Performance Evaluation of Red Clay Soils stabilized with Bluegum Sawdust Ash and Sisal Fiber as Low-Volume Road Sub-base Materials

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ABSTRACT

The engineering properties of Red Clay Soils (RCS) in tropical regions are frequently inadequate for road construction due to a number of factors, including high compressibility, high creep rates, high plasticity, low strength, and swelling potential. This research project examines the potential of stabilizing RCS using Bluegum Sawdust Ash (BSDA) and Sisal Fiber (SF) to develop a cost-effective and environmentally sustainable material for use in low-volume roadways. Tests were conducted on both unstabilized and stabilized soil samples to evaluate a range of physical properties, including Atterberg limits, compaction, Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR). BSDA was introduced in increments from 2% to 10% at 2% intervals, with 6% of it being optimal. This resulted in a reduction in the Plasticity Index (PI) from 20.78% to 10.90% and a significant increase in both the UCS and the CBR values. The addition of SF resulted in further enhancement of stabilization, with an increase in the soaked CBR to 28.12% and UCS to 736.011 kN/m³. This triphasic approach, which combines RCS, BSDA, and SF, offers a sustainable and economical solution for the construction of road subbases in civil engineering.

Keywords-Red Clay Soils (RCS); Bluegum Sawdust Ash (BSDA); Sisal Fiber (SF); subbase material; low volume road construction

I. INTRODUCTION

Low-Volume Roads (LVRs) represent a substantial proportion of the global road network, comprising over 30 million kilometers, or approximately 60% of the worldwide road network, over 70% in Sub-Saharan Africa (SSA), and 80% in Kenya [1–3]. These roads are vital for economic and social activities. However, they often suffer from poor construction materials, which leads to frequent failures, particularly in adverse weather conditions. RCS, which are prevalent in these areas, pose challenges due to their high plasticity, low strength, and poor compaction properties. The Sustainable Development Goals (SDGs) of the United Nations (UN) and the national initiatives that direct international and domestic sustainable development activity are made possible in large part by these roads. RCS is primarily composed of iron oxide (hematite) and microcrystalline silica. It is formed from deep soil deposits that have been subjected to prolonged weathering, high temperatures, and significant rainfall [4, 5]. They are invariably associated with a high acidity, with a pH range from 4.0 to 6.0 [6]. As authors in [7] note, RCSs are prevalent in many tropical countries. However, they are not commonly employed in infrastructure construction due to the significant challenges they present in road sub-base construction [8]. They are regarded as "problematic soil," exhibiting a number of unfavorable characteristics. These include low compatibility, high creep rates, high plasticity, low strength, and swelling potential. These traits are attributed to a combination of factors, including a high surface area, high moisture content, high clay content retention, and a porous hematite surface. Furthermore, it was observed that the drying of red soil results in a high moisture content, which, when combined with the process of compaction, leads to a low dry density. The stabilization of soil with agents, such as cement and lime, has enhanced the engineering properties of RCS [9-11]. However, this process is associated with considerable energy consumption and a notable environmental impact. The escalating costs and deleterious effects of traditional stabilizers have prompted research into locally accessible alternatives, including BSDA, rice husk ash, and sugar cane bagasse ash [12]. Cement production is a significant contributor to global CO_2 emissions, representing 4-8% of the total, and is a major source of degradation of natural resources. Additionally, the sludge from concrete batch plants and limestone released by cement production negatively affects aquatic ecology. The wastewater released by these processes further increases construction costs. It is therefore necessary to investigate the potential of locally sourced alternatives, with particular attention to BSDA as a binder, for the stabilization of the RCSs.

Sawdust is a byproduct of the timber industry, with an estimated 100 million tons of BSDA generated annually worldwide [13]. In the United States alone, approximately 3 million tons are annually produced [14]. The improper disposal of this waste can result in adverse environmental and health consequences, particularly in developing countries that lack the necessary infrastructure for effective waste management. BSDA is a valuable source of mineral nutrients, making it an effective material for soil stabilization. The mineral content remains unaltered throughout the combustion process. This stability is of great consequence for the development of technologies that can use these minerals in soil systems [15]. Furthermore, its deployment in stabilization can diminish energy consumption, conserve natural resources, reduce costs, and serve as a promising renewable energy source. The research indicates that BSDA diminishes the plasticity index and enhances the strength of RCSs. However, it impacts moisture-density relationships by increasing the Optimum Moisture Content (OMC) and decreasing the Maximum Dry Density (MDD). The use of SF as a stabilizer has been shown to enhance tensile strength and reduce cracking, thereby complementing the benefits of BSDA. The sisal plant (Agave sisalana), indigenous to Mexico, has been extensively cultivated in a multitude of countries, particularly in regions characterized by arid and warm climates. The fibers, which are renowned for their strength, durability, affordability, and elasticity, are predominantly deployed in the production of rope and have recently emerged as a promising material for soil reinforcement [16]. SF enhances soil cohesion, ductility, and shear strength, and is employed in cement or polymeric composites. However, the large quantities of by-product production have minimal commercial value. It is of great importance to consider the length and percentage of the fiber in question, as an excessively long fiber or one exceeding 1.25% can lead to a reduction in shear strength [17].

