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Research Article

Evaluation of Geotechnical Properties of Black Cotton Soil Reinforced with Sisal Fibre for Waste Containment Application

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Received: 8 February 2022; **Revised:** 27 April 2022; **Accepted:** 29 April 2022

Abstract: Compacted Black Cotton Soils (BCS) used in geotechnical constructions such as dams and clayey liners in waste containment facilities can suffer from cracking due to swelling and shrinking during wet and dry seasons respectively. In order to reduce the shrinkage of the clayey soil, discrete fibre reinforcement such as the Sisal Fibre (SF) technique was used. An experimental study was carried out on the natural and the modified properties of the soil which include Atterberg limits, compaction, Unconfined compressive strength UCS (i.e., for varying Moulding Water Content (MWC) relative to Optimum Moisture Content (OMC); OMC-2, OMC, OMC+2, OMC+4) and Volumetric Shrinkage Strain (VSS) at MWC relative to OMC; (OMC-2, OMC, OMC+2, OMC+4) were determined, for different percentages inclusion of sisal fibre (0, 0.5, 1, 1.5 and 2% SF). Results obtained show that the liquid limit and plasticity index of the natural soil are 44.47% and 18.65% which increased with an increase in the sisal fibre content. OMC increased from a value of 19% for the natural soil to a peak value of 24.5% at 1.5% of sisal fibre and thereafter decreased. The natural soil has a Maximum Dry Density (MDD) of 1.55 Mg/m^3 which decreased to 1.5 Mg/m^3 at 1.5% additive. The VSS of the modified soil significantly decrease compared to the natural soil and it continually decreased as the percentage of sisal fibre increased. The lowest VSS values were observed at 2% SF, having values of 2.85, 3.5, 4.75, and 5.5% for OMC-2, OMC, OMC+2, and OMC+4, respectively. The UCS initially increased and thereafter decreased. Based on the results, soil optimally treated with a maximum of 0.5% sisal fibre and compacted with OMC-2 significantly improved the soil and is recommended for use in waste containment applications.

***Keywords*:** black cotton soil, moulding water content, optimum moisture content, sisal fibre, unconfined compressive strength, volumetric shrinkage strain, waste containment application

1. Introduction

In civil engineering, soils with properties that cannot be safely used for construction purposes without adopting some stabilization measures are known as problem soils [1]. These soils pose a problem to construction works as a result of their low strength properties, and in such scenarios, the field engineer has no chose rather than collect materials from a borrowed pit that has suitable materials or improve by stabilizing the existing soils [2]-[3]. Stabilization of soil

DOI: https://doi.org/10.37256/est.3220221354

encompasses the processes of alteration of soil properties to improve its strength characteristics. Stabilization enhances the shear strength, lessens shrinkage properties, and improves its load-bearing capacity [4]. Salahudeen and Sadeeq [5] defined soil stabilization as improving the strength property of deficient soil to meet up a specific property suitable for engineering application.

BCS is dark or gray colored expansive clays and is a typical example of problem soils [6]. BCS is so-referred to in some regions of the world since the cotton plant thrives well on them. They have colors ranging from light gray to dark gray and black. Two groups of parent rock materials have been linked with the formation of expansive soils. The first set encompasses the sedimentary rock of volcanic origin, found predominantly in North America, South Africa, and Israel, while the second set of parent materials consists of basic igneous rocks predominantly found in India, Nigeria, and southwestern U.S.A [6]-[7]. The abundance of BCS in India and other parts of the world has also been reported in several kinds of literature [8]-[14].

In Nigeria, BCS is mostly found in the northeastern region of Nigeria, covering an area of over 104,000 km^2 [15]-[17]. When dry, BCS appears very hard with attendant high bearing capacity. However, when wet, it absorbs a significant quantity of water, swells swiftly, and thus leads to a decline in bearing capacity; thus resulting in excessive settlement and prior failure of the structures or road pavements built on them [1]. BCS undergoes swell shrink behaviour owing to the existence of montmorillonite as the dominant clay mineral in the soil. Highway construction on cohesive or clayey soils such as black cotton soil has been a challenge to engineers. The high swelling and shrinkage characteristics, attributed to medium/high compressibility, give rise to cracks in the pavement structure [18]. Roads built on BCS soils and subjected to vehicular traffic, heave, and crack due to swelling and shrinkage with changing moisture conditions [19]. BCS soil used in this study is a kind of problematic soil with high swelling potential as reported in a previous study by the author [6].

Construction of buildings or roads on BCS requires the removal of the soil in the entire area and replacing it with a granular soil of higher bearing capacity. However, replacing BCS in an area is not economical and will lead to an increase in the cost of construction. Improving such deficient soil with cement or lime which are well-known industrially manufactured additives will improve the soil engineering properties. However, over-reliance on the utilization of industrially made soil stabilizing additives like cement and lime has over time resulted in an increase in environmental pollution and the cost of construction for engineering purposes [6]. Thus, substituting this approach with agricultural waste such as sisal fibre, sawdust ash, locust bean waste ash [1], [16], [18], and industrial waste such as marble dust, iron ore tailings [4], [17], etc. for engineering applications will assist in minimizing the environmental problems caused by cement/lime production. It has also been reported in literatures [6], [16] that cement production processes give rise to carbon (IV) oxide (CO_2) in large quantities. Thus, replacing cement with other options such as sisal fibre will tackle the environmental problems caused by carbon (IV) oxide (CO_2).

Several pieces of literature [20]-[29] reported on various types of additives used as admixtures for soil improvement. For instance, Young et al. [20] modified granitic residual soil using fly ash, ground bottom ash, blast furnace slag with lime, red mud, and phosphogypsum as activators. Results recorded a significant increase in the 28 days strength and microstructural changes in the modified soil. Trung and Dong [21] considered the use of spent coffee ground, oyster shell, and ground-granulated blast furnace slag for geotechnical engineering applications. The report recorded an improvement in the unconfined compressive strength results. An eco-friendly and sustainable soil improvement method called Microbial-Induced Calcite Precipitation (MICP) has also been reported in pieces of literature for different engineering applications, waste containment applications [22]-[23], and roads and embankments [24].

A recent study focused on determining the behaviour of soil reinforced with fibres randomly with sodium silicate as a binder [2], [30]-[32]. The use of natural materials such as jute, and bamboo, as reinforcing materials in soil improvement has been used in countries like India, the Philippines, Bangladesh, etc. [18]. Anil et al. [31] evaluated the effect of both sisal and Polyvinyl Alcohol (PVA) fibre on the properties of loam soil. Result documented from the study shows that sisal fibre portends to be more effective in enhancing the strength of the soil than PVA. Several other researchers [33]-[35] reported on soil improvement carried out using sisal fibre, cone fibre, and jute fibre with positive outcomes. The use of fibres for different engineering applications has been reported in literatures [36]-[44].

Ehrlich et al. [38] experimented on the Hydro-mechanical behaviour of a lateritic soil modified with Polyethylene fibres for waste containment application. Results show an increase in both the hydraulic conductivity and the tensile strength of the fibre modified lateritic soil. Improvement of cement-stabilized clay reinforced with glass fibers was conducted by Bo et al. [44]. Glass fiber contents used for soil improvement are in the rations of 0, 1, 2, 3, and 4% by weight of the dry soil. Results show an improvement in the shear strength parameters of glass fiber reinforced clay soil better than the cement-stabilized clay. The cohesion of the cement-stabilized clay reinforced with 4% glass fiber content is 2.8 times greater than that of the cement-stabilized clay.

Natural fibres like bananas and jute are good for making composites. They have numerous gains which comprise low cost, renewability, low density, high tensile strength, high stiffness, and biodegradability [45]. Normally, natural fibres are locally available and less economical. Among all the natural fibres, sisal fibres having high tensile strength significantly improve the shear strength of the soil [46]. This study focused on evaluating the influence of sisal fibre in improving BCS for use as a containment material. The precise objective includes the determination of changes in the properties of the modified soil with varying concentrations of the dosage of fibre.

2. Materials and methods

2.1 *Materials*

2.1.1 *Black cotton soil*

The black cotton soil was gotten by disturbed sampling technique from Akko LGA, along Gombe Adamawa Road, with a geographic location of latitude 10.308920° and longitude 11.213692°. The topsoil at about 0.5 m was removed so as to get the soil without organic deposits which are contained in the topmost part of the soil. The sample was collected in sacks, and the sample that was used to determine the natural moisture content was collected and tied properly in an aired tight polythene bag in order to avoid moisture loss while transporting the soil. The soil samples were then air-dried then sieved through BS No. 4 (4.76 mm aperture).

