Effect of Cement Kiln Dust and Sugarcane Bagasse Ash on Black Cotton Soil to be used as Road Subgrade Material in Flexible Pavement Construction

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ABSTRACT

Cement, lime, and Fly Ash (FA) are the major traditional soil stabilizers. Cement production contributes 0.8-0.9 tons of carbon emissions per ton of cement, while lime production generates around 1.2 tons of CO_2 per ton of cement. FA is not readily available in all regions, necessitating the exploration of alternative stabilizing agents. Cement Kiln Dust (CKD) and Sugar-Cane Bagasse Ash (SCBA) are waste products from cement and sugarcane production, respectively. This study investigated the use of CKD and SCBA to stabilize black cotton soil. CKD was incorporated into the soil at 0, 2, 4, 6, 8, and 10% for standard Proctor compaction, consistency limits, Free Swell Index (FSI), Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR) testing. The optimal CKD content based on UCS and CBR was 6%, while the optimal CKD-SCBA composite was 6% CKD and 10% SCBA. The third part of the Kenyan Road Design Manual (KRDM III) categorizes subgrades by strength based on the CBR, ranging from S1 to S6. Subgrades classified as S1 exhibit the lowest strength (CBR of 2-5%), while S6 denotes the highest strength (CBR of 30% or greater). The untreated black cotton soil, with a CBR of less than 2%, was unsuitable as a subgrade. The CKD-SCBA composite improved the soil's CBR to 16.43%, upgrading it to an S4 subgrade, which can reduce the pavement thickness and associated costs. Other enhancements included an increase in UCS from 97.5 kPa to 555.81 kPa, a reduction in the FSI from 86% to 45%, and a reduction in Plasticity Index (PI) from 26.18% to 15.26%.

Keywords-expansive soil; cement kiln dust; sugarcane bagasse ash; stabilization

I. INTRODUCTION

Road pavement distresses arise from the combined effects of traffic loading, environmental factors, and geotechnical issues associated with expansive subgrade soils [1]. Longitudinal cracks are a prime example of road defects caused by expansive soils, which can result in substantial repair expenses [2-4]. In 2004, the Ethiopian Road Authority (ERA) spent approximately ETB300 million, with ETB30 million having been allocated for road maintenance, and it was noted that some issues stemmed from the use of expansive soil [5]. The solution to problems related to expansive subgrade is to stabilize it through mechanical means and chemical additives. Traditional chemical stabilizers include lime, cement, FA, and bitumen. However, the production of one ton of lime generates around 1200 kg of CO_2, accounting for 2% of total CO_2 emissions from the lime industry [6, 7]. Similarly, cement production contributes 5 to 7% of the global CO_2 emissions, with over 4 Gt having been produced in 2017 [8]. Additionally, not all regions have access to coal-fired power plants to source FA.

CKD is a waste material produced during cement manufacturing, accounting for approximately 6 to 20% of the total cement output [9, 10]. The presence of chemical compounds, such as chlorides and potassium-based minerals, impedes the reuse of CKD in cement production. Studies have shown that CKD can contain a chloride content ranging from 0.35 to 15.4% of the CKD weight, which exceeds the permissible chloride content limit in cement, which is typically one-thousandth of the cement weight [11, 12]. This indicates that not all CKD is effectively reused and is instead disposed of in landfills. In 2006, a report from the Portland Cement Association revealed that around 1403 metric tons of CKD were transported to landfills, while only 261 metric tons were transported from landfills for reuse [13].

Alternative calcium-based materials can help decrease the dependence on cement and lime for soil stabilization. CKD, a waste product, can minimize the use and disposal of cement and lime due to its high calcium oxide content that enables participation in pozzolanic reactions. Several studies have incorporated CKD with other high-calcium additives, like FA, cement, lime, and Ground Granulated Blast Furnace Slag (GGBS) [9, 14-16]. These investigations have demonstrated enhanced UCS, CBR, and reduced plasticity when using CKD.

However, there is also evidence that when CKD is combined with low-calcium additives, it can enhance performance by increasing the maximum dry density and reducing plasticity. Examples of studied low-calcium additives that improved density and plasticity with CKD include metakaolin and periwinkle ash [17, 18]. Both studies were conducted in Nigeria. These materials were blended with CKD due to their silica (SiO_2) and alumina (Al_2O_3) content, which are fundamental for pozzolanic reactions. CKD acts by supplying free lime that is used in pozzolanic reactions to react with silica and alumina from other additives. The results are the soil binding gels C-S-H and C-A-H, as shown by (1) and (2), respectively. However, CKD contains heavy metals and oxides of concern whose leachates can harm the environment. Nevertheless, a study by the Texas Transportation Institute showed that CKD leachates can have metal toxicity levels that do not exceed the regulatory limits [19]. The United States Environmental Protection Agency (EPA) has classified CKD as non-harmful to the environment when used in industrial applications [20, 21]. Equation (1) refers to the C-S-H gel and (2) to the C-A-H gel:

$$3Ca(OH)_2 + 2[SiO_2] \rightarrow [3(CaO) \cdot 2(SiO_2) \cdot 3(H_2O)] \quad (1)$$

$$3Ca(OH)_2 + Al_2O_3 + 6H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 6H_2O \quad (2)$$