The objective of the present study is to ascertain whether SDA and treated SF can be employed as an additive to enhance the geotechnical characteristics of RCS, therefore rendering it a viable material for use as a road sub-base in low-volume roadways. This will facilitate the usage of BSDA and SF as stabilizing agents for clayey soil, hence addressing the issue of road failure. This shift towards alternative, locally available stabilization agents is indicative of the researchers' commitment to identifying environmentally friendly and resource-efficient stabilization solutions. In this regard, the combined use of the BSDA and SF holds considerable promise, suggesting a synergistic modification strategy that could substantially improve the geotechnical characteristics of RCS [18].

II. MATERIALS AND METHODS

A. Materials

The materials used in this study included RCS, BSDA, and treated SF. The soil sample was selected for analysis and was collected at a depth of 500 meters below the surface from the vicinity of the Jomo Kenyatta University of Agriculture and Technology (JKUAT) campus in Kiambu County. The soil samples were sealed in plastic bags to prevent moisture loss and packed in sacks. The soil was then air-dried and subjected to a variety of laboratory tests in accordance with the standards set forth by the British Standards Institution (BS) and the American Society for Testing and Materials (ASTM). These tests include the determination of specific gravity [19], Atterberg limits, free swell index, standard proctor compaction test, CBR [20], and UCS [21]. The bluegum sawdust (BSD) was procured from local carpentry workshops in Juja, Kenya and was subjected to carbonization at temperatures between 3,200 °C and 3,500 °C for an approximately oxygen-free environment, with the objective of obtaining ashes. Subsequently, the material was sieved using the BS 0.105 mm sieve and incinerated at a temperature of 8,000 °C for 30 minutes. The chemical composition of RCS and BSDA was analyzed utilizing scanning X-ray Fluorescence (XRF) at the Ministry of Mining Laboratory in Nairobi. Lastly, SF was procured from Makueni County, Kenya. The SF was treated with sodium borohydride (NaBH4) (1% wt./vol), as proposed in [17]. A length of 3.4 cm of sisal fiber was used in the experiment. Additionally, the fiber properties, including tensile strength and elongation, were evaluated. The materials are presented in Figure 1. The study adopted a phased methodology, introducing BSDA in increments from 2% to 10% at 2% intervals. Subsequently, additional tests were performed with the optimal BSDA concentration in conjunction with SF at varying proportions from 0.25% to 1.25%, as those employed in [14, 15]. The compaction tests and UCS tests were conducted in accordance with the relevant standards [19, 21]. The samples were prepared by compacting them at their corresponding OMC and MDD values. The UCS results were determined after 7, 14, and 28 days of curing. The CBR test was conducted in accordance with the methodology outlined in [20]. The samples were subjected to an oven curing process for a duration of seven days, followed by a seven-day immersion in water.

B. Methods

1) Atterberg Limits

In the field of geotechnical engineering, the Atterberg limit test is of significant importance for the evaluation of the properties of cohesive soils, particularly regarding the assessment of soil behavior in response to changes in water content. The test was conducted in order to ascertain the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) of the soil sample in accordance with the standards set forth in BS 1377-2 (1990) [19].

(a) (b) (c)

Fig. 1. Materials used in the research (a) RCS, (b) BSDA, (c) SF.

2) *Compaction Test*

The Standard Proctor test was applied to ascertain the relationship between the moisture content and dry density of the soil, in accordance with the standards set forth in BS 1377-2 (1990) [20]. The test was performed with a compactive effort of 600 kN-m/m³, with the soil sample compacted in three layers, each receiving 27 blows. Subsequently, the compacted samples were weighed, and the actual water content was determined. Then, the optimal water content for attaining the MDD of each sample was determined from the moisture-density curves.