2.1.2 *Sisal fibre*

Sisal fibre was obtained at a local market in Building Materials, Jos Plateau State, Nigeria. Required sisal fibre was gotten by processes called decortications, as contained in Badami [30]. Decortication involves the process where the leaves of sisal plants are beaten and crushed by a rotary wheelset that has blunt knives, while the leaves are washed away by water, only fibre remains. A typical sisal plant is shown in Figure 1.

Figure 1. Uncut sisal fibre used for the present investigation

2.1.3 *Sodium borohydride*

Sodium borohydride was sourced from a chemical shop in Jos.

2.2 *Methods*

2.2.1 *Soil Preparation*

The preparation process involves sieving the soil through a 0.425 mm sieve for the Atterberg limits test while that of compaction, volumetric shrinkage, and unconfined compressive strength were sieved through 4.76 sieves. The sisal fibre was cut to an average length of about 1cm and treated with Sodium borohydride ($NaBH_4$) at 1%/wt as recommended in the literature [47]. Sodium borohydride was used to remove the cellulose (i.e., a biodegradable material that can decay with time) content of the sisal fibre that is responsible for its decaying with time when used for soil improvement. After removing the cellulose, the treated sisal fibre was air-dried before mixing with the soil for the various tests.

2.2.2 *Index properties*

Index tests were carried out for the untreated soil based on the specification outlined in BS 1377 [48].

2.2.3 *Atterberg's limits*

Atterberg limits include the determination of the liquid limit, plastic limit, and the plasticity index of both the natural and modified soil sample. The test was also coordinated according to BS 1377 [48] for the untreated soil and BS 1924 [49] for the modified soil sample.

Liquid Limit (LL)

The test was done using air-dried soil and passing BS No. 40 (425 µm aperture). About 300 g of the sieved sample was placed on a glass plate and mixed properly with tap water until it forms a uniform paste. After thorough mixing with water, a small portion was collected and put in the Casagrande apparatus. A groove was made at the center of the cup filled with the soil, with the aid of a grooving tool. The Casagrande apparatus is turned via the handle to raise the cup and drop until the two parts of the soil come in touch with the base of the groove. Each turning of the handle makes a rise and fall of the groove (i.e., a blow). The number of blows in which that occurs is documented and a small measure of the soil sample from the groove apparatus is taken and the moisture content is then obtained. The procedure was then repeated for the soil samples mixed with varying percentages of the sisal fibre (i.e., 0, 0.5, 1, 1.5, and 2% sisal fibre by dry weight of soil) and the required numbers of blows were obtained and recorded.

Plastic Limit (PL)

A slice of the soil/soil mixed with the sisal fibre used in carrying out the LL test was obtained for creating the PL. A small soil/soil mixed with sisal fibre was turned between the palms of the hand up until it become dry adequately forming a thread-like structure of about 3 mm thick before it crushes (despite the soil being moderately drier compared to the soil used for LL test). The crushed soil is at that point placed into a moisture content container in order to obtain the moisture content of the crumbled soil sample. The progression is reiterated for all proportions of the sisal fibre (i.e., 0, 0.5, 1, 1.5 and 2% sisal fibre by dry weight of soil).

Plasticity Index (PI)

The soil/soil-sisal fibre Plasticity Indices (PI) is the mathematical difference between the liquid limit of the natural/various mixes l and their resultant plastic limits.

2.2.4 Compaction test

The compaction test was carried out for the natural and modified soil (i.e., at different percentages of sisal fibre), all agreeing to BS 1377 [48] (1990) Part 4 and BS 1924 [49] (1990) respectively using the British Standard Light energy.

Maximum Dry Density (MDD)

3 kg of soil was used for the compaction of the natural soil and (water was added at 5% at each stage). The sample was compacted into a 1,000 cm^3 (of mass ml); in 3 layers of each getting 27 blows using a 2.5 kg rammer falling over a height of 300 mm (i.e., British Standard Light, BSL energy). The collar is then removed after compaction, and frills the compacted soil with the upper part of the mould with the aid of a straight edge and weighed. Then two small samples were then removed from the mould and sliced through to get a small portion of the soil for moisture determination. The sample was thereafter detached from the mould, then crumble and another 5% of water was further added and the same process as the initial was reiterated until the minimum of five sets of samples were gotten and their respective moisture content samples collected. The bulk density was computed from each compacted layer using equation 1:

$$\rho = \frac{m_2 - m_1}{1000} \tag{1}$$

The dry density was also calculated using the equation 2;

$$\rho_d = \frac{100\rho}{100 + w} \tag{2}$$

Where w is the moisture content of each compacted layer.

The values of dry densities were obtained from equation 2 and plotted against their corresponding moisture content, and the Maximum Dry Densities (MDD) were deduced as the maximum point on the resultant curves. The same procedure was repeated for the soil reinforced with the sisal fibre to achieve their moisture content and dry density from the plotted curve.

Optimum Moisture Content (OMC)

The resultant values of moisture content at MDD, obtained from the graph of dry density versus moisture contents give the Optimum Moisture Contents (OMC).

2.2.5 *Strength characteristics*

Unconfined Compressive Strength (UCS)

UCS tests were done on the soil sample following BS 1377 [48] using the BSL energy level. The compaction of both natural and modified soil samples (sample with sisal fibre admixture) was compacted in 1,000 cm^3 mould at varying moisture content relative to OMC (i.e., OMC-2, OMC, OMC+2, and OMC+4 to simulate field condition in waste containment application). The samples were removed from the mould and the top portion of the cylinder was properly trimmed into a cylinder of 38 mm in diameter and 78.2 mm in height. The samples from the compaction mould were then cured for 48 hours (2 days) before crushing with the machine. The UCS was gotten using equation 3.

$$\text{Unconfined compressive strength} = \frac{\text{Failure load}}{\text{Surface Area of Specimen}} \tag{3}$$

2.2.6 *Volumetric shrinkage test*

The volumetric shrinkage upon desiccation was measured by extruding compacted cylindrical specimens (twenty in number) from the compaction mould and allowing the cylindrical specimens to dry on a laboratory table. The samples were prepared by compacting the soil samples using the BSL. Four soil samples were extruded for natural soil and each fibre concentration, (for 0.5% one sample was extruded each for OMC-2, OMC, OMC+2, and OMC+4 and the same was repeated for 1%, 1.5%, 2% sisal fibre). The samples were kept in the laboratory and measurements were taken; for weight, diameter and height at intervals of five days from day one to day thirty, to determine the volume of the sample in relation to the time duration.

3. Results and discussions

3.1 *Untreated soil index properties*

Preliminary tests conducted on the natural soil showed that the soil is greyish black color and with a relatively low moisture content of 3.90%. The essential characteristics of the natural soil are provided in Table 1 below. The soil was classified by AASHTO [50] and ASTM [51] as A-7-6 (25) and CL in that order. The soil has a liquid limit of 45.18%, a plastic limit of 25.82%, and a plasticity index of 19.43%. The soil has a maximum dry density of 1.55 Mg/m^3 using British Standard Light and a specific gravity of 2.41. Referring to the properties of the soil, the soil is of low plasticity. The grain size plot of the natural soil is given in Figure 2.

Table 1. Untreated soil index properties

Properties	Quantities
Passing 75 µm	77.69
Moisture content	3.90
Liquid limit %	45.18
Plastic limit %	25.82
Plasticity index %	19.43
Specific gravity	2.41
MDD Mg/m^3	1.55
OMC %	19.0
UCS	
AASHTO classification	A-7-6 (25)
NBRRI classification	Low swell potential
USCS	CL
Colour	Greyish black
Dominant clay mineral	Montmorillonite

3.2 *Effect of sisal fibre on modified properties of soil*

3.2.1 *Atterberg's limits*

Liquid limit

The liquid limit of black cotton soil with variations in percentages of sisal fibre is provided in Figure 3. The liquid limit of BCS initially increased from its natural value of 43.4% to the highest value of 55.9% at 1% sisal fibre content (i.e., 50.12% increment), and subsequently declined to the least value of 49.4% at 2% sisal fibre content. Values of 43.4, 50.94, 55.87, 50.31 and 49.36 were recorded at 0, 0.5, 1, 1.5 and 2% sisal fibre in that order. The initial increase in the sisal fibre content could be attributed to the absorption capacity of sisal fibre to absorb more water. A similar observation was reported in pieces of literatures [35], [44], [52]. However, treatment of the soil with more than 1% sisal fibre content resulted in a decline in the liquid limit of the modified soil. The possible reason for the reduction could be associated with an increase in the stiffness of the soil with a higher concentration of fibre in the soil. Also improved soil work-ability with higher sisal fibre content could be responsible for the decline in the liquid limit. Similar observations were made in the works of literature [27]-[29], [44].