SCBA is a waste biomass resulting from the combustion of bagasse after sugar extraction. The waste bagasse is burned to provide energy to sugar mills, with SCBA as the byproduct. Globally, SCBA production is estimated at 40 to 60 million tons annually, and Kenya generates around 1.6 million tons of which approximately 75% remains unused for renewable energy purposes [22-26]. Additionally, due to the limited disposal sites, most of this SCBA is not properly disposed of [27, 28]. The sugarcane production industry from which SCBA originates faces various climate change-related threats, such as drought, rising sea levels, increased evapotranspiration, frost, and diseases [29]. However, higher CO_2 levels and rising temperatures can potentially enhance the sugarcane yields. Over the past five decades, there has been a threefold increase in the sugarcane production, driven by the growing demand [30]. Advancements in genetic modification and improved management strategies are expected to enable the industry to persist despite climate challenges, ensuring a continued supply of SCBA for future utilization.

SCBA has been utilized to reduce the reliance on cement and lime by either combining them with a certain content of cement or lime or partially replacing the individual cementitious materials. In [31], it was demonstrated that partially replacing cement content with SCBA could improve the UCS of peat soil in Malaysia up to 190 kPa at a 5% replacement rate, outperforming unreplaced cement. A similar approach was employed in [32] to enhance the UCS of highly plastic clay in Thailand to 1.435 MPa at a 20% replacement rate after 28 days of curing. Additionally, the combination of lime and SCBA has been used to improve the mechanical properties of highly plastic soil, black cotton soil, and highly plastic silty soil, respectively [30, 33, 34]. The findings from these three studies confirm that the use of lime alone is less effective compared to when it is combined with SCBA. Other calcium-based materials, such as FA, gypsum, and marble waste dust, have also been combined with SCBA, illustrating how the utilization of silica from SCBA can improve the performance of the calcium-containing additives, thereby increasing the value of SCBA as a soil stabilizer [35-38].

In addition to the aforementioned calcium-based activators that facilitate pozzolanic reactions, sodium-based alkaline activators, such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), have emerged as alternatives for activating SCBA in soil stabilization [39, 40]. However, these sodium-based activators are costly, and the processing of sodium silicate contributes to carbon emissions. By combining SCBA with a high-calcium additive, such as CKD, the amorphous silica content of the blend is increased, thus promoting the proliferation of soil-binding gels as described in (1). This, in turn, enhances the strength-imparting capabilities of both SCBA and CKD.

II. RESEASRCH GAP

Previous studies have utilized CKD with diverse additives, but none of them has incorporated SCBA for stabilizing soils in subgrade applications. The novelty of the present research lies in combining these two waste materials to stabilize expansive black cotton soil from Kenya, with the aim of meeting the higher CBR requirements for road subgrade applications. This approach can be applied in other regions worldwide where SCBA is available, as in Kenya, to improve the properties of expansive soils. The findings of this study promote the principles of a circular economy and reduce the dependency on materials with high carbon emissions, hence contributing to the environmental protection efforts.

III. MATERIALS AND METHODS

A. Materials

The CKD utilized in this investigation was procured from Bamburi Cement in Mombasa, Kenya. The chemical composition of the material was attained through XRF testing conducted at the Ministry of Petroleum and Mining laboratory in Kenya. The SCBA and the undisturbed black cotton soil were obtained from Sukari Industries Ltd in western Kenya and Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya, respectively. The chemical composition of these three materials was determined via XRF tests performed at the Kenya Ministry of Petroleum and Mining laboratory services. Additionally, the microstructural state of the materials was assessed through Scanning Electron Microscope (SEM) tests conducted in the JKUAT Food Fortification Science Laboratories.


(a) (b) (c)

Fig. 1. Physical appearance of used materials. (a) Black cotton soil, (b) CKD, and (c) SCBA, burned on top and calcinated on bottom.

B. Methods

1) Cement Kiln Dust and Sugar-Cane Bagasse Ash Stabilizers

The CKD was sieved through a 0.075mm sieve to increase its fineness. The black-colored SCBA was recalcined to reduce its carbon content and enhance the amorphous nature of silica. This process was conducted using a Bogie Hearth muffle Furnace (BHF-1200-175), at a constant temperature of 800 °C for half an hour [25]. This transformation resulted in a change in color from black to grey, as depicted in Figure 1(c). Furthermore, the mechanical and physical properties of the black cotton soil were evaluated through various tests, including consistency limits, FSI, UCS, and CBR.

2) Determination of Particle Size Distribution

The Particle Size Distribution (PSD) of the soil was analyzed using sieve analysis and a hydrometer test to determine the proportion of particles smaller than 0.075 mm, in accordance with the British Standard BS 1377: Part 2-1990 [41]. The Liquid Limit (LL) was established using the cone penetrometer test, while the Plastic Limit (PL) was determined by rolling the wetted soil material until it displayed cracks at a 3 mm diameter, indicating a loss of plasticity. These limits were ascertained in line with BS 1377: Part 2-1990. The specific gravity was measured using the pycnometer method as per BS 1377 Part 2. UCS testing was conducted in accordance with ASTM D2166, with the samples having been molded in a 50 mm diameter and 100 mm depth mold [42]. For CBR determination, the samples were molded as per BS 1377: Part 4:1990 and tested after four days of soaking in water. This study considered the subgrade classes outlined in KRDM III, which are included in the Kenya Pavement Design Guidelines for low-volume sealed roads, as presented in Table I [43].