3) *California Bearing Ratio (CBR)*

The soil samples, including the original soil and soil-BSDA mixtures, were subjected to the CBR test in accordance with the standards set forth in BS 1377-4 (1990) [19]. The dimensions of the CBR mold were 127 mm in height and 150 mm in diameter, with a loading plunger weight of 2.5 kg. All samples were compacted at their respective optimum moisture content and maximum dry density, as determined by the compaction tests. Following this, the compacted samples were subjected to an oven-curing process for a period of seven days, after which they were immersed in water for an additional seven days prior to loading. The load corresponding to the penetration was recorded and plotted in order to determine the CBR value for each sample. The final CBR value was taken to be the maximum value between 2.5 mm and 5.0 mm of plunger penetration into the soil.

4) *Unconfined Compressed Strength Tests*

In order to assess the efficacy of BSDA and SF in soil stabilization, it is crucial to ascertain the extent to which the treated samples demonstrate an increase in strength relative to the original soil. The UCS of the remolded soil samples was determined in accordance with the standards set forth in ASTM D2166-06 [21] using the prescribed level of effort. Subsequently, a cylindrical soil core was extracted from the mold using a sampling tube and extruder. The UCS specimens, with a diameter of 52 mm and a height of 105 mm, were cast and allowed to cure for 7, 14, and 28-day periods prior to the measurement of their unconfined compressive strength.

III. RESULTS AND DISCUSSION

A. *Characteristics of RCS, BSDA, and SF*

1) *Particle Size Distribution of RCS*

The engineering properties of neat red clay soil are presented in Table I for analysis purposes. As shown in Figure 2, the grading chart reveals a soil with a fine particle distribution, predominantly below 0.1 mm in size. This is indicative of a high clay content, which is associated with a proclivity for expansion and shrinkage, potentially impacting the durability of construction on such soil. The particle size distribution curve demonstrates a gradual and continuous gradation devoid of distinct gaps, which typically indicates a well-graded soil, despite the dominance of fine particles due to its clayey nature. This underscores the challenges associated with its use as a subbase construction material. The RCS has been classified as A-7-6 according to the AASHTO system, confirming that it is primarily a fine-grained soil with a high clay content of 67.2%. The silt component constitutes 22.8% of the soil, while sand represents approximately 9.8%. The gravel fraction is the smallest, comprising only 0.2% of the soil. This finding characterizes the soil as gravelly sandy and silty clay. This classification and particle size distribution indicate that the soil has a high surface area, which results in enhanced water retention capabilities and plasticity. However, the soil is unsuitable for use as a subbase material [22]. Therefore, it was necessary to stabilize the soil to make it suitable for use as a road subbase material. The Cu was 8.9 (≥5) and the Cc was 2.7 (within 1-3), indicating that the soil is well-graded. The mean specific gravities of BSDA and RCS were found to be 1.79 and 2.42, respectively. The majority of inorganic soils, as documented in the literature, exhibit specific gravities between 2.60 and 2.80 [23]. In this instance, the specific gravity is less than 2.6, indicating the presence of organic components in the sample used for the analysis. Based on a LL of 46.4 and a PL of 23.7%, the soil sample's PI was calculated to be 22.7%. The elevated concentration of fine particles within the soil is the primary factor contributing to the high plasticity index [20]. This high plasticity was in conjunction with the considerable Free Swelling Index (FSI) of 118% and the notable Linear

Shrinkage (LS) of 11.40%. The specific gravity of BSDA was found to be 1.79% [24, 25], which is indicative of a low value of Gs, as a result of the significant number of pores and the presence of fibrous carbon particles.

TABLE I. PHYSICO - MECHANICAL PROPERTIES OF RCS

Properties	Percentage (%)	Standard Used
Moisture content	6.06	BS1377-2:1990
Specific gravity	2.42	ASTM D 854-92-2009
Gravel,	0.2	BS1377-2 1990
Sand content	9.8	BS1377-2 1990
Silt content	22.8	BS1377-2 1990
Clay content	67.2	BS1377-2 1990
Liquid limits	45.53	BS1377-2 1990
Plastic limit	24.75	BS1377-2 1990
Plasticity index	20.78	BS1377-2 1990
Linear Shrinkage	11.40	BS1377-2 1990
Free Swell Index (FSI)	118	BS1377-2 1990
Optimum Moisture Content (OMC)	28	BS1377-2- 1990
Maximum Dry Density (MDD), kg/m^3	1.48	BS1377-4-1990
California Bearing Ratio (CBR)	1.99	BS1377-4-1990
Unconfined Compressive Strength (UCS), kN/m^2	24.47	ASTM D2166-6-2006
AASHTO classification	A-7-6	AASHTO