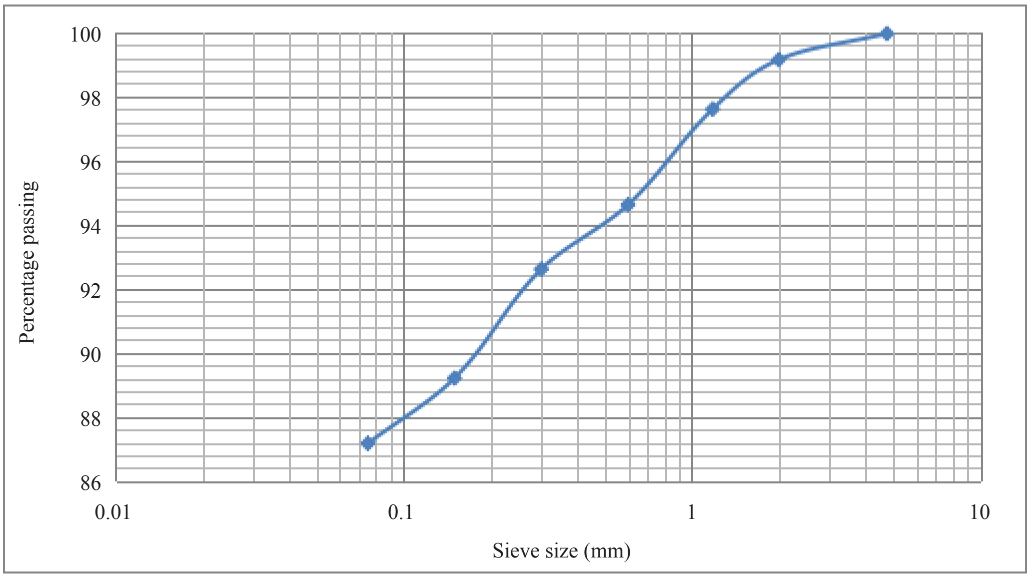

Figure 2. Grain size plot of the natural soil

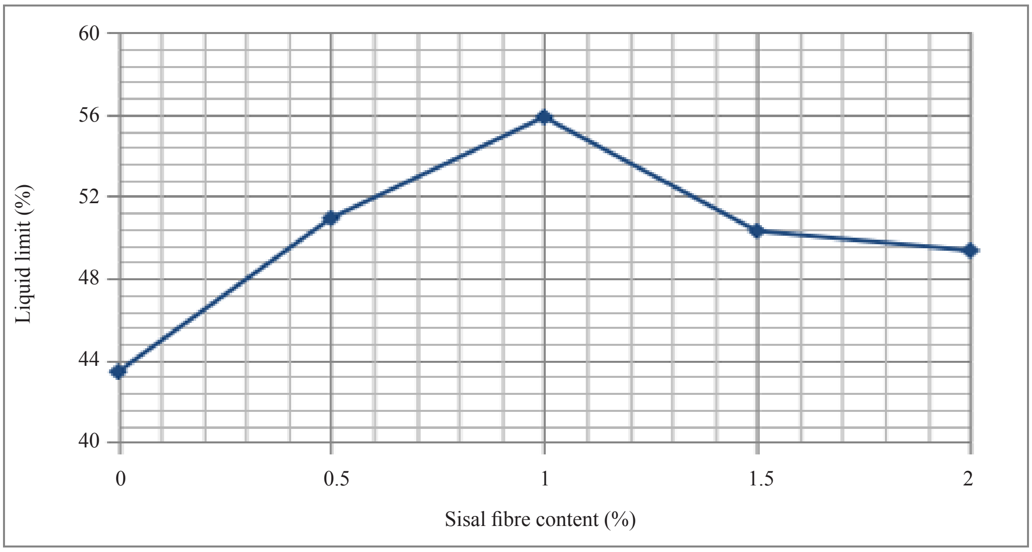

Figure 3. Plot of the liquid limit versus percentages of sisal fibre

Plastic limit

Figure 4 shows the plot of changes in plastic limit with respect to percentages of sisal fibre. The plastic limit of the soil varies with percentages of additives, from the result the plastic limit of the soil at its natural state was 25.82%, which is reduced with respect to percentages of sisal fibre. The plastic limit decreased with an increase in the addictive content. Values of 25.8, 15.55, 20.97, 22.95, and 22.38 were recorded at 0, 0.5, 1, 1.5 and 2% sisal fibre in that order. Friction forces of resistance established between the soil and the sisal fibre that served as a reinforcing material could be responsible for the decline in the plastic limit of the modified soil [44], [52]. Also, an increase in water absorption capacity of the modified soil with higher sisal fibre content may be responsible for the recorded trend.

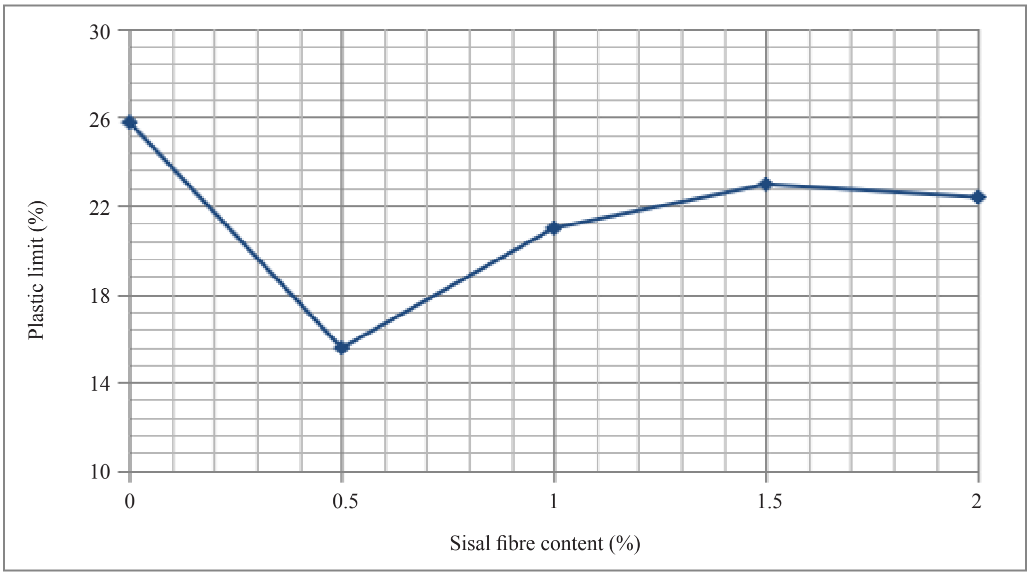

Figure 4. Plastic limit of the soil with variations in percentages of sisal fibre

Plasticity index

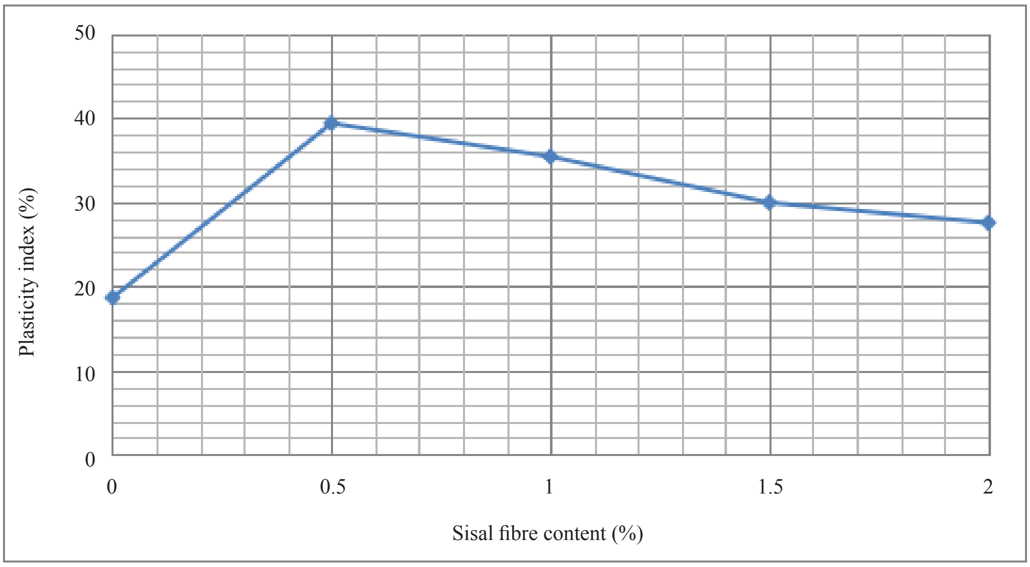

Figure 5. Variation of plasticity index of black cotton soil versus percentages of sisal fibre