TABLE I. SUBGRADE CLASSES IN KRDM III

Subgrade Class	CBR
S1	2 - 5%
S2	5 - 10%
S3	7 - 13%
S4	10 - 18%
S5	15% - 30%
S6	≥ 30%

3) Black Cotton Soil Stabilization

The black cotton soil was stabilized using a unary blend of CKD, followed by a binary blend of CKD and SCBA. The initial phase of stabilization involved incorporating CKD at 2, 4, 6, 8, and 10% by weight of the soil-CKD mixture. The consistency limits, UCS, and CBR were evaluated for the soil-CKD mixtures across these CKD dosages. These tests were conducted in accordance with the standards for characterizing expansive soils. CBR curing was performed for 7 days, followed by 7 days of soaking in water. Subsequently, the optimum soil-CKD combination was determined based on the UCS, CBR, and PI values. The optimal CKD ratio from previous experimental studies was maintained while varying the SCBA dosage from 5 to 25% at 5% increments, resulting in an optimal CKD and SCBA binary blend for soil stabilization.

IV. RESULTS AND DISCUSION

A. Cement Kiln Dust and Sugar-Cane Bagasse Ash Characterization

The XRF analysis of CKD, raw, and calcinated SCBA is portrayed in Table II. The results indicate that CKD contains 71.1% CaO and 18.56% SiO_2, making it suitable for pozzolanic reactions and the production of C-S-H binding gel. Additionally, CKD has 5.9% Al_2O_3. Conversely, the combined contents of 86.14% SiO_2, 3.83% Al_2O_3, and 5.23% Fe_2O_3 in SCBA exceed the ASTM C618 minimum requirement of 70% for pozzolanic materials [44, 45].

TABLE II. MATERIAL CHEMICAL COMPOSITION

Component	Soil	CKD	Raw SCBA	Calcined SCBA
Al_2O_3	9.67	5.90	6.78	3.83
SiO_2	76.9	18.56	57.53	86.14
Fe	8.33	3.06	8.70	5.23
CaO	1.18	71.1	7.84	1.67
K2O	0.80	0.25	18.63	2.54
Mn	1.52	0.05	0.52	0.29
MgO	-	-	-	0.3
Ti	0.973	0.227	-	-
LOI	-	-	7.48	2.07

The high silica and alumina content of SCBA suggests its potential to form C-S-H and C-A-H gels, which can improve strength and reduce plasticity in expansive soils. The SEM images in Figure 2 show that CKD is composed of fine-grained, porous particles, while the processed SCBA comprises large, cannular, and highly asymmetrical shapes, consistent with previous studies [46-48]. However, the pre-calcination SCBA morphology was characterized by more flaky particles.

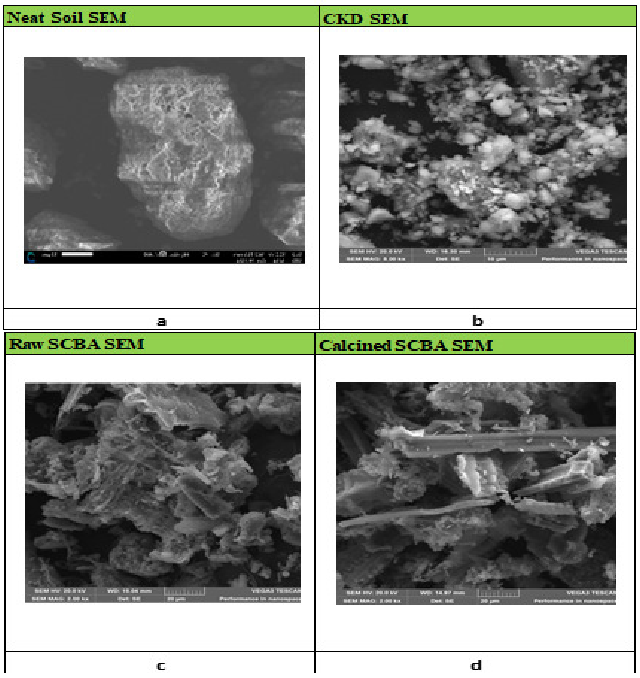

Fig. 2. SEM results of (a) neat soil, (b) CKD, (c) raw SCBA, and (d) calcined SCBA.

B. *Black Cotton Soil Characterization*

The chemical composition of the black cotton soil is also presented in Table II. The results reveal that the soil has a significant amount of ferric oxide implying that the soil has a significant amount of smectite minerals, which are iron-based, providing expansive properties. An analysis of the soil's SEM images reveals the presence of voids, suggesting the need for cementitious materials [49, 50]. The physical and mechanical properties of the soil are summarized in Table III.

