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RESEARCH PAPER

Evaluation of bagasse ash treated lateritic soil as a potential barrier material in waste containment application

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Abstract Laboratory tests were conducted on a reddish-brown lateritic soil treated with up to 12 % bagasse ash to assess its suitability in waste containment barriers applications. Soil samples were prepared using four compaction energies (i.e. reduced Proctor, standard Proctor, West African Standard or 'intermediate' and modified Proctor) at −2, 0, 2 and 4 % moulding water content of the optimum moisture content (OMC). Index properties, hydraulic conductivity (*k*), volumetric shrinkage and unconfined compressive strength (UCS) tests were performed. Overall acceptable zones under which the material is suitable as a barrier material were obtained. Results recorded showed improved index properties; hydraulic conductivity and UCS with bagasse ash treatment up to 8 % at the OMC. Volumetric shrinkage strain increased with higher bagasse ash treatment. Based on the overall acceptable zone obtained, an 8 % optimal bagasse ash treatment of the natural lateritic soil makes it suitable for use in waste containment barrier application.

Keywords Bagasse ash · Compaction · Hydraulic conductivity · Lateritic soil · Liner · Unconfined compressive strength · Volumetric shrinkage

1 Introduction

Many communities in developing countries rely on surface water and groundwater as a primary source of drinking water of which a variety of threats to its quality exists. Rapid industrial development has increased hazardous waste generation several folds in developing countries. Heavy metals, organic compounds and other toxic effluents continue to be deliberately released into the environment by manufacturing, mining and oil firms. Streams and other sources of domestic water consumption, especially those in rural areas are now known to have recorded lethal levels of toxicity with attendant risks to human lives.

Discharge from textile companies is characterized by high concentration of caustic chemicals, resulting in high pH of the land, intense colouration derived from dyes, fibrous materials, toxic organic chemicals and heavy metals pollute land. Waste from the oil industry contains oil, grease and heavy metals, volatile organic compounds and all these pollute groundwater [24].

One good method of controlling/preventing groundwater contamination is to place the waste material in an engineered containment facility with a liner and cover (hydraulic barrier). The primary purpose of the liner system is to prevent/minimize the migration of leachate directly into the underlying soil during both the active disposal period as well as the post-closure or inactive period. The purpose of the cover system is to prevent the generation of leachate by minimizing the amount of precipitation percolating through the waste during the inactive (post-closure) period, provide containment and prevent physical dispersion by wind and water [54].

Sugar cane is a major raw material for sugar production. Bagasse is the residue obtained after the juice is extracted from the cane in the sugar milling industry. When bagasse is left in the open, it ferments and decays, which when inhaled in large doses can result in respiratory disease known as *bagassosis* [33]. It implies that there is a need for safe disposal of the pollutant. However, the availability of bagasse as a by-product of sugar production has made it an

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attractive fuel for the sugar industry and this practice tends to be the most economical method of disposal.

Bagasse ash is a by-product of the bagasse combustion process. It is considered a waste material and is stock piled, but the material is a pozzolan rich in amorphous silica. However, with increased strict enforcement of environmental regulations and the increasing cost of solid waste disposal, the sugar industry will be searching for beneficial ways to use its bagasse ash. Bagasse ash has been proved to be a good additive for some engineering works [44–46, 50, 51, 55].

Lateritic soils are pedogenic materials and they constitute a major group of residual soils formed under tropical and sub-tropical conditions. Ola [39] defined them as all products of tropical weathering with red, reddish-brown or dark-brown colour with or without nodule or concretions and generally (but not exclusively) found below hardened ferruginous crust or hardpan. They find use both as foundation and construction materials consequently; interest has developed in using lateritic soil treated with bagasse ash as a suitable hydraulic barrier (liner and cover). This application has the potential to use large quantities of bagasse ash generated and will be particularly advantageous to landfill operation in areas where sugar cane production is high.

This study was basically aimed at the evaluation of compacted lateritic soil treated with bagasse ash for use as a hydraulic barrier material in waste containment systems. The objectives were to investigate how the material could be compacted; at what compaction moisture the required hydraulic conductivity would be achieved; determine whether the compacted material has a low potential to shrink and crack; determine whether the compacted material has adequate shear strength and delineate an acceptable plane of compaction for each of the above property. Finally, providing an overall acceptable compaction plane under which the material will satisfy all the above property and be applicable for use in the field.