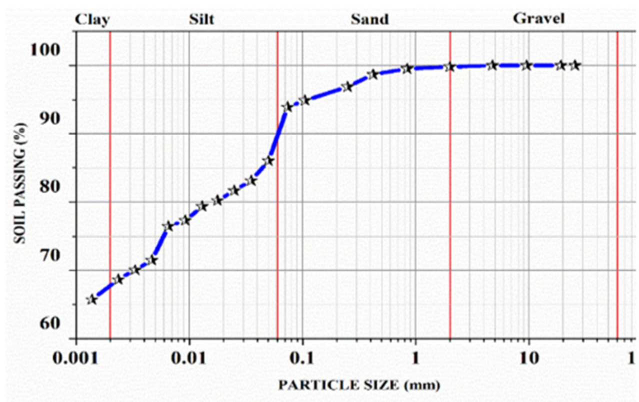

Fig. 2. Particle size distribution of the RCS.

2) Chemical Composition of RCS and BSDA

As displayed in Table II, the chemical composition of the research materials indicates the presence of a greater number of oxides in the RCS, specifically silicon oxide (SiO_2) at 44.4%, aluminum oxide (Al_2O_3) at 18.8%, ferrous oxide (Fe_2O_3) at 26.5%, and calcium ($Ca(OH)_2$) at 2.1%. This type of soil can be stabilized with pozzolanic material that has a high content of CaO, thereby forming cementitious properties. The calcined BSDA was found to contain a high proportion of CaO (69.4%) and MgO (9.5%), rendering it an appropriate material for stabilization purposes. The dissolution of SiO_2 and Al_2O_3 from the soil results in the formation of a secondary cementitious product, known as "tobermorite gel" [26], which is a combination of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). This novel cementitious product enhances the strength of the mixture. As indicated by [13, 27], the cementitious or pozzolanic properties of a CaO content between 10% and 20% were satisfied. Moreover, the ratio of (CaO + MgO)/SiO_2 was found to exceed 1 for cementitious materials, as previously observed [27].

TABLE II. CHEMICAL COMPOSITION OF RCS, BSDA

Element	Percentage (%)	
	RCS	BSDA
SiO_2	44.40	10.11
Al_2O_3	18.82	1.81
Fe_2O_3	26.55	0.83
TiO2	4.74	0.12
Ca $(OH)_2$	2.10	69.44
`MgO	0	9.52
K_2O	1.54	6.08
P_2O_5	0	4.43
CL	0.26	3.29
Mn	0.24	2.17
S	0.16	1.26
LOI		3.98

a) Sisal Fiber Properties

The treatment of SF with sodium borohydride (NaBH4) (1% wt/vol) for 60 minutes led to an increase in cellulose content by 9.31%, while simultaneously reducing the hemicellulose and lignin content by 14.91% and 33.41%, respectively. These findings demonstrate the effectiveness of the treatment, as presented in Table III. The water absorption of SF was found to be 43.58%, with a specific gravity of 0.73. These findings are consistent with those reported in similar studies [17, 28], and they have implications for the workability of soil mixes. The tensile strength of the treated and untreated SF exhibited no notable variation, with the untreated fibers displaying a value of 373.4 N/mm² and the treated fibers exhibiting a value of 373.3 N/mm². These values fall within the reported range of (373 ± 28) N/mm² [29], but are lower than some values (511 N/mm²-635 N/mm²) reported in [28, 30, 31]. The elongation at break for SF is 2.8 ± 0.29%, which aligns with the data reported in [32].

TABLE III. CHEMICAL COMPOSITION OF SISAL FIBER

Composition	Untreated (%)	Treated (%)	Percentage change (%)
Cellulose	64.03	71.22	7.19
Hemicellulose	19.89	15.26	4.63
Lignin	16.78	11.45	5.33

B. Physical and Mechanical Properties of Stabilization of the RCSs with BSDA

1) Atterberg Limits

The principal objective of integrating the BSDA was to reduce the PI of RCS to satisfy the suitability criteria for subbase construction, as shown in Figure 3. In accordance with the standards set forth in [19], the objective PI was established at a level below 12% for the materials utilized in the subbase. The incorporation of BSDA into RCS in proportions ranging from 0% to 10%, with an increment of 2%, has been observed to markedly enhance the workability of the resulting mixture while exerting a notable reduction in its flexibility. Prior to the addition of BSDA, the soil exhibited a PI of 22.40%. However, with the incorporation of BSDA, a notable reduction in the PI was observed, reaching a minimum of 10.90% at a 6% BSDA content. This value was identified as the optimal point in the study. At values exceeding this threshold, the PI began to increase. This reduction in PI demonstrates the efficacy of

