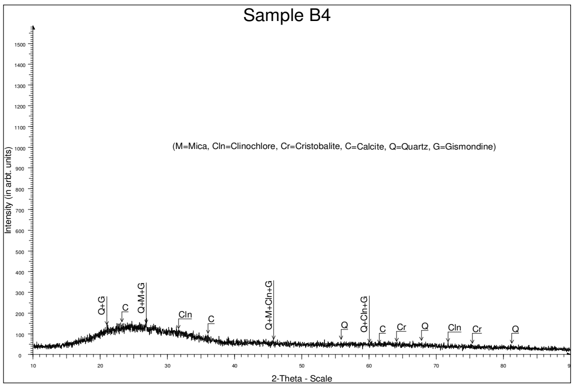

Fig. 8. XRD pattern of B4.

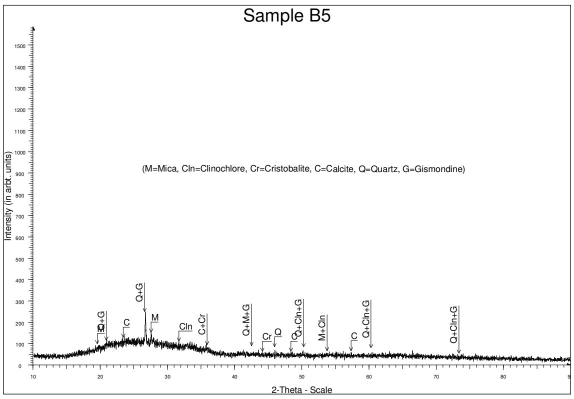

Fig. 9. XRD pattern of B5.

Pozzolanic reactions result in the formation of new reaction products whose peaks are identified in the phase identification process. Authors in [57] reported the formation of CSH, calcite, and portlandite along with quartz in hydrated pastes of lime-SCBA binders.

V. FINDINGS

The current study involved the investigation of the effects of SCBA and SDA to cement stabilization of LS road base. A series of cement doses were added to the LS to obtain the optimum cement content. This optimum cement content was partially replaced with SCBA and SDA to study their effects on the strength and structure of the cement stabilized LS. The findings of the research shed light on the following critical issues:

- The OMC and MDD of LS increased with the increase in cement content from 18.0% to 24.7% and 1.72 g/cc to 1.79 g/cm^3, respectively.
- The CBR of LS increased with the increase in cement content up to 7%, from 30.9% to 175.7% and thereafter decreased to 102.6% at 9% cement content.
- The UCS of LS increased from 0.275 MPa to 2.729 MPa with the increase in cement content.
- The OMC of LS stabilized with cement, SCBA, and SDA increased from 24.5% to 26.4% with reduction in cement content and increase in SCBA and SDA content, while the MDD reduced from 1.77 g/cm^3 to 1.74 g/cm^3.
- Both UCS and CBR decreased with the reduction of cement content and increase of SCBA and SDA content from 2.258 MPa to 0.287 MPa and 175.7% to 32.3%, respectively.
- From the XRF investigation, the CaO and SiO_2 contribute to the development of strength in cement, SCBA and SDA stabilized lateritic soils;
- From the XRD patterns, it was found that mica, calcite, and quartz phases play a very important role in the increase and decrease of the strength of the samples.

VI. CONCLUSIONS

- SCBA and SDA were found to successfully enhance the stabilization performance of LS.
- Ground improvement, subbase, and base course of flexible pavements could use SCBA and SDA as auxiliary additives in cement to stabilize the LS. Moreover, this soil stabilization technique is both cost-effective and environmentally friendly.
- By using industrial and agricultural waste, it becomes possible to control the production of cement and the extraction of lime resources and also enhance the disposal and management of industrial and agricultural waste, which could be very beneficial.
- The use of SCBA and SDA in LS can provide promising stabilization effects, similar to the conventional method and can prove to be a good alternative to the existing methods of soil treatment.
- The utilization of SCBA and SDA promote waste reduction and recycling, being an environmentally friendly and sustainable green material.

VII. NOVELTY/CONTRIBUTION

To the best of our knowledge, no previous study has investigated the effects of SCBA-SDA-cement on LS in terms of strength and microstructure. This study explored the effect of the partial replacement of cement with SCBA and SDA in LS stabilization by considering OMC, MDD, UCS, CBR, and microstructure properties.

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