2 Background

A barrier system usually includes one or more of the following: liners, covers and slurry cut-off walls. Liners and covers are two main engineered components of a waste disposal system (e.g. landfills). The objective of placing each component is to prevent pollution of ground water with water containing contaminants leached from waste (leachate). The suitability of any material for construction of a liner depends on the following factors [18, 19, 23]:

(a) Hydraulic conductivity, which is a measure of the material's ability to provide containment of leachate. A low hydraulic conductivity (*k*) which is very important; and generally values not greater than 1×10^{-9} m/s are required for a liner material to be acceptable. This maximum value has been specified by the codes of various regulatory agencies [24, 56].

(b) Durability and resistance to weathering are the qualities of bonding in the material, which should be strong enough to withstand the destructive forces of environmental elements. Shrinkage cracking which is caused by desiccation should not be excessive. This is based on the work of several researchers [14, 29], on how desiccation induced cracking affect the hydraulic conductivity of compacted clay; particularly for waste containment covers which are exposed to the atmosphere where overburden stresses are low. Kleppe and Olson [29] in their work on desiccation studies of compacted slabs of clay revealed that major cracking which they defined as cracks greater than 10 mm wide occurred when volumetric shrinkage strains (VSS) in cylindrical specimens compacted to the same water content and dry density were greater than 4 % using the same material. Hence a maximum VSS of 4 % was suggested [19] because soils with minimal volumetric shrinkage during drying will have minimal potential to crack when dried and ultimately not undermine the hydraulic conductivity.

(c) Constructability (i.e. the material should be reasonably workable) in terms of placement and compaction under field condition. A minimum unconfined compressive strength (UCS) of 200 kPa was suggested, which is the lowest value for very stiff soils based on the work of some researchers [52].

(d) Compatibility with leachate, which means that the liner must maintain its strength and low permeability after prolonged contact with leachate solution and should have an absorptive attenuative capacity for critical pollutants such as heavy metals, etc.

Shackelford [54] reported that the following materials could be used in the construction of compacted clay liners: (1) natural soils (from borrow source), (2) blended soils or soil mixture, (3) amended or chemically stabilized clay soils. Several researchers [2, 3, 7, 13, 17, 21, 22, 31, 44, 47] have carried out studies with the listed materials in hydraulic barrier applications (waste containment facilities).

3 Materials and methods

3.1 Soil

The soil used in this study is a naturally reddish-brown with inclusion of white mottles lateritic soil obtained by the method of disturbed sampling from a borrow pit in Shika area of Zaria (Latitude 11°15′N and Longitude 7°45′E), Nigeria. A study of the geological and soil maps of Nigeria following [5, 9], respectively, shows that the samples taken belong to the group of ferruginous tropical soils derived from acid igneous and metamorphic rocks. Previous studies [41] on soils from this area have been shown to contain kaolinite as the dominant clay mineral. The soil is classified as A-7-6 (10) according to AASHTO soil classification system [1] and low plasticity clay (CL) according to the unified soil classification system [11].

3.2 Bagasse ash

The bagasse ash used in this study was prepared by collecting sugar cane residue, which was stacked in heaps and openly burnt. The burnt bagasse was left for 12–24 hours to ash at a temperature of 500–700 °C. The ash was then passed through BS No. 200 sieve with 75 μm aperture. The sieved ash was stored in air tight containers to avoid prehydration until usage. The bagasse ash was mixed with the soil to form four soil-bagasse ash mixtures in stepped increment of 4 % from 0 to 12 % by weight of dry soil. The oxide composition of bagasse ash used is given in Table 1.

3.3 Index properties

Laboratory tests were conducted to determine the index properties of the natural soil and soil-bagasse ash mixtures in accordance with British Standards [15, 16].