TABLE III. PHYSICAL AND MECHANICAL PROPERTIES OF SOIL

Property	Value
Colour observations	Dark grey
Moisture content (%)	10.59
Gravel proportion (%)	1.70
Sand fraction (%)	8.50
Silt fraction (%)	22.20
Clay fraction (%)	67.70
LL (%)	55.82
PL (%)	29.64
PI (%)	26.18
Linear shrinkage (%)	15.07
Specific gravity (%)	2.48
Free-SI (%)	86.00
Classification (AASHTO)	A-7-6
MDD (g/cm³)	1.342
Optimum moisture content (%)	26
Soaked CBR (%)	1.63
UCS (kPa)	95.70

The findings demonstrate that the soil is classified as an A-7-6 soil according to the AASHTO soil classification system, rendering it unsuitable for use as a subgrade material [51]. The CBR value was less than 2%, which is the threshold specified in KRDM III, because such soils have no assigned subgrade class, making them poor for subgrade applications unless stabilized [43]. Furthermore, the PSD analysis of the soil confirmed that it is an expansive clay soil, as it has a high percentage of clay particles, amounting to 67.7%.

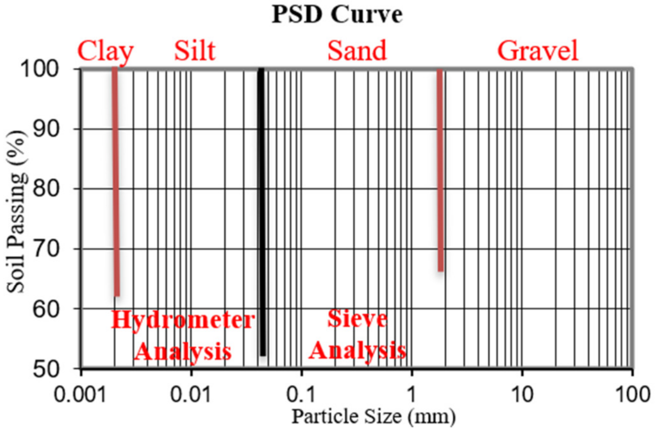

Fig. 3. PSD of black cotton soil.

C. *Effect of Cement Kiln Dust on the Mechanical and Physical Properties of Expansive Soil*

1) *Effect of Cement Kiln Dust on Maximum Dry Density and Optimum Moisture Content*

The incorporation of CKD into the soil-CKD matrix during compaction led to an increase in Maximum Dry Density (MDD) and a decrease in the Optimum Moisture Content (OMC) for CKD contents of 2, 4, and 6%. This can be attributed to the reduced availability of free water for each CKD dosage. Conversely, with an increase in the CKD content to 8% and 10%, there was a decrease in MDD and an increase in OMC. These findings are consistent with [52, 53].

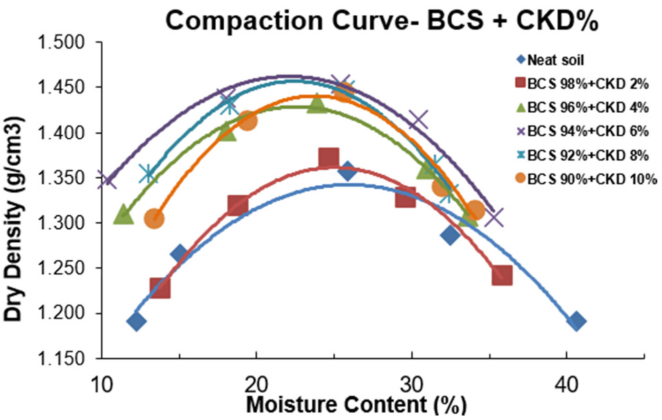

Fig. 4. Influence of CKD on MDD and OMC during soil compaction.

The increase in MDD is due to the filler effect of the denser CKD fine particles. However, after a 6% CKD content, MDD decreases, which may be caused by the segregation of fine CKD particles and agglomerated soil particles. The decrease in OMC as CKD content increasesmis a result of water being consumed during the hydration process, leaving less water retained [52]. The restricted water movement is a consequence of the cement paste formation, as the water is utilized in the hydration reaction, leaving little surrounding the solid surfaces [54]. Nevertheless, beyond the 6% CKD content, OMC increases due to the fines provided by the CKD particles, which require more water, while the CKD may no longer be actively involved in the hydration process [52].

2) Effect of Cement Kiln Dust on Consistency Limits

The effect of CKD content on the consistency limits of the black cotton soil is illustrated in Figure 5. The LL decreased, from 55.82 to 45.1%, as the CKD content increased from 0 to 10%. The LL and PI decreased by approximately 19% and 9%, respectively. This phenomenon is attributed to the high calcium ion (Ca^{2+}) content in CKD, which causes an ion exchange that disrupts the clay minerals. This reduction in the diffuse double layer of clay minerals in the soil results in an increased attraction force between particles, leading to agglomeration [15]. The plasticity reduction in the soil-CKD mixture is directly proportional to the free lime content [55]. This trend of a decreasing PI with an increasing CKD content is explained by this phenomenon. The minimal change in the PL is consistent with the findings in [56]. However, it is important to note that the lowest achieved PI in this study was still above the 15% index recommended by PDG 1 for using expansive soils with minimal problems [43].