BSDA in modifying the soil's consistency limits, thereby enhancing its workability and reducing its susceptibility to moisture fluctuations, which is vital for stabilizing soil as a subbase material in construction applications [9, 13–15, 33]. The linear shrinkage, which is dependent on the plasticity characteristics, decreased from 11.40% to 7.56%, as depicted in Figure 4. At the outset of the combination of RCS with BSDA, the PL exhibited a more rapid and pronounced increase than the LL, resulting in low PI values. Upon reaching the optimal BSDA content of 6%, both limits exhibited an increase. This is due to the fact that the combination of RCS and BSDA resulted in an increase in the ratio of fine particles present in the mixture, which can be attributed to the difference in specific gravity between the two materials. Consequently, the water demand of the mixture increased, leading to higher plastic and liquid limits and a subsequent increase in PI. The reduction in linear shrinkage can be attributed to the substantial volume of BSDA incorporated into the soil, which has led to a decline in the clay particles to soil ratio. A reduction in the clay particles/soil ratio will result in a corresponding reduction in linear shrinkage [14, 33].

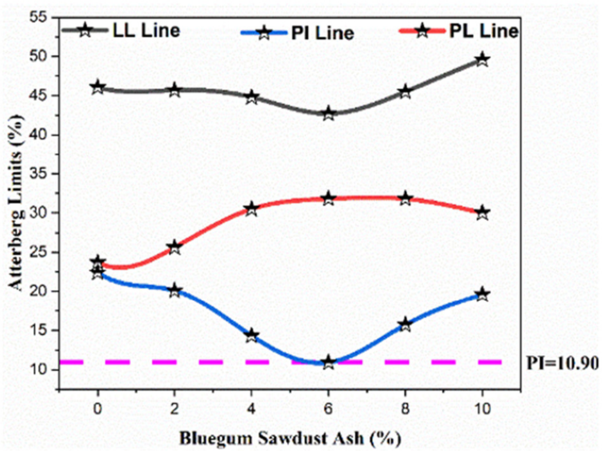

Fig. 3. Effect of BSDA on Atterberg limits of the RCS.

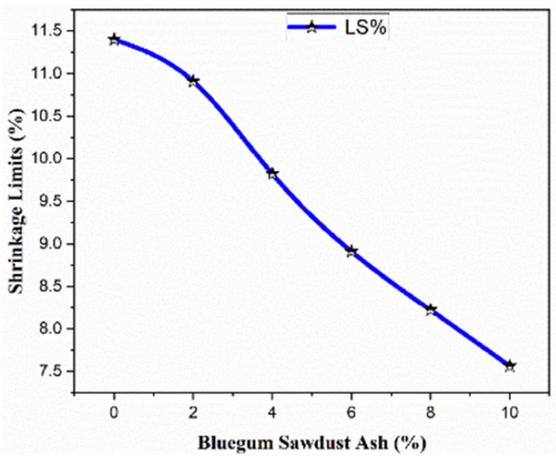

Fig. 4. Effect of BSDA on linear shrinkage of the RCS.

2) *Compaction Characteristic*

As illustrated in Figure 5, the experimental data revealed that with the augmented addition of BSDA, there was an observed increase in OMC while MDD remained constant. The MDD decreased potentially because the soil became lighter with the increased stabilizer content, which may have resulted in a rise in the ideal moisture content due to the increased requirement for water to maintain its hydrated state. While the PI was enhanced, the MDD of 1,235 kg/m³ attained at the optimal BSDA dosage is still below the standard range of 1,325-2,016 kg/m³ [34]. It is imperative to investigate the potential of locally available materials to enhance the MDD and reduce the OMC, as these parameters are crucial in assessing the suitability of the material for construction applications. The objective is to develop a durable and reliable low-volume road material that can facilitate safe and efficient transportation for the local community. This underscores a crucial deficiency in the investigation of sisal fiber as a reinforcement material. The higher water absorption capacity of SF [28], suggests that it may have the potential to increase MDD. Additionally, it enhances tensile strength and mitigates the risk of cracking and deformation in clay soils.

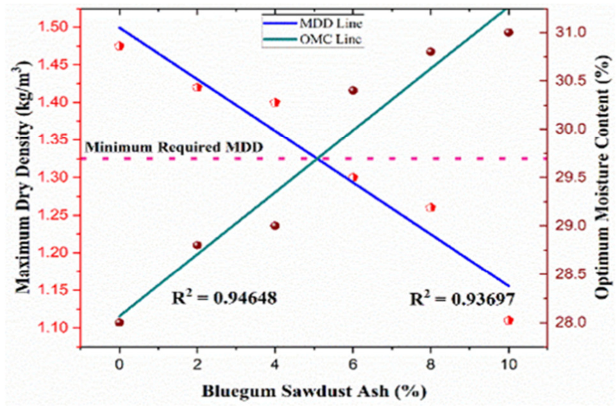

Fig. 5. Effect of BSDA on moisture density relationship.