3.4 Compaction tests

Four compaction energies (i.e. namely reduced Proctor, standard Proctor, West African Standard or ‘intermediate’ and modified Proctor), simulating the variation in compactive efforts that might occur in the field, were used to prepare samples for tests involving moisture–density relationship, volumetric shrinkage, UCS and hydraulic conductivity. Air dried soil samples passing through BS sieve with 4.76 mm aperture mixed with 0, 4, 8 and 12 % bagasse ash by weight of dry soil were used. The reduced Proctor compaction energy is derived from 2.5 kg rammer falling through 300 mm onto three layers in a BS (Proctor) mould, each receiving 15 uniformly distributed blows; standard Proctor and modified Proctor compactions were carried out in accordance with British Standard [15]. West African Standard (WAS) or ‘intermediate’ compaction is the energy derived from a 4.5-kg rammer falling through 450 mm onto five layers, each receiving 10 blows.

Table 1 Oxide composition of bagasse ash

Oxide	Bagasse ash (%)
CaO	10.01
SiO_2	43.32
Al_2O_3	2.67
Fe_2O_3	1.17
MgO	1.85
Na_2O	0.04
K_2O	17.41
SO_3	5.89
Loss on ignition	10.37

Following [45]

3.5 Volumetric shrinkage

The volumetric shrinkage upon drying was measured by extruding cylindrical specimens, compacted using the four compactive efforts listed above on well-mixed soil–bagasse ash mixtures [with up to 12 % bagasse ash contents (BAC) by dry weight of soil] at four moulding water contents [i.e. 2 % dry of optimum (−2 %), optimum moisture content (OMC) (0 %), 2 % wet of optimum (+2 %) and 4 % wet of optimum (+4 %)] from the compaction moulds. The extruded cylindrical specimens were air dried on a laboratory table at a uniform temperature of 29 ± 2 °C and relative humidity values of 28 % until measurements became relatively constant. Three measurements of diameter and height for each specimen were taken every 5 days with the aid of a vernier calliper accurate to 0.05 mm. The average diameters and heights were used to compute the VSS.

3.6 Unconfined compressive strength

This test was carried out in accordance with British Standards [15]. Air dried soil-bagasse ash mixtures were compacted at moulding water contents −2, 0, +2 and +4 % of the OMC using four energy levels. After each compaction, the soil was extruded from the mould and sealed with double wrapping in polythene bags and kept in the humidity room for a period of 48 hours to allow for uniform moisture distribution and curing at a constant temperature of 25 ± 2 °C. After curing, the samples were trimmed into cylindrical undisturbed specimens, which were placed in a load frame machine driven strain controlled at 0.10 %/min until failure occurred. Three specimens were used for each test and the average result taken.

3.7 Hydraulic conductivity

This was measured using the rigid wall permeameter under falling head condition as recommended by Head [27]. A relatively short sample of 127 mm height was connected to a standpipe, which provided both the head of water and the means of measuring the quantity of water flowing through the sample. Compacted soil-bagasse ash samples at the different BAC (i.e. 0, 4, 8 and 12 %) and different moulding water contents (−2, 0, +2 and +4 % of the OMC, respectively) using four compactive efforts were immersed in a water tank for a minimum period of 24–48 hours to allow for full saturation and the samples were restrained from swelling vertically during saturation. The fully saturated test specimen was then connected to a permeant liquid (tap water). During permeation, test specimens were free to swell vertically (i.e. no vertical stress was applied). Hydraulic gradient ranged from 5 to 15. Tests lasted for 24–48 hours and were only discontinued when steady flows were established (i.e. when there was no statistically significant trend in hydraulic conductivity over time).

4 Discussion of test results

4.1 Index properties

The particle size distribution curves of the soils used are shown in Fig. 1, and a summary of the index properties is given in Table 2.

The liquid limit (LL) of the soils decreased with higher bagasse ash treatment, while the plastic limit (PL) increased resulting in a decrease in plasticity index (PI) from 24 to 9 % for bagasse ash treatment up to 12 %. Linear shrinkage (LS) also decreased with higher bagasse ash content. The particle size curves show that 77.6 % of the particle sizes are greater than 0.0042 mm, 84.5 % greater than 0.0045 mm, 85.4 % greater than 0.0045 mm and 88.8 % greater than 0.0046 mm for 0, 4, 8 and 12 % bagasse ash treatments, respectively. These changes were probably due to physico-chemical reactions (i.e. cation exchange), that depended on particle surface ion hydration and interparticle attractive forces [36]. These results are consistent with those reported by other researchers [28, 38, 49]. The increase in particle size as well as decrease in PI and LL with higher bagasse ash treatment shows that the engineering properties of the soils improved.