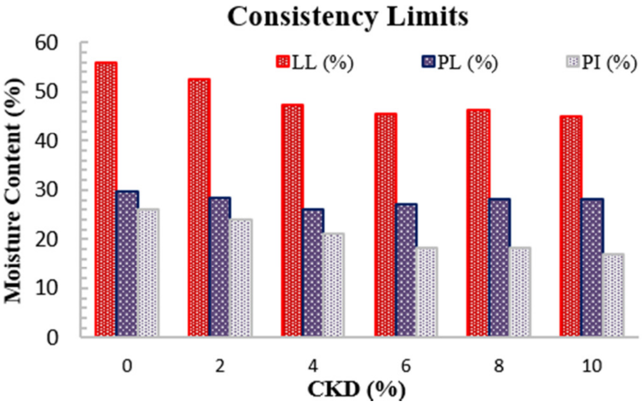

Fig. 5. Effect of CKD on soil consistency limits.

3) Influence of Cement Kiln Dust on Free Swell Index

Figure 6 displays the impact of CKD on FSI. The findings indicate that increasing the CKD content from 0 to 10% led to a 34% decrease in FSI. Despite this substantial reduction, the soil's FSI at 10% CKD still categorizes it as moderately expansive, according to the 1987 Indian Standards classification [57, 58]. The overall decline in FSI can be attributed to the isomorphic exchange of ions, which alters the mineral arrangement of clay particles and reduces the thickness of the water layer [56].

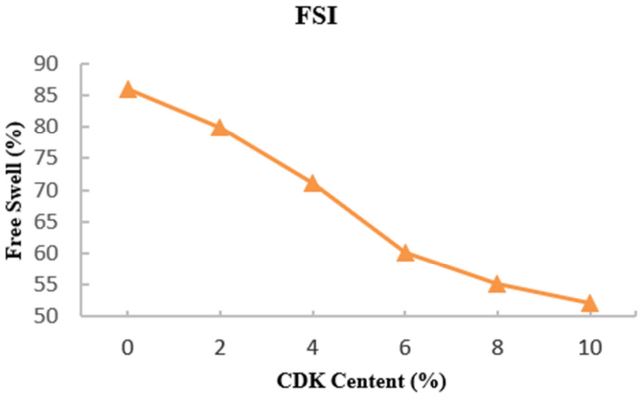

Fig. 6. Influence of CKD on soil FSI.

4) Effect of Cement Kiln Dust on Unconfined Compressive Strength

The impact of CKD on UCS for 7, 14, and 28-day curing periods is presented in Figure 7. The findings indicate that UCS increases to a peak of 230.0 kPa at 6% CKD for 7 days of curing, while for 14 and 28 days, the peaks are 254.1 and 296.77 kPa, respectively. The 7-day cured specimens align with the compaction characterization, where the optimum MDD is at 6% CKD in the CKD-soil mixture. The variation in UCS with an increase in the CKD content and curing days is consistent with [52]. The post-hydration Ca^{2+} ions facilitate ion exchange, contributing to enhanced mechanical strength [59, 60]. The pozzolanic reactions in the specimens produce cementitious gels during curing over time, leading to soil particle binding and void reduction, thereby increasing strength [15, 60, 61]. The decrease in UCS after reaching its optimum value at 6% CKD for 7 days of curing and 8% CKD for 14 and 28 days of curing might be attributed to excessive CKD at this point, causing brittleness due to the dispersion of soil particles from the free lime in CKD [52].

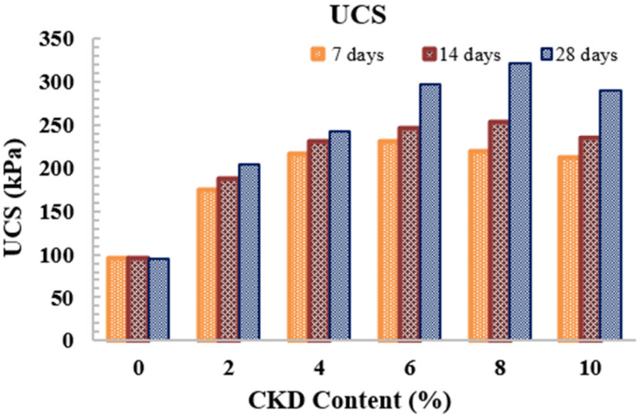

Fig. 7. Effect of CKD on UCS at 7, 14 and 28-days curing period.

5) Effect of Cement Kiln Dust on California Bearing Ratio

Figure 8 illustrates the influence of CKD on CBR. The results demonstrate that increasing the CKD content from 0 to 6% led to a rise in CBR from 1.62 to 7.54%; however, further increasing CKD to 10% reduced CBR to 6.96%. The elevated CBR values met the subgrade CBR requirements specified in the KRDM III for S2 and S3 subgrade classes, which represents a significant improvement given that the original soil was below the S1 subgrade class [43]. Being consistent with the compaction characteristics of stabilized specimens, CBR reached its maximum at 6% CKD content. The increase from 1.62% to 7.54% can be attributed to the induration of soil particles resulting from the participation of liberated CaO, silicate, and alumina minerals from the CKD in pozzolanic reactions [62, 63].