The variation of the plasticity index of soil mixed with additives in various percentages is shown in Figure 5. The decrease in plastic limit and increase in liquid limit were accompanied by an overall initial increase in the plasticity index value from a value of 18.65% to 39.36% at 0.5%, 35.50% at 1.0% additive while at 1.5% and 2.0% the plasticity index were 29.94% and 27.54% respectively. The recorded decrease in plasticity index with a higher proportion of sisal fibre may be due to the increase in the frictional resistance between the soil particles, through its interaction with the sisal fibre, thus causing a fall in the swelling perspective of the soil. Stephen [53] also reported a similar trend when researching the influence of bagasse ash on the stabilization of soil. Moreover, a reduction in the plasticity index with an increment in the sisal fibre content may be linked to the reduction in the shrinkage behaviour of the modified soil as a result of sisal fibre incorporated into the soil mix [44]. Ibrahim and Fourmont [25] and Diambra et al. [26] reported that cement-stabilized soil reinforced with fibers has a significantly higher potential to expand when compared to cement-stabilized soil.

The one-way Analysis of Variance (ANOVA) test on the liquid limit result is given in Table 2. The result shows that the effects of sisal fibre on BCS were statistically significant (i.e., $F_{CAL} = 741.2866 > F_{CRIT} = 5.317655$).

The one-way Analysis of Variance (ANOVA) test on the plastic limit result is given in Table 2. The result shows that the effects of sisal fibre on BCS were statistically significant (i.e., $F_{CAL} = 94.8149 > F_{CRIT} = 5.317655$).

The one-way Analysis of Variance (ANOVA) test on the plasticity index result is given in Table 2. The result shows that the effects of sisal fibre on BCS were statistically significant (i.e., $F_{CAL} = 67.03882 > F_{CRIT} = 5.317655$).

Table 2. ANOVA for plasticity properties of black cotton soil mixed with sisal fibre

Property	Source of variance	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Liquid limit	Sisal fibre	1	741.2866	3.57E-09	5.317655	$F_{CAL} > F_{CRIT}$ SS
Plastic limit	Sisal fibre	1	94.8149	1.04E-05	5.317655	$F_{CAL} > F_{CRIT}$ SS
Plasticity index	Sisal fibre	1	67.03882	3.69E-05	5.317655	$F_{CAL} > F_{CRIT}$ SS

SS-Statistically Significant

3.2.2 *Effect of sisal fibre on compaction characteristics*

Maximum dry density

Figure 6 shows the variation of MDD with varying percentages of sisal fibre. The MDD initially increased from 1.55 Mg/m^3 at 0%, to 1.60 Mg/m^3 at 0.5% and thereafter decreased to 1.53 Mg/m^3 at 2% of fibre content. The reducing trend in MDD can be accredited to the sisal fibre having a low density as related to that of the soil and thus decreasing the normal unit weight of the solids in the mixture [35], [52]. The fibre now occupies more space than is supposed to be filled with soil, thus creating some voids in the mixture. The reduction may also be due to the fact that the sisal fibre failed to make a good bonding with the soil matrix as the sisal content increased, resulting in a decrease in the soil density. A similar observation is documented in Peddaiah et al. [54].

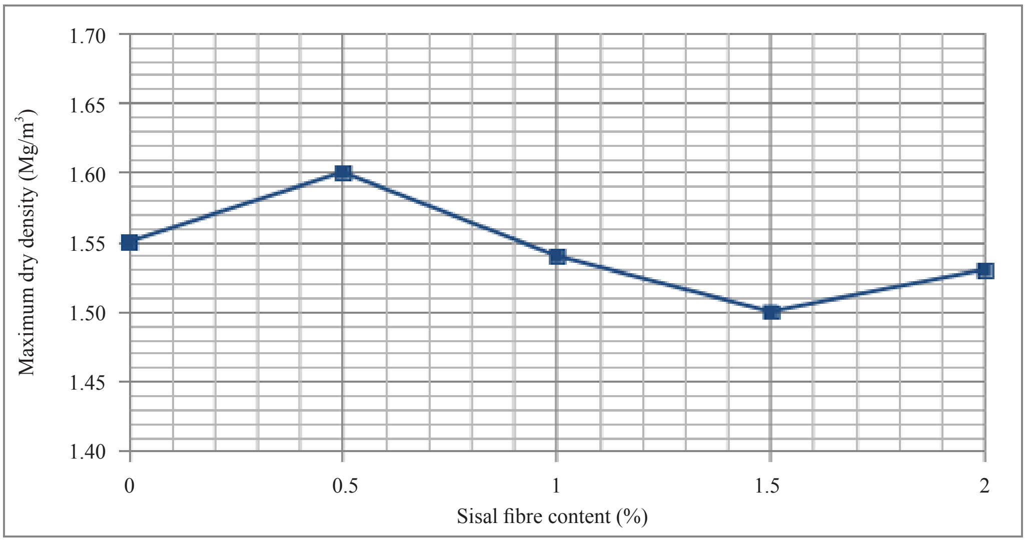

Figure 6. Variation of maximum dry density versus percentages of sisal fibre

Optimum moisture content

The variations in OMC of the soil with respect to percentages of sisal fibre are provided in Figure 7. The natural soil has an OMC of 19%, while for the modified soil at 0.5, 1, 1.5, and 2% sisal fibre, the OMC would be 19.5%, 22%, 24.5%, and 23% respectively. The results show that there was an increase in the optimum moisture content of the modified soil compared to the natural soil. This could be a result of the absorption of moisture by the fibre during the compaction process. As the fibre content in the soil increased, more water was needed to lubricate the soil surface leading to an increase in the OMC. This suggests that the fibre, which naturally had a high water absorption capacity, caused the increase in OMC. A similar statement was reported in literatures [35], [52].

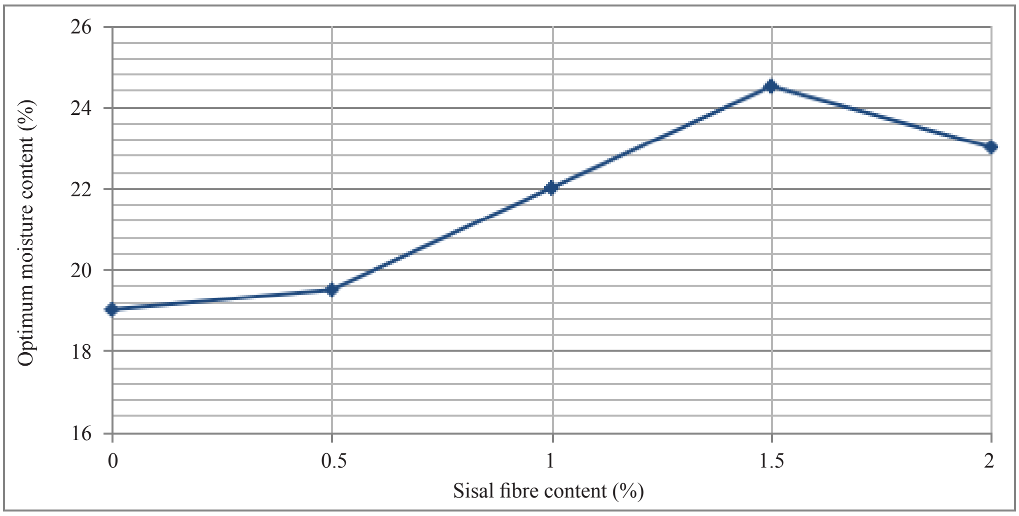

Figure 7. Variation of optimum moisture content versus percentages of sisal fibre

One-way Analysis of Variance (ANOVA) test on the MDD result is shown in Table 3. Results show that the effects of sisal fibre on MDD is not statistically significant ($F_{CAL} = 2.362 < F_{CRIT} = 5.318$).