3) *California Bearing Ratio (CBR)*

As shown in Figure 6, the CBR exhibited an increase from 1.99% to 6.93% at the optimal content level, with the highest value noted at 10% BSDA (10.01%). The Asphalt Institute [35] has recommended a CBR from 7% to 20% for highway sub-base materials and 0% to 7% for subgrade materials. While it has not met the requisite range at the optimal value, the application of BSDA to RCS has demonstrated a notable enhancement in CBR values, which serve as a crucial indicator of soil strength and stability in road sub-base construction [36]. This increase in CBR can be attributed to the pozzolanic reactions, as presented by (1) and (2), between the SiO_2 in RCS and the CaO_2 in BSDA, which enhance the bearing capacity. Therefore, the sample exhibits a poor load-bearing capacity at optimal content, indicating its unsuitability as a subbase material that is likely to fail in construction applications. The fundamental pozzolanic reaction is exemplified by:

$$Ca^{2+} + 2(\mathrm{OH}) \pm \mathrm{SiO_2}(\,clay\ silica) \rightarrow \mathrm{CSH} \quad (1)$$

$$Ca^{2+} + 2(\mathrm{OH}) \pm Al_2O_3(\,clay\ alumina) \rightarrow \mathrm{CAH} \quad (2)$$

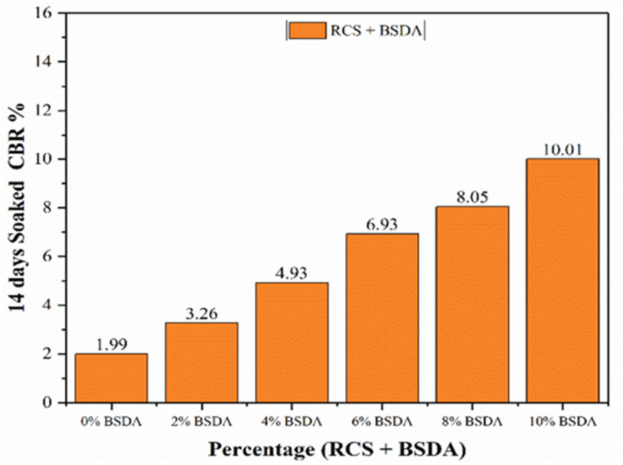

Fig. 6. Effect of BSDA on CBR values.

4) *Unconfined Compressive Strength (UCS)*

The UCS test results are presented in Figure 7 for various curing periods (7, 14, and 28 days). The findings indicated that the UCS values exhibited an upward trend in conjunction with an increase in BSDA content and prolonged curing periods. This observed increase in strength can be attributed to the cementitious properties of the binder, namely RCS and BSDA, which facilitate the solidification of the soil matrix and enhance its strength. These findings are in accordance with those previously reported in [28, 35]. Figure 7 also shows that the curing period resulted in an increase in the UCS values. The latter was more pronounced when the clayey soil was stabilized with 6% to 8% BSDA compared to other proportions for 28 days. The UCS values of the 6% BSDA-stabilized red clayey soil did not meet the sub-base requirement of 687–1373 kN/m², as specified in [36]. These findings indicate that the stabilized samples are unsuitable for use as subbase material. However, they may be suitable for use as subgrade material in low-volume road construction.

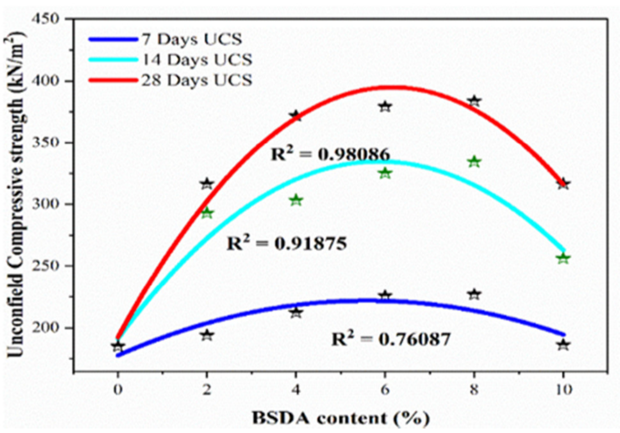

Fig. 7. Effect of BSDA on UCS.