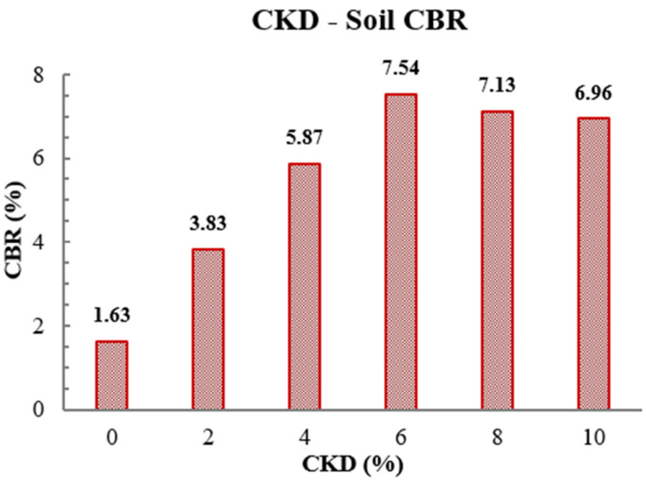

Fig. 8. Effect of CKD on CBR.

D. *Effect of Sugar-Cane Bagasse Ash on Physical and Mechanical Properties of Soil- Cement Kiln Dust Mix*

1) *Effect Of Sugar-Cane Bagasse Ash On Maximum Dry Dencity and Optimum Moisture Content For Soil- Cement Kiln Dust Mix*

The study examined the compaction characteristics of soil containing varying percentages of SCBA and a constant 6% CKD, as depicted in Figure 9. The results demonstrate that as the SCBA content increased from 0 to 25%, the MDD decreased while the OMC increased. This can be attributed to the lower specific gravity of SCBA of 2.00 compared to the soil of 2.48, resulting in a lighter material [64]. Additionally, the OMC declined with a rising SCBA content. The consistent increase in OMC from 22.5% to 27.8% indicates a greater water demand due to the high specific surface area of the fine SCBA particles [33]. This phenomenon, also observed in other ash types, such as Rice Husk Ash and Saw Dust Ash, may be advantageous during construction by facilitating easier compaction when the soil is moist [30, 65, 66].

2) *Influence Of Sugar-Cane Bagasse Ash on Consistency Limits for Soil- Cement Kiln Dust*

The influence of SCBA on the LL and PI of the soil-CDK mixture is displayed in Figure 10. It is observed that the LL decreased from 45.45 to 42.30%, with an increase in SCBA from 0 to 25%, and the PI also decreased from 18.23 to 12.80% with the same increase in SCBA. This reduction is attributed to the flocculation and agglomeration of soil particles, which tend to create a sand-like texture and nature in the soil [37]. The comparison of the 6% CKD content used with the soil and the 6% CKD and SCBA combination shows that SCBA enhances the performance of CKD. The PI of the soil at 6% CKD improved to 18.23%, which is slightly above the recommended value of 15% by the Kenyan standards PDG 1 to ensure minimal problems from expansive clays [43]. However, with the introduction of SCBA, the PI dropped even further to 12.8% at 25% SCBA, which is within the PDG 1 recommended range to ensure minimal problems from expansive clays [43]. This is due to the fact that the SCBA ash introduced more amorphous silica, which reacts with the high free lime from CKD, resulting in flocculation and agglomeration.

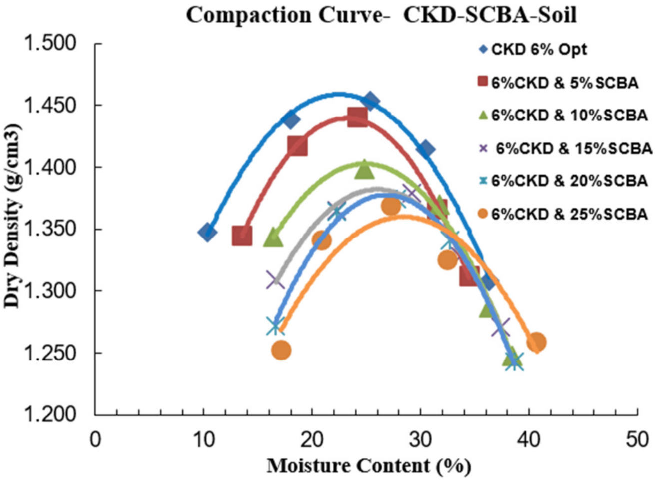

Fig. 9. Effect of SCBA on MDD and OMC for soil-CKD composite.

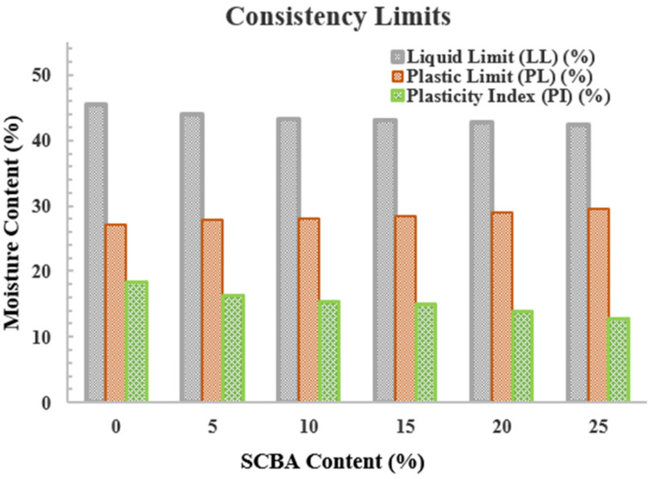

Fig. 10. Influence of SCBA on the consistency limits of soil-CKD composite.