One-way Analysis of Variance (ANOVA) test on the OMC result is shown in Table 3. Results show that the effects of sisal fibre on OMC is statistically significant ($F_{CAL} = 350.7107 > F_{CRIT} = 5.318$).

Table 3. One-way variance (ANOVA) for compaction characteristic of black cotton soil with sisal fibre mixtures

Property	Source of variance	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
MDD	Sisal fibre	1	2.362	0.162841	5.318	$F_{CAL} < F_{CRIT}$ NS
OMC	Sisal fibre	1	350.7107	6.83E-08	5.318	$F_{CAL} > F_{CRIT}$ SS

NS = Not Statistically Significant, SS = Statistically Significant

3.2.3 *Unconfined compressive strength*

Effect of sisal fibre on unconfined compressive strength

Daniel and Wu [55] as well as Rowe et al. [43] suggested an arbitrary lowest UCS value of 200 kN/m^2 as a requirement for soil to be used as liner and cover to withstand the bearing stress in the landfill. The inclusion of sisal fibre was done at 0.5, 1, 1.5, and 2% with the length of sisal fibre at 1 cm. Samples were compacted at OMC-2, OMC,

OMC+2, and OMC+4 relative to OMC of compaction.

Generally, UCS values initially increased from their natural values for all MWC considered to a maximum record high at 0.5% sisal fibre then progressively decreased up to 2% sisal fibre content (see Figure 8). The initial increase may be associated with the increase in frictional resistance between the soil and the fibre within the soil structure. Related researches reported similar findings [31], [52], [54], [56]. Bo et al. [44] who worked with glass fibres found out that as the fibre content in the modified soil increase, higher interfacial friction between the fibre and the soil particle is formed which lead to an increase in both the compressive and tensile strength of the treated soil. The decrease in the UCS values beyond 0.5% sisal fibre content could be a result of a reduction in the friction developed between the soil and the reinforcing material with a further increase in the sisal fibre content [35], [52], [57]. Prabakar and Siridihar [58] also concluded that the inclusion of fibre exceeding 0.75% will lead to a decrease in the shear strength. Anil et al. [31] reported in their studies that a decrease in the density of the modified soil with fibre leads to a decrease in the UCS of the soil. This shows that as the fibre content increased above 0.5%, it tends to reduce the bonding between the soil and the fibre. Thus field application should ensure that an optimal quantity of sisal fibre is added to the soil during improvement for waste containment application to withstand the bearing stress in the landfill.

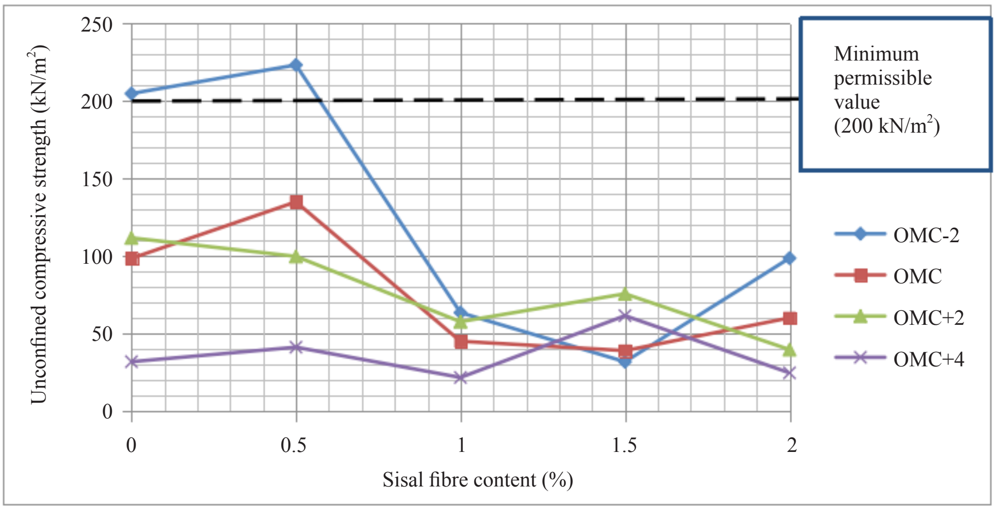

Figure 8. Effect of sisal fibre on unconfined compressive strength

Effect of MWC on UCS

The graphical relationship between UCS and MWC is presented in Figure 9. The UCS values generally lessened with increase in MWC. The decline could be a result of the reduction in the friction developed between the soil and the reinforcing material with increasing MWC [47]. Based on the recorded result, it can be said that an increase in water within the soil matric tends to disintegrate the soil particle thereby reducing the strength of the soil. Similar findings were reported by Amadi [59] and Oluremi [60]. Ramash and Sivapullaiah [61] in their study on the influence of MWC on soil stabilized with lime, reported that the UCS values decreased with an increase in the MWC. The decrease in UCS values was due to the increase in the distance between the soil particles caused by a higher quantity of water in the soil. Similar behaviour was reported by Nethravath et al. [62]. Table 4 gives the Two-way ANOVA which was statistically satisfactory.

A two-way Analysis of Variance (ANOVA) test on the UCS result is given in Table 4. The result shows that the effects of moisture content and sisal fibre content on BCS were statistically significant (i.e., $F_{CAL} = 4.242055 > F_{CRIT} = 3.490295$) for moisture content and ($F_{CAL} = 3.554646 > F_{CRIT} = 3.259167$) for sisal fibre content. The influence of moisture content is more noticeable when compared with that of sisal fibre content.

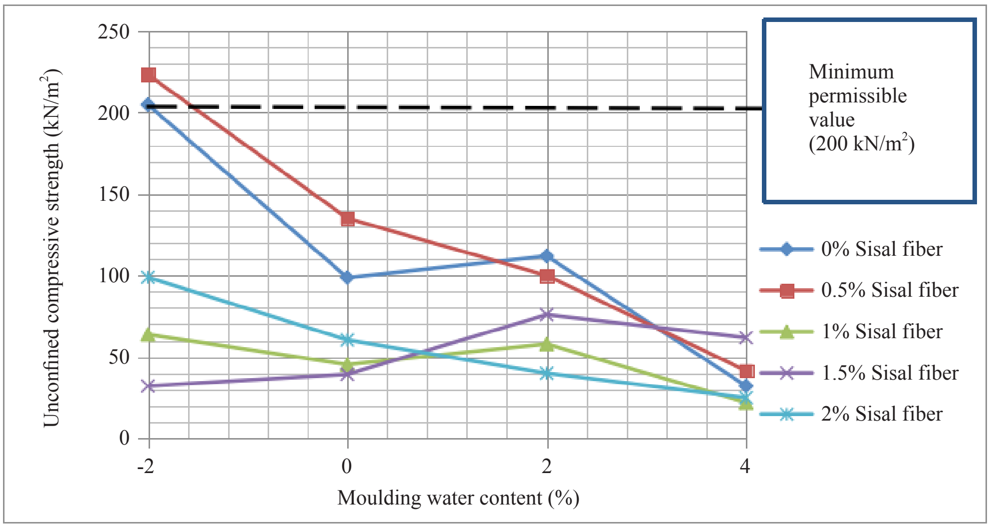

Figure 9. Plot of moulding water content versus UCS

Table 4. Two-way variance (ANOVA) for the effect of Moulding water content on UCS

Property	Source of variance	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
UCS	Moisture content	3	4.242055	0.029246	3.490295	$F_{CAL} > F_{CRIT}$ SS
	Sisal fibre	4	3.554646	0.039103	3.259167	$F_{CAL} > F_{CRIT}$ SS

SS-Statistically Significant

3.2.4 *Volumetric shrinkage*

Effect of sisal fibre on the volumetric shrinkage

The fibre was added to the soil at a stepped concentration of 0, 0.5, 1, 1.5, and 2% sisal fibre content having an approximate length of 1 cm. The shrinkage values were taken at MWC of OMC-2, OMC, OMC+2, and OMC+4.