Table 2 Properties of the natural and treated soils

Property	Bagasse ash content, %			
	0	4	8	12
Natural moisture content, %	6.5	–	–	–
Liquid limit, %	42	39.5	37.3	34.3
Plastic limit, %	18	19	23	25
Plasticity index, %	24	20.5	14.3	9.3
Linear shrinkage, %	6	5.5	4.7	3.5
Percentage passing BS no. 200 sieve	56.7	60.1	64.4	65.5
AASHTO classification	A-7-6 (10)	A-7-6 (10)	A-7-6 (10)	A-7-6 (5)
USCS classification	CL	CL	CL	CL
Specific gravity	2.61	2.53	2.44	2.35
Maximum dry density, Mg/m^3				
Reduced Proctor	1.69	1.7	1.66	1.61
Standard Proctor	1.75	1.72	1.71	1.67
West African Standard	1.81	1.79	1.77	1.75
Modified Proctor	1.93	1.92	1.9	1.86
Optimum moisture content, %				
Reduced Proctor	18.5	19	20.2	20.5
Standard Proctor	16	17	18.3	19.8
West African Standard	15.7	16.5	17.2	18.1
Modified Proctor	12.9	13.8	14.8	15.7
pH value	6.7			
Colour	Reddish brown			
Dominant clay mineral	Kaolinite			

Reduced Proctor: 336.4 kJ/m^3 of compaction energy or 55.56 % of standard Proctor, standard Proctor 605.9 kJ/m^3 of compaction energy, West African Standard 1,009.2 kJ/m^3 of compaction energy, modified Proctor: 2,723.5 kJ/m^3 of compaction energy

AASHTO American Association of State Highway and Transport Officials, *USCS* unified soil classification system

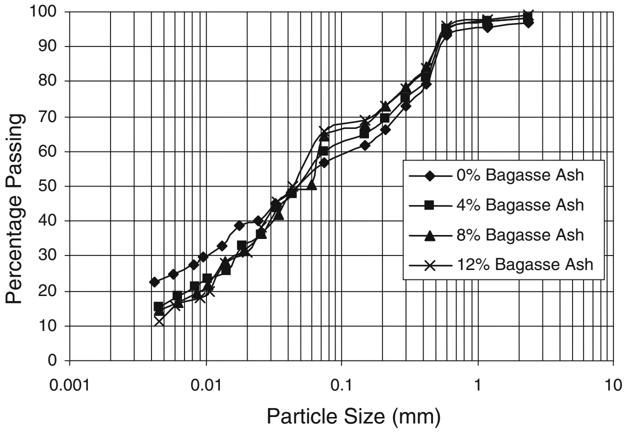

Fig. 1 Particle size distribution curves for the natural and stabilized soils

4.2 Compaction characteristics

The effects of bagasse ash content on the maximum dry density (MDD) and OMC of the lateritic soil-bagasse ash mixtures are shown in Fig. 2. The MDD generally decreased with higher bagasse ash treatment up to 12 % for all compactive efforts used. This was probably due to the initial simultaneous flocculation and agglomeration of

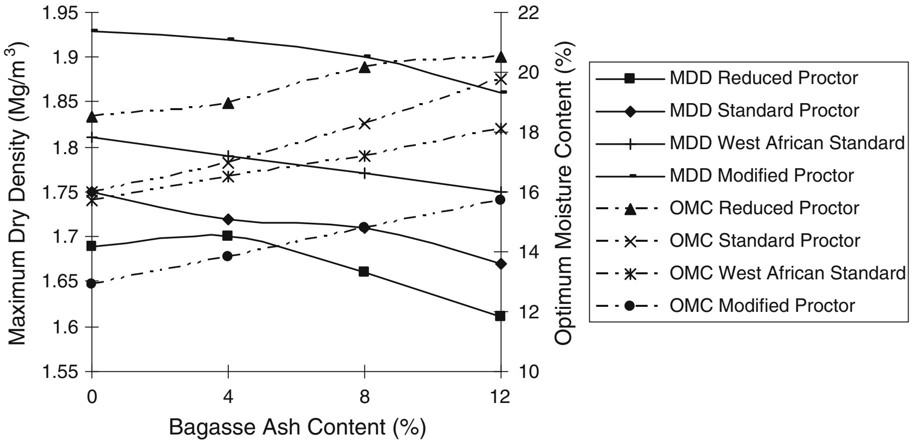

Fig. 2 Variation of maximum dry density and optimum moisture content with bagasse ash content

clay-sized particles caused by cation exchange leading to increase in volume and decrease in dry density [30]. Also, this was due to the comparatively low specific gravity value of 2.20 of the bagasse ash compared to that of the soil which is 2.61. The OMC increased with higher bagasse ash treatment up to 12 % for all compactive efforts. The OMC ranged from 18.5 to 20.5, 16 to 19.8, 15.7 to 18.1 and 12.9 to 15.7 % from the least to the highest compactive effort, respectively. This was due to the increase in fines content because of inclusion of bagasse ash with larger surface area that required more water to react. It could also be due to the larger amounts of water required for the hydration of the bagasse ash. These results are in agreement with those reported by [28, 38, 48, 49].

4.3 Hydraulic conductivity

The variation of hydraulic conductivity with compaction moulding water content for soils with different BAC is shown in Fig. 3. Hydraulic conductivity generally decreased with higher moulding water content. Compaction with higher moulding water contents resulted in soils that were devoid of macro-pores which conduct flow. The higher water content deflocculated the particle structure of the soils thus reducing voids; consequently, the arrangement of individual particles influenced by moulding water content controlled the hydraulic conductivity [4, 32]. Furthermore, soft wet clods of soil are easier to remould resulting in smaller interclub voids and hence lower hydraulic conductivity [12, 25, 37, 40]. This result is consistent with those reported by other researchers [10, 30, 42, 53].

For the natural soil, the hydraulic conductivity values recorded for all samples compacted at moulding water contents in the range −2 to +4 % of the OMC with the modified Proctor and West African Standard energies are less than the regulatory 1×10^{-9} m/s (see Fig. 3a). The regulatory hydraulic conductivity value was obtained at 15.1 and 18.5 % moulding water contents for samples compacted with the standard Proctor and reduced Proctor efforts, respectively. At 4 % bagasse ash treatment, all samples compacted at moulding water contents ranging from −2 to +4 % of the OMC with modified Proctor, West African Standard and standard Proctor efforts recorded hydraulic conductivity values less than the regulatory 1×10^{-9} m/s (see Fig. 3b). The maximum permissible hydraulic conductivity of 1×10^{-9} m/s was obtained at 18.5 % moulding water content for samples compacted with the reduced Proctor effort.

It was observed that at 8 % bagasse ash treatment, all samples compacted with moulding water contents in the range −2 to +4 % of the OMC for modified Proctor, West African Standard and standard Proctor efforts recorded hydraulic conductivity values less than 1×10^{-9} m/s. The maximum permissible hydraulic conductivity of 1×10^{-9} m/s was obtained at 19.7 % moulding water content for samples compacted with the reduced Proctor effort (see Fig. 3c). At 12 % bagasse ash treatment, all samples compacted with moulding water contents in the range −2 to +4 % of the OMC for modified Proctor, West African Standard and standard Proctor efforts recorded hydraulic conductivity values less than 1×10^{-9} m/s. The maximum hydraulic conductivity of 1×10^{-9} m/s was obtained at 19.2 % moulding water content for reduced Proctor effort (see Fig. 3d).

Generally, hydraulic conductivity decreased with higher compactive effort for all bagasse ash treatments. This was due to increased penetration by the compaction rammer on soil surface resulting in closer alignment of particles along the failure surface thus, yielding decreased frequency of large voids that could conduct flow.