3) *Effect Of Sugar-Cane Bagasse Ash on Free Swell Index of Soil- Cement Kiln Dust*

The investigation revealed that the addition of SCBA significantly influenced the FSI of the soil-CKD composite, as depicted in Figure 11. The results demonstrate a substantial decline in FSI from 60% for the soil treated solely with 6% CKD to 41% as the SCBA content increased from 0 to 25%. Initially, the soil was classified as medium expansive, with an FSI exceeding 50%. However, a further reduction in FSI beyond the 50% threshold reclassified the soil as lowly expansive. This significant decrease can be attributed to the chemical reactions between the CaO in CKD and the silica present in SCBA, which reduce the repulsive forces between the clay particles [67, 68].

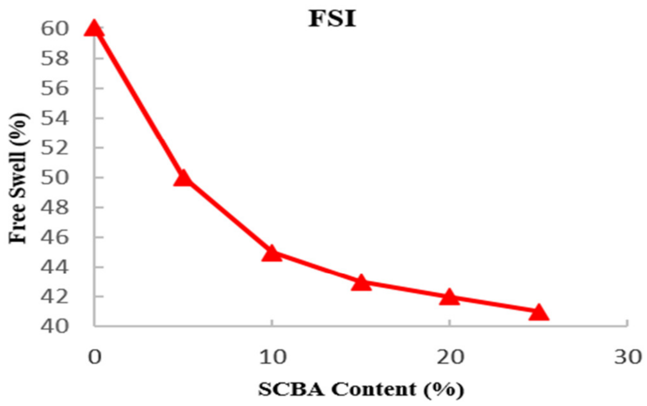

Fig. 11. Effect of SCBA on FSI of soil-CKD composite.

4) Influence Of Sugar-Cane Bagasse Ash on Unconfined Compressive Strength Of Soil- Cement Kiln Dust

Figure 12 demonstrates the impact of SCBA on the UCS of soil-CDK mixtures at 7, 14, and 28-days of curing. For a specific SCBA content, the UCS increased to a maximum value at 10% SCBA with 6% CKD after which it declined. The optimal UCS was 555.8 kPa, representing a 112% increase compared to the soil-CKD 6% mixture. This optimal UCS value denotes a 477% improvement over the unimproved expansive soil's UCS of 95.70 kPa. This UCS enhancement satisfies the ASTM D4609-2 requirement of at least a 349 kPa increase for a stabilizer to be considered acceptable. The significant UCS increase can be attributed to the formation of C-S-H and C-A-H gels through hydration and pozzolanic reactions, which bind the soil grains and provide a stronger soil matrix, enhancing compressive strength [32, 69].

The results further demonstrate that UCS increased with the curing age for all SCBA contents, with the 28-day curing achieving the highest strength. While the 7-day peak of 395.38 kPa did not meet the ASTM D4609-2 UCS requirements, the 14-day peak of 444.85 kPa did satisfy the incremental requirements. The changes in the peak strength from 7, 14, and 28 days of curing, with 395.38 kPa, 444.85 kPa, and 555.81 kPa respectively, showcase the development of pozzolanic reaction products over time, which contribute to the strength impartation. This suggests that SCBA-CKD may be more suitable for road constructions demanding delayed strength development, rather than highways requiring early strength development and quick project completion [70]. After the optimal 10% SCBA addition, the UCS started decreasing, likely due to the liberated CaO from CKD being insufficient to react with the silica and alumina in SCBA, leaving some SCBA unreacted [32, 71].

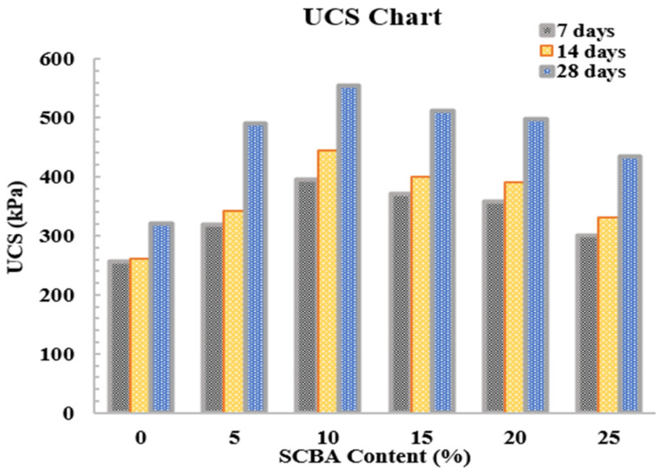

Fig. 12. Influence of SCBA on UCS of soil-CKD composite.

5) Effect Of Sugar-Cane Bagasse Ash On California Bearing Ratio Of Soil- Cement Kiln Dust

The study investigated the effect of SCBA on the CBR of soil-CDK mixtures. The results showed that the CBR increased from 7.54% at 6% CKD to a maximum of 118% at 10% SCBA content after which it began to decrease. The soil-CKD-SCBA mixture with 6% CKD and 10% SCBA was classified as S4 subgrade according to the KRDM III standard. This increase in CBR was likely due to the cementation and pozzolanic reactions, which enhanced the frictional resistance to penetration [38]. This was attributed to the adequate availability of calcium required for the formation of C-S-H and C-A-H, which contributed to the improved resistance to penetration.