The graphical relationship between volumetric shrinkage and MWC is presented in Figure 10. It was documented that the Volumetric Shrinkage of the Soil (VSS) significantly decreased with an increase in fibre content. The progressive decline could be linked to the fact that sisal fibre stiffens the soil and the addition of more fibre leads to the adsorption of more water leading to a reduction in the VSS [35], [52]. Also, the reduction in the VSS with an increase in sisal fibre content could be a result of the reduction in the swelling potential and desiccation cracking of the modified soil. Similar observations were made by Ehrlich el al. [38]. Bo et al. [44] reported that the addition of fibers to soil can aid in mitigating the expansion deformation of the clay soil, thus fibre has a good influence on suppressing the expansion of clay soils.

Effect of MWC on the volumetric shrinkage

The relationship between volumetric shrinkage and MWC for the specimens is shown in Figure 11. Volumetric shrinkage strain increased with increasing MWC. The increase in VSS values was due to an increase in the distance between the soil particles caused by a higher quantity of water in the soil. Similar behaviour was reported by Nethravath et al. [62]. However, with higher sisal fibre content the VSS values decreased. The decrease is a result of an increment in the soil cracking and swelling resistance [38]. A maximum acceptable volumetric shrinkage value of 4% was recorded at MWC of OMC-2 and OMC treated with 1 to 2% sisal fibre. At moulding water content of OMC+2, the maximum acceptable volumetric shrinkage value of 4% was recorded at 2% sisal fibre only. OMC+4 did not meet the regulatory maximum of 4% volumetric shrinkage for all sisal fibre mixes. In general, soil compacted at the dry side of OMC tends to favour and meet the requirement for use of the modified soil for landfill purposes. Hence, during fieldwork, it is very important to ensure that an optimal blend of both the sisal fibre and MWC are added to the soil to achieve the desired compacted landfill that will meet the requirement of both desiccation cracking and soil bearing pressure.

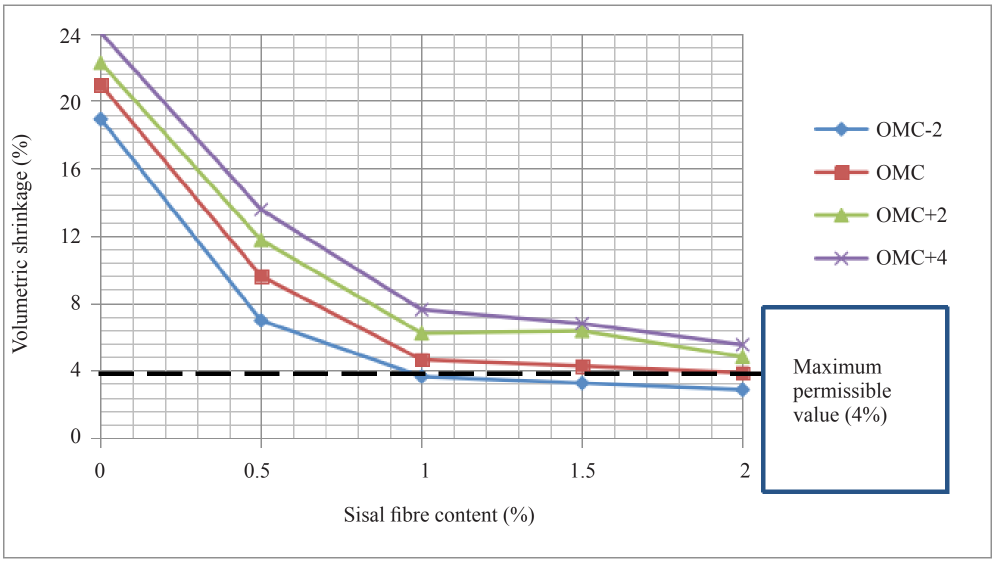

Figure 10. Effect of sisal fibre on volumetric shrinkage after 15 days

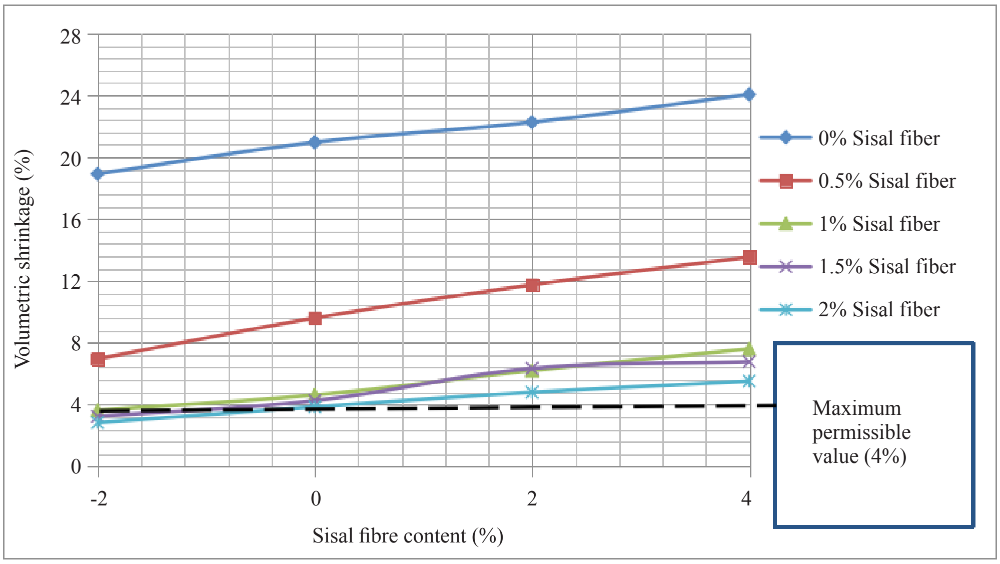

Figure 11. Effect of moulding water content on volumetric shrinkage after 15 days

A two-way Analysis of Variance (ANOVA) test on the VSS result is given in Table 5. The result shows that the effects of moisture content and sisal fibre content on BCS were statistically significant (i.e., F_{CAL} = 44.08524 > F_{CRIT} = 3.490295) for moisture content and (F_{CAL} = 439.2374 > F_{CRIT} = 3.259167) for sisal fibre content. The influence of sisal fibre content is more noticeable when compared with that of moisture content.

Table 5. Two-way variance (ANOVA) for the effect of sisal fiber on volumetric shrinkage

Property	Source of variance	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Volumetric shrinkage	Moisture content	3	44.08524	1.67E-06	3.490295	$F_{CAL} > F_{CRIT}$ SS
	Sisal fibre	4	439.2374	2.54E-12	3.259167	$F_{CAL} > F_{CRIT}$ SS

SS-Statistically Significant

3.2.5 *Regression Analysis*

Regression analysis for unconfined compressive strength, UCS

Past researches used regression models for geotechnical engineering applications [17], [54]. The model developed using UCS as a dependent factor and sisal fibre content, SF; plasticity index, PI; maximum dry density, MDD; optimum moisture content, OMC and moulding water content, MWC as independent factors is shown in equation 4. Results show a strong relationship between UCS and the compaction parameters (i.e., MDD and OMC) with positive coefficients, which designates that the MDD and OMC greatly influence the UCS values of the compacted soil. The possible explanation for this could be due to changes in the interfacial friction caused by the effect of sisal fibre in the soil that influences OMC and MDD, hence the UCS. Thus, increasing the MDD and OMC will lead to an increase in the UCS of the treated soil. The density of compaction in the field and the optimum amount of water added should be carefully monitored to achieve the desired results. In the case of SF, PI and MWC, a strong negative relationship was established with UCS. This implies that an increase in these variables reduces the UCS of the treated soil. Thus, an optimal quantity of SF is required during field compaction and specification to achieve the desired strength. In general, the MDD has shown to be more effective in predicting the UCS values of the soil when compared with the other independent variables because of its high coefficient (see equation 4).

$$UCS = -3980.68 - 40.57SF - 5.17PI + 2316.20MDD + 31.60OMC - 13.28MWC \tag{4}$$

$$R^2 = 0.54$$

Regression analysis for volumetric shrinkage strain, VSS

The model developed using VSS as a dependent factor and sisal fibre content, SF; plasticity index, PI; maximum dry density, MDD; optimum moisture content, OMC and moulding water content, MWC as independent factors is shown in equation 5. Results show a strong connection between VSS and MDD; MWC with positive coefficients which designates that the MDD and MWC greatly influence the UCS values of the compacted soil. Thus it implies that an increase in MDD and MWC will lead to a corresponding increase in VSS of the treated soil. In the case of SF, PI, and OMC, all show negative coefficients. As these variables with negative coefficients increased, the VSS of the treated soil decreased. In general, all these variables should be carefully monitored during field application to achieve a reduction in the swelling potential and desiccation cracking of the modified soil.

$$VSS = -5.11 - 5.1SF - 0.57PI + 28.26MDD - 0.39OMC + 0.73MWC \tag{5}$$

$$R^2 = 0.989$$

4. Conclusions

Based on the AASHTO and USCS classifications, the study classified the BCS as A-7-6 (25) with low to moderate plastic clay (CL), the following conclusions were drawn:

1. The liquid limit of BCS initially increased from its natural value of 43.4% to the highest value of 55.9% at 1% sisal fibre content (i.e., 50.12% increment), and subsequently declined to the least value of 49.4% at 2% sisal fibre content. Plastic limits are reduced with an increase in the percentages of sisal fibre. In the case of the plasticity index, an initial increase was recorded and thereafter decreased with an increase in sisal fibre content.