The effect of bagasse ash content on hydraulic conductivity for the various compactive efforts at the OMC is

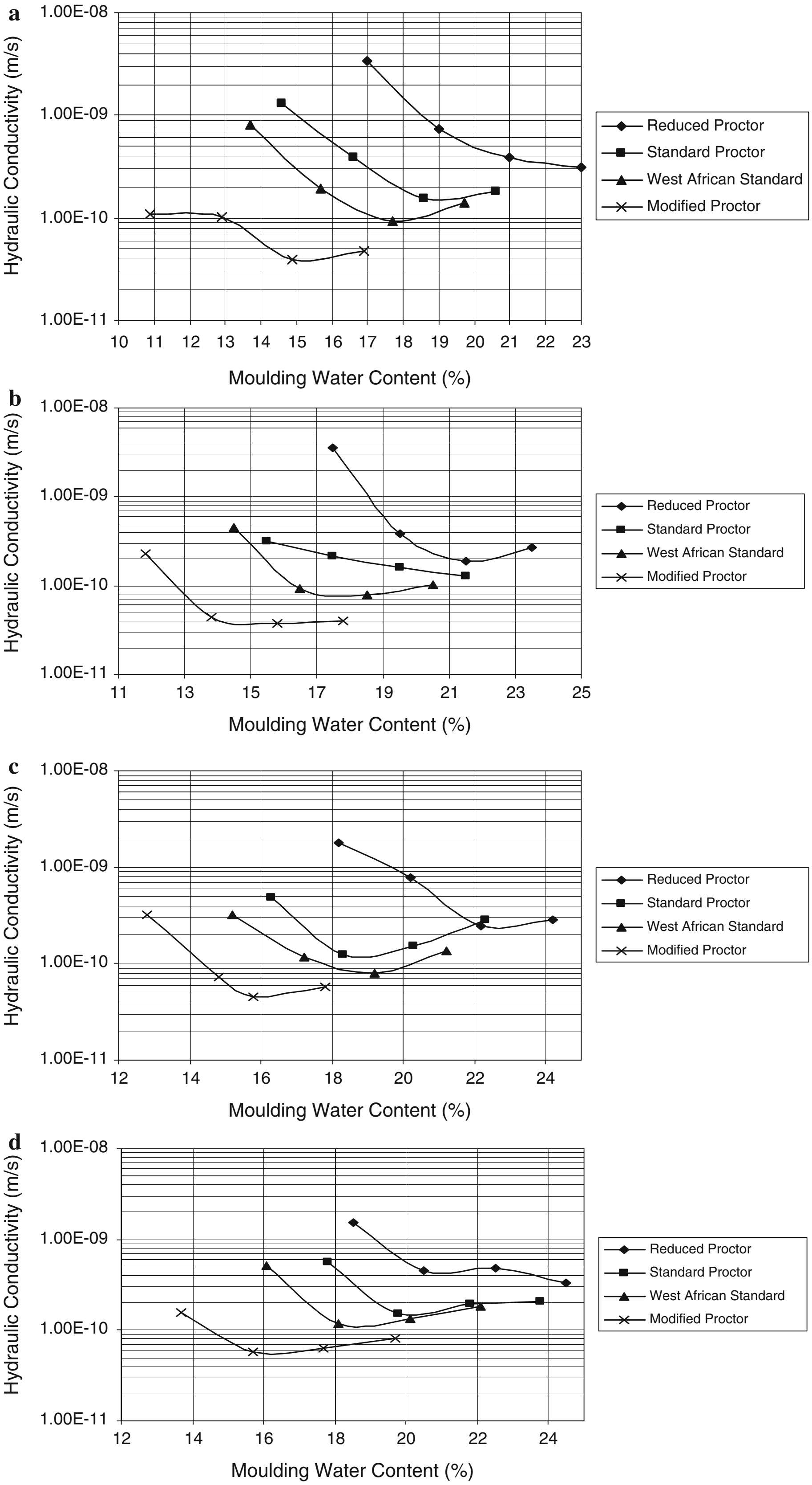

Fig. 3 Variation of hydraulic conductivity with moulding water content for **a** natural soil, **b** 4 % BAC, **c** 8 % BAC, **d** 12 % BAC