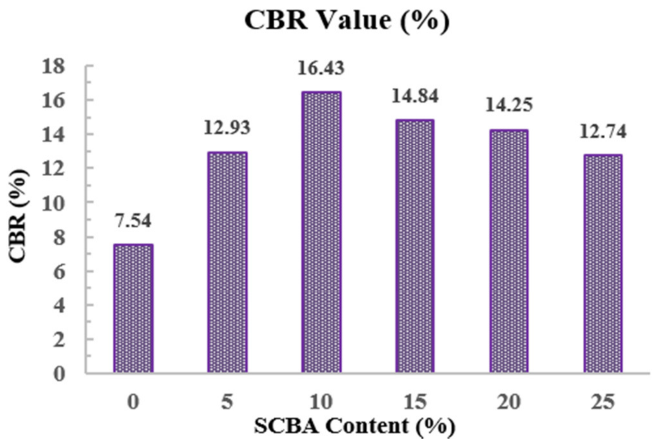

Fig. 13. Effect of SCBA on CBR of soil-CKD composite.

However, the exhaustion of CaO in CKD beyond 10% SCBA led to a reduction in CBR, as there was insufficient free lime to react with the increasing silica content [30]. Therefore, the optimum SCBA dosage in this study was determined to be

10%, as CBR values decreased beyond this point. The increased SCBA content in the blends resulted in a reduction in the available CaO to react with the amorphous minerals in the SCBA.

6) Microstructural Analysis of Black Cotton Soil Blended with Cement Kiln Dust And Sugar-Cane Bagasse Ash

The SEM analysis of the black cotton soil reveals that it lacks intensive dense packing, exhibiting voids, instead. However, the optimum blend of the soil, which is 6% CKD with 10% SCBA, demonstrates that the voids in the soil are filled with the stabilizers. This is attributed to the formation of hydrates, such as C-S-H and C-A-H, which facilitate the micro-filling of the voids, thereby increasing the density and micro-packing of the matrices, and hence enhancing its strength. Compared to the 6% CKD specimen, the 6% CKD with 10% SCBA blend exhibits a higher degree of dense packing due to the increased extent of the C-S-H and C-A-H gels formed, with the latter having a more significant portion of the gels as a result of the SCBA added to the CKD. While the 6% CKD specimen has pores despite its dense packing, the 6% CKD with 10% SCBA blend has fewer pores and more dense packing. This explains the superior strength of the CKD-SCBA-soil samples compared to the CKD-soil samples.

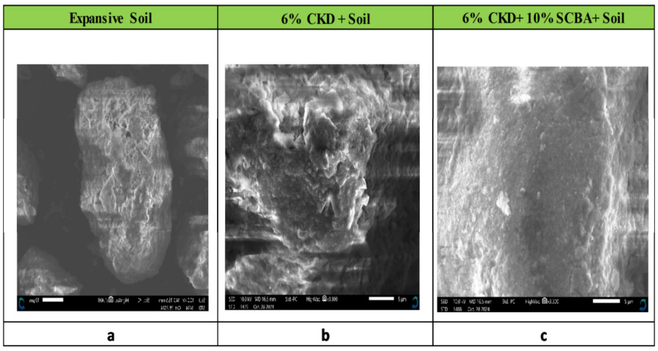

Fig. 14. SEM of (a) expansive soil, (b) optimum of CKD, and (c) optimum of CKD including optimum of SCBA and soil.

V. CONCLUSIONS

In this study, the effects of the addition of Cement Kiln Dust (CKD) and Sugar-Cane Bagasse Ash (SCBA) on the engineering properties of the expansive soil were evaluated and the following conclusions were drawn:

- Combining CKD and SCBA improved the consistency limits, and reduced the Free Swell Index (FSI) compared to using CKD separately. The reduction in the plasticity and swelling of black cotton soil by the CKD-SCABA composite makes CKD-SCBA suitable for stabilizing expansive soils.
- The CKD-SCBA optimum in stabilizing the black cotton soil was 6% CKD with 10% SCBA.
- The CKD-SCBA composite reduced the Plasticity Index (PI) of the soil to 15.26%, which slightly exceeds the recommended maximum PI of 15% for minimizing the challenges associated with expansive soils. Nevertheless, the reduction in plasticity enhances the soil's suitability for use as a road subgrade, particularly under traffic conditions where moderate plasticity can still be tolerated.
- The CKD -SCBA composite enhanced the soil's California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) better than CKD separately. The CBR and UCS findings satisfied the used standards for road designs. The substantial improvements of UCS and CBR show that combining CKD and SCBA will increase the strength of highly plastic expansive clays and silts that have low load-bearing capacity so as to be used for/as road subgrade.
- The SEM imaging for the optimum CKD-SCBA composite present a change of the packing of the soil particles. The images illustrate the filling of voids caused by CKD-SCBA indicating that the filler effect was caused by the C-S-H and C-A-H gels that were a result of the pozzolanic reactions of CKD and SCBA. This is consistent with the strength findings of the treated samples.

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