2. The MDD initially increased from 1.55 Mg/m^3 at 0%, to 1.60 Mg/m^3 at 0.5% and thereafter decreased to 1.53 Mg/m^3 at 2% of fibre content, while OMC increased from its natural value up to 1.5% sisal fibre and thereafter decreased.

3. Generally, UCS values initially increased from their natural values for all MWC considered to a maximum record high at 0.5% sisal fibre then progressively decreased up to 2% sisal fibre content. VSS significantly decreased with an increase in fibre content.

4. Based on the results obtained, soil optimally treated with a maximum of 0.5% sisal fibre and compacted with OMC-2 met the governing minimum UCS value of 200 KN/m^2 and maximum volumetric shrinkage of 4%, thus recommended for use in a landfill application.

Conflict of interest

The authors declared that there is no personal or organisational conflict of interest.

References

[1] I. N. Obeta, C. C. Ikeagwuani, C. M. Attama, and J. Okafor, "Stability and durability of saw dust ash-lime stabilised black cotton soil," *Nigerian Journal of Technology*, vol. 38, no.1, pp. 75-80, 2019.

[2] A. B. D. Oluyemi and A. O. Owolabi, "Engineering characteristics of soils from major borrow pits in Akure Town, Ondo State, Nigeria," *Journal of Science and Technology Research*, vol. 2, pp. 57-63, 2003.

[3] A. Bolarinwa and S. A. Ola, "A review of the major problem soils in Nigeria," *FUOYE Journal of Engineering and Technology*, vol. 1, no.1, pp. 20-25, 2016.

[4] P. S. Neeladharan, "Stabilization of soil by using marble dust with sodium silicate as binder," *International Journal of Advanced Research Trends in Engineering and Technology*, vol. 5, no. 5, pp. 45-49, 2018.

[5] A. B. Salahudeen and J. A. Sadeeq,"California bearing ratio prediction of modified black clay using artificial neural networks," In Proceedings of West Africa Built Environment Research (WABER) Conference, 5-7 August 2019, Accra, Ghana, 2019, pp. 268-281.

[6] K. J. Osinubi, P. Yohanna, and A. O. Eberemu, "Cement modification of tropical black clay using iron ore tailing as admixture," *Journal of Transportation Geotechnics*, vol. 5, pp. 35-49, 2015.

[7] R. M. Plait, "Determination of swelling pressure of black cotton soil-A method," In Proceedings of the third international conference on soil mechanics and foundation engineering. Zurich, Switzerland, 16th-27th August, 1953, vol. 1, pp. 170-172.

[8] H. B. Seed, R. J. Woodward, and R. Lundgren, "Prediction of swelling potential for compacted clays," *Journal of the Soil Mechanics and Foundations Division*, vol. 88, no. 3, pp. 53-87, 1962.

[9] R. G. Venkatappa and G. V. Ramana, "State of the art report: Lime-soil stabilization," Indian Roads Congress-Highway Research Board, Special Publication No.1. 2000.

[10] R. K. Katti, A. R. Katti, and D. R. Katti, "Behaviour of saturated expansive soil and control methods," CBIP, Oxford and IBH, New Delhi. 2002.

[11] IS2720-41, "Indian standard, Methods of test for soils, Part 41 Measurement of swelling pressure of soils," 1977 (reaffirmed 2002).

[12] IS1498-1970, "Indian standard, classification and identification of soils for general engineering purposes," Bureau of Indian Standards, 1970 (reaffirmed 2007).

[13] K. Kamil and D. Saniye, "Measurement of swelling pressure: Direct method versus indirect methods," *Canadian*

Geotechnical Journal, vol. 48, no. 3, pp. 354-364, 2011.
[14] K. Watanabe and G. R. Venkatappa, "Construction and field measurement of high-speed railway test embankment built on Indian expansive soil, black cotton soil," *Soils and Foundations*, vol. 61, no. 1, pp. 218-238, 2021.
[15] S. A. Ola, "The geotechnical properties of black cotton soils of northeastern Nigeria," in *Tropical Soils of Nigeria in Engineering Practice*, S. A. Ola Ed. Balkama, Rotterdam, 1983, pp. 85-101.
[16] K. J. Osinubi, M. A. Oyelakin, and A. O. Eberemu, "Improvement of black cotton soil with ordinary portland cement-locust bean waste ash blend," *Electronic Journal of Geotechnical Engineering*, vol. 16, no. 1, pp. 619-627, 2011.
[17] P. Yohanna, J. R. Oluremi, A. O. Eberemu, K. J. Osinubi, and J. E. Sani, "Reliability assessment of bearing capacity of cement-iron ore tailing blend black cotton soil for strip foundation," *Geological and Geotechnical Engineering*, vol. 37, no. 2, pp. 915-929, 2019.
[18] S. J. R. Basha and R. P. Kavin, "Stabilization of soft subgrade and embankment soil by using alkaline solution and reinforcing with sisal fibre," *International Journal and Magazine of Engineering, Technology, Management and Research*, vol. 3, no. 8, pp. 704-721, 2016.
[19] G. Sridevi, M. Rama Rao, J. Padmini, B. Priyanka, and M. Swapna, "Effect of lime Stabilized fly ash layer on CBR values of black cotton soil," In Proceedings of Indian Geotechnical Conference, 2005, pp. 305-319.
[20] Y. S. Kim, T. Q. Tran, G. O. Kang, and T. M. Do, "Stabilization of a residual granitic soil using various new green binders," *Construction and Building Materials*, vol. 223, pp. 724-735, 2019.
[21] T. T. Le, S. S. Park, J. C. Lee, and D. E. Lee, "Strength characteristics of spent coffee grounds and oyster shells cemented with GGBS-based alkaline-activated materials," *Construction and Building Materials*, vol. 267, 120986, 2021.
[22] P. Yohanna, T. S. Ijimdiya, O. E. Adrian, and J. O. Kolawole, "Diffusion study of municipal solid waste contaminants in compacted lateritic soil treated with bacillus coagulans," *Japanese Geotechnical Society Special Publication*, vol. 9, no. 7, pp. 343-350, 2021.
[23] P. Yohanna, O. E. Adrian, T. S. Ijimdiya, and J. O. Kolawole, "The effect of bacillus coagulans and moulding water content on the unconfined compressive strength of lateritic soil," *Engineering Science and Technology*, vol. 3, no. 1, pp. 69-83, 2022.
[24] J. O. Kolawole, O. E. Adrian, T. S. Ijimdiya, and P. Yohanna, "Bio-cementation of lateritic soil using microbial-induced calcium carbonate precipitation techniques for use as road and embankment materials," In Conference of the Arabian Journal of Geosciences (CAJG 2019), 2019, pp. 115-119.
[25] E. Ibrahim and S. Fourmont, "Behavior of sand reinforced with fibers, soil stress-strain behavior: Measurement, modeling and analysis," In Proceedings of the Geotechnical Symposium in Roma, Rome, Italy, 2006, pp. 807-818.
[26] A. Diambra, E. Ibraim, W. Muir, and A. R. Russell, "Fibre reinforced sands: experiments and modelling," *Geotextiles and Geomembranes*, vol. 28, no. 3, pp. 238-250, 2010.
[27] D. Mujah, H. Hazarika, F. Ahmad, N. Yasufuku, and K. Omine, "Development of ground improving geomaterial using recycled glass fibers," In Proceedings of the JSCE Annual Meeting and Conference, Ehime University, Matsuyama, Japan, September, 2011.
[28] D. Mujah, F. Ahmad, H. Hazarika, and A. Safari, "Evaluation of the mechanical properties of recycled glass fibers-derived three dimensional geomaterial for ground improvement," *Journal of Cleaner Production*, vol. 52, pp. 495-503, 2013.
[29] F. Ahmad, D. Mujah, H. Hazarika, and A. Safari, "Assessing the potential reuse of recycled glass fibre in problematic soil applications," *Journal of Cleaner Production*, vol. 35, pp. 102-107, 2012.
[30] S. S. Badami, "Stabilization of black cotton soil by random inclusion of sisal fibre," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 6, no. 2, pp. 1535-1542, 2017.
[31] A. K. Sharma, S. Prasannan, and S. Kolathayar, "Comparative study of sisal and PVA fiber for soil improvement," In Geo-Congress 2019: Soil Improvement. Reston, VA: American Society of Civil Engineers, 2019, pp. 298-304.
[32] R. Gobinath, I. I. Akinwumi, O. D. Afolayan, S. Karthikeyan, M. Manojkumar, S. Gowtham, and A. Manikandan, "Banana fibre-reinforcement of a soil stabilized with sodium silicate," *Silicon*, vol. 12, no. 2, pp. 357-363, 2020.
[33] J. Giridhar, Kishore, and R. M. V. G. K. Rao, "Moisture absorption characteristics of natural fibre composites," *Journal of reinforced plastics and composites*, vol. 5, no. 2, pp. 141-150, 1986.
[34] H. N. Ramesh, K. V. Manoj Krishna, and H. V. Mamatha, "Strength performance of lime and sodium hydroxide treated-coir fibre reinforced soil," In Proceedings of Indian Geotechnical Conference, 2011, pp. 523-525.
[35] J. E. Sani, R. K. Etim, and A. Joseph, "Compaction behaviour of lateritic soil-calcium chloride mixtures,"