C. *Strength Characteristics of Stabilized RCS with SF*

1) *Compaction Proctor Test*

Figure 8 depicts the variation in MDD and OMC due to the addition of varying percentages of SF. MDD increased by approximately 4.8%, from 1455 kg/m³ to 1525 kg/m³, while the OMC decreased from 28.0% to 20%. This finding aligns with the standards reported in [15, 31] when SF was incorporated. The changes in compaction characteristics can be attributed to the addition of SF, which fills and occupies voids between soil particles, thereby minimizing spaces. Consequently, the incorporation of SF resulted in an enhancement of the compaction characteristics of the RCS. An additional factor contributing to the observed increase in MDD and reduction in OMC is the intensification of the compaction effort. Additionally, authors in [37, 38] observed that increased compaction effort generally results in higher MDD and lower OMC, and vice versa. However, when SF is increased to 1.25%, MDD decreases, indicating a limit to the beneficial effects of SF on soil density. Additionally, OMC slightly increases with higher SF levels, suggesting a greater moisture requirement for optimal compaction at these concentrations. This nuanced response emphasizes the importance of carefully calibrating the amounts of BSDA and SF to achieve optimal compaction results for construction applications [25, 26, 39, 40].

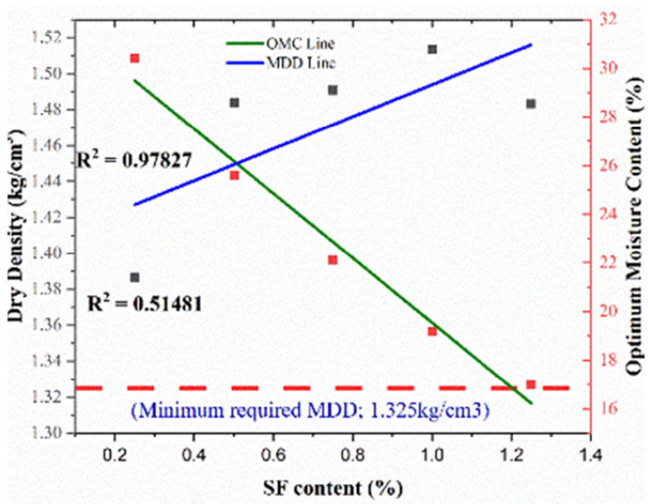

Fig. 8. Effect of SF with optimum BSDA on moisture density relationship.

2) *California Bearing Ratio Strength Improvement*

The results presented in Figure 9 show that the incorporation of SF resulted in a significant enhancement in CBR values, rising from 6.93% at the optimal BSDA to 28.12% with an 1% SF addition. This resulted in a systematic improvement in the mechanical characteristics of the soil, thus enabling the attainment of certain strength parameters associated with its load-bearing capabilities. It is essential to ascertain the precise percentage of SF that will optimally stabilize the soil, in order to maximize its load-bearing capacity while maintaining its structural integrity. This meets the requirement set forth in [32], where it is stated that a CBR from 7% to 20% is suitable for use as a highway sub-base material, whereas a CBR from 0% to 7% is appropriate for subgrade materials.

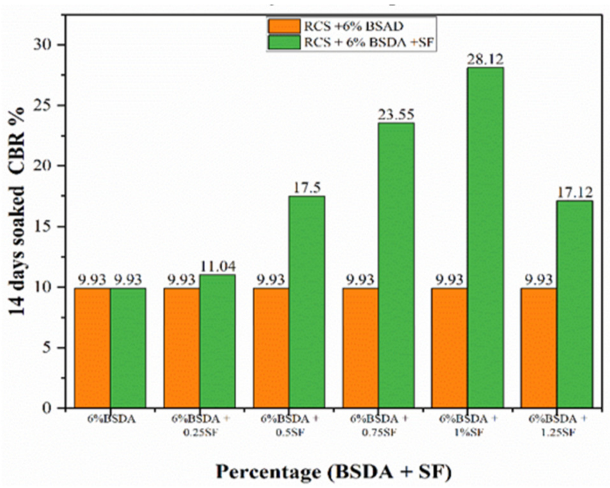

Fig. 9. Influence of SF with optimum BSDA on CBR.

3) Unconfined Compressive Strength (UCS) Improvement

As shown in Figure 10, the UCS value of 736.01KN/m², obtained at 6% BSDA and 1% SF, cured for 28 days, meets the minimum standard for a subbase material, as defined in [36] and ASTM-D2166-06 [12], which is (687-1,373) kN/m². This renders it an appropriate subbase material for road construction. The improvement in the UCS is more substantial when a longer curing period is employed. The pozzolanic reaction between SiO_2 in the RCS and CaO_2 in the BSDA becomes more intense with the passage of time. Nevertheless, the incorporation of a greater proportion of BSDA into the mixture results in enhanced water retention, attributable to the substantial presence of clay particles, which in turn precipitates the disintegration of soil particles.