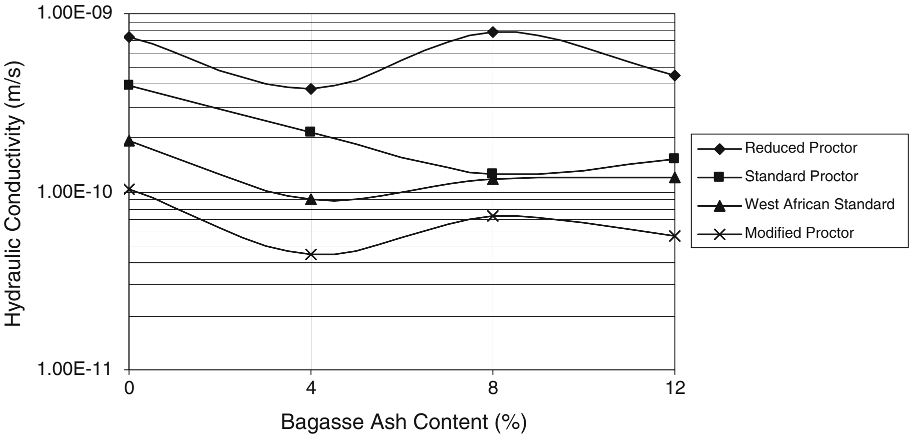

Fig. 4 Variation of hydraulic conductivity with bagasse ash content at optimum moisture content effort

shown in Fig. 4. Generally, the trend is that of an initial decrease to minimum values and subsequent increases in hydraulic conductivity values.

The initial decrease in hydraulic conductivity was probably due to the reduction in pore spaces as the fines from the bagasse ash filled the voids thus reducing water flow. It could also be due to cation exchange reactions between bagasse ash and the soil [10, 30]. On the other hand, the increase in hydraulic conductivity could be due to the presence of excess bagasse ash that would have changed the soil matrix leading to increased flocculation. A reported minimum hydraulic conductivity value for lateritic soil treated with 8 % bagasse ash indicating that optimum values would occur between 4 and 8 % bagasse ash treatment was reported [49].

4.4 Unconfined compressive strength

The variation of UCS with moulding water content is shown in Fig. 5. The UCS reduced with higher moulding water content for all cases of bagasse ash treatment. The main factors responsible for the strength of a soil are the cohesion and frictional resistance between the soil particles in contact. As the moulding water increased, the soil fabric was increasingly deflocculated thus, reducing the shear resistance. Furthermore, higher water content resulted in loss of cementation between the particles therefore leading to loss in strength due to reduced cohesive resistance.

For the natural soil, samples compacted at moulding water contents in the range −2 to +4 % of the OMC for modified Proctor effort recorded UCS values greater than the minimum 200 kPa required for liners (see Fig. 5a). This minimum value was obtained at moulding water contents of 19.3, 20.96 and 20.96 % for samples compacted at West African Standard, standard Proctor and reduced Proctor efforts, respectively. At 4 % bagasse ash treatment, all samples compacted at moulding water contents in the range −2 to +4 % of the OMC at the modified Proctor and West African Standard energies recorded UCS values greater than 200 kPa; at the standard Proctor and reduced Proctor compactive efforts, the regulatory minimum UCS values were obtained at 21.48 and 22.6 % moulding water contents, respectively (see Fig. 5b).

For 8 % bagasse ash treatment, all samples compacted at moulding water contents in the range −2 to +4 % of the OMC had UCS values greater than 200 kPa; minimum 200 kPa values were obtained at 21.8 % moulding water content for samples compacted at the energies of the standard Proctor and reduced Proctor (see Fig. 5c). At 12 % bagasse ash treatment, it was observed that UCS values greater than 200 kPa were recorded for all samples compacted at moulding water contents in the range −2 to +4 % of OMC for modified Proctor and West African Standard efforts. Minimum UCS values were obtained at 23.8 and 24.4 % moulding water contents for samples prepared at standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 5d). These results are consistent with those reported [8, 43] although fly ash and blast furnace slag, respectively, were used. Generally, the UCS increased with higher compactive effort due to closer packing of the soil fabric that increased the bonding forces.

The effect of bagasse ash content on UCS for the various compactive efforts at the OMC is shown in Fig. 6. Results obtained indicate that irrespective of the compactive effort employed to prepare samples at the OMC, the UCS increased with higher bagasse ash content up to 8 %, which is in agreement with the results reported by other researchers [38, 51].

The increase in strength with higher bagasse ash content up to 8 % can be attributed mainly to the increase in the pH value of the soil water as a result of the partial dissociation of calcium hydroxide. The calcium ions combined with the