Geotechnical and Geological Engineering, vol. 37, no. 4, pp. 2343-2362, 2019.
[36] N. C. Consoli, R. R. de Moraes, and L. Festugato, "Parameters controlling tensile and compressive strength of fiber-reinforced cemented soil," *Journal of Materials in Civil Engineering*, vol. 25, no. 10, pp. 1568-1573, 2012.
[37] A. A. S. Correia, P. J. V. Oliveira, and D. G. Custodio, "Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders," *Geotextiles and Geomembranes*, vol. 43, no. 2, pp. 97-106, 2015.
[38] M. Ehrlich, M. S. S. Almeida, D. Curcio, "Hydro-mechanical behavior of a lateritic fiber-soil composite as a waste containment liner," *Geotextile and Geomembranes*, vol. 47, no. 1, pp. 42-47, 2019.
[39] L. Festugato, E. Menger, F. Benezra, E. A. Kipper, and N. C. Consoli, "Fibre-reinforced cemented soils compressive and tensile strength assessment as a function of filament length," *Geotextiles and Geomembranes*, vol. 45, no. 1, pp. 77-82, 2017.
[40] A. Hamidi and M. Hooresfand, "Effect of fiber reinforcement on triaxial shear behavior of cement treated sand," *Geotextile and Geomembranes*, vol. 36, pp. 1-9, 2013.
[41] Q. Xue, H. J. Lu, Z. Z. Li, and L. Liu, "Cracking, water permeability and deformation of compacted clay liners improved by straw fiber," *Engineering Geology*, vol. 178, no. 21, pp. 82-90, 2014.
[42] O. P. J. Venda, A. A. S. Correia, J. M. N. P. C. Teles, and D. G. Custódio, "Effect of fibre type on the compressive and tensile strength of a soft soil chemically stabilised," *Geosynthetics International*, vol. 23, no. 3, pp. 171-182, 2016.
[43] R. K. Rowe, R. W. I. Brachman, M. S. Hosney, W. A. Take, and D. N. Arnepalli, "Insight into hydraulic conductivity testing of GCLs exhumed after 5 and 7 years in a cover," *Canadian Geotechnical Journal*, vol. 54, no. 8, pp. 1118-1138, 2017.
[44] B. Ruan, S. L. Zheng, J. D. Teng, H. Ding, and C. Ma, "Analysis on the triaxial shear behavior and microstructure of cement-stabilized clay reinforced with glass fibers," *Advances in Civil Engineering*, vol. 2020, 8842091, 2020.
[45] N. K. Sharma, S. K. Swain, and U. C. Sahoo, "Stabilization of a clayey soil with fly ash and lime: A micro level investigation," *Geotechnical and Geological Engineering*, vol. 30, no. 5, pp. 1197-1205, 2012.
[46] R. Sindhujha, and K. Muthukkumaran, "Behaviour of problematic soil stabilized with sisal fibers," *International Journal of Earth Science and Engineering*, vol. 9, no. 6, pp. 2867-2870, 2016.
[47] A. G. O. Moraes, M. R. Sierakowski, T. M. Abreu, and S. C. Amico, "Sodium borohydride as a protective agent for the alkaline treatment of sisal fibers for polymer composites," *Composite Interfaces*, vol. 18, no. 5, pp. 407-418. 2011.
[48] B. S. 1377, *Methods of Test for Soils for Civil Engineering Properties*. British Standard Institution: London, UK, 1990.
[49] B. S. 1924, *Methods of Testing for Stabilized Soils*. British Standards Institute: London, 1990.
[50] AASHTO, *Standard Specification for Transportation, Material and Methods of Sampling and Testing*, 14th ed., Amsterdam Association of State Highway and transportation official, Washington D.C., 1986.
[51] ASTM, *Annual Book of Standards*. American Society for Testing and Materials. Philadelphia. 1992, vol. 04.08.
[52] J. E. Sani, P. Yohanna, R. K. Etim, I. C. Attah, and F. Bayang, "Unconfined compressive strength of compacted lateritic soil treated with selected admixtures for geotechnical applications," *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 4, no. 2, pp. 801-815, 2019.
[53] A. T. Stephen, "Stabilization potential of bagasse ash on black cotton soil," Unpublished M.Sc. Thesis, Ahmadu Bello University, 2006.
[54] S. Peddaiah, A. Burman, and S. Sreedeep, "Experimental study on effect of waste plastic bottle strips in soil improvement," *Geotechnical and Geological Engineering*, vol. 36, no. 5, pp. 2907-2920, 2018.
[55] D. E. Daniel and Y. K. Wu, "Compacted clay liners and covers for arid sites," *Journal of Geotechnical Engineering*, vol. 119, no. 2, pp. 223-237, 1993.
[56] J. E. Sani, P. Yohanna, and I. A. Chukwujama, "Effect of rice husk ash admixed with treated sisal fibre on properties of lateritic soil as a road construction material," *Journal of King Saud University-Engineering Sciences*, vol. 32, no. 1, pp. 11-18, 2020.
[57] D. Das, D. Kaundinya, R. Sarkar, and B. Deb, "Shear strength enhancement of sandy soil using hair fibre," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 5, no. 5, pp. 8278-8283, 2016.
[58] J. Prabakar and R. S. Sridhar, "Effect of random inclusion of sisal fiber on strength behavior of soil," *Construction and Building Materials*, vol. 16, no. 2, pp. 123-131, 2002.
[59] A. A. Amadi, "Hydraulic Contaminant Transport Performance of Compacted Lateritic Soil-Bentonite Mixtures

Proposed as Waste Containment Barrier," Unpublished Ph.D Thesis, Civil Engineering Department, Ahmadu Bello University, Zaria, Nigeria, 2008.
[60] J. R. Oluremi, "Evaluation of Waste Wood Ash Treated Lateritic Soil for use in Municipal Solid Waste Containment Application," Unpublished doctoral dissertation, Ahmadu Bello University, Zaria, 2015.
[61] H. N. Ramash and P. V. Sivapullaiah, "Role of moulding water content in lime stabilization of soil," *Proceedings of the Institution of Civil Engineers-Ground Improvement*, vol. 164, no. 1, pp. 15-19, 2011.
[62] S. Nethravathi, H. N. Ramesh, B. C. Udayashankar, and L. Priya, "Effect of moulding water content on the strength behaviour of black cotton soil treated with bagasse ash and lime," *International Research Journal of Engineering and Technology*, vol. 5, no. 7, pp. 2163-2167, 2018.