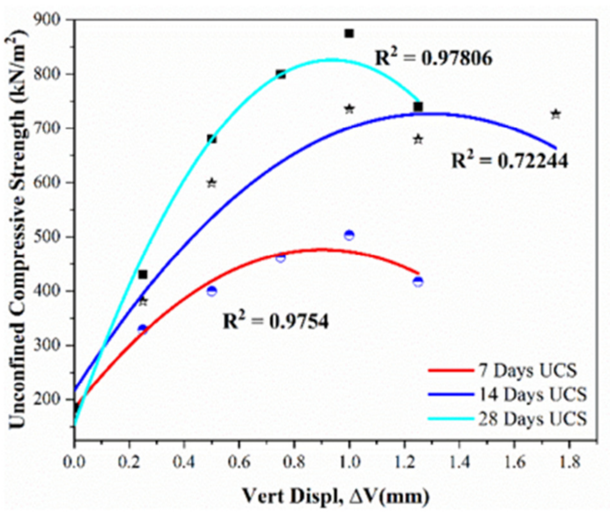

Fig. 10. Influence of SF with optimum BSDA on UCS.

The presence of SF, which exhibits higher water absorption and reinforcement behavior, absorbed the excess moisture present in the mixture intended for the BSDA hydration reaction, thereby increasing the extent of hydration and resulting in higher UCS values [25]. When soil particles begin to separate due to the presence of excess water, SF can act to hold them together, filling and occupying voids between soil particles, and hence minimizing the spaces between them. This resulted in an increase in soil strength, leading to higher UCS values. Consequently, the combined use of BSDA and SF enhances tensile strength and mitigates the likelihood of cracking and deformation in soil. The results obtained following the incorporation of SF into the mixture demonstrated superior outcomes compared to those achieved through the utilization of BSDA alone.

IV. CONCLUSIONS

Red Clay Soil (RCS) is distinguished by a high Plasticity Index (PI) of 20.48% and a Free Swell Index (FSI) of 118%, in conjunction with a low California Bearing Ratio (CBR) of 1.99% and a Unconfined Compressive Strength (UCS) value of 24.47 kN/m². These characteristics render it unsuitable for use as a road sub-base material, as it fails to meet the requisite standards. It is therefore imperative to stabilize RCS in order to enhance its fitness as a road sub-base material. In contrast to previous studies, cement or lime was employed as a stabilizing agent for RCS. This comprehensive investigation of the stabilization of RCS with calcinated Bluegum Sawdust Ash (BSDA) and treated Sisal Fiber (SF) with sodium borohydride ($NaBH_4$) (1% wt./vol.) underscores the significance of meticulously selecting additive percentages to augment soil characteristics. The study employed a phased methodology, whereby BSDA was introduced in increments from 2% to 10% at 2% intervals. Furthermore, SF was introduced in increments from 2% to 10% at intervals of 2% in the study, with the optimal percentage obtained between 0.75% and 1%. The principal findings of the study are:

- The incorporation of a 6% BSDA concentration has been demonstrated to markedly diminish the soil's Plasticity Index (PI) and shrinkage limits, consequently enhancing workability and reducing its propensity to undergo moisture-induced volume alterations. Similar outcomes were documented in [9, 13-15, 19, 33]. Although the PI was enhanced, the MDD of 1235 kg/m³ attained at the optimal BSDA level was found to be below the standard range of 1325-2016 kg/m³ [34].
- Furthermore, the incorporation of SF in the range from 0.25% to 1.25% has been observed to significantly enhance soil strength, with the most pronounced improvements in CBR and UCS occurring at intermediate SF levels from 0.75% to 1%. These findings align with those reported in [29, 30, 41]. The considerable enhancement in strength indicates that the concurrent use of BSDA and SF has the potential to significantly augment the load-bearing capacity and overall strength of RCSs.
- The findings of this study indicate that the incorporation of BSDA and SF into RCS can be used as a sub-base

construction material for low-volume roads, thereby facilitating eco-friendly and cost-effective solutions.

It is recommended that the products of this study be considered as a sub-base material for low-volume roads, including surfaces for footpaths, tracks, and roads in remote and steep rural areas prone to soil erosion. Further research may be conducted on the RCS with other pozzolanic materials, such as banana peel ash, to produce admixtures that qualify as road subbase material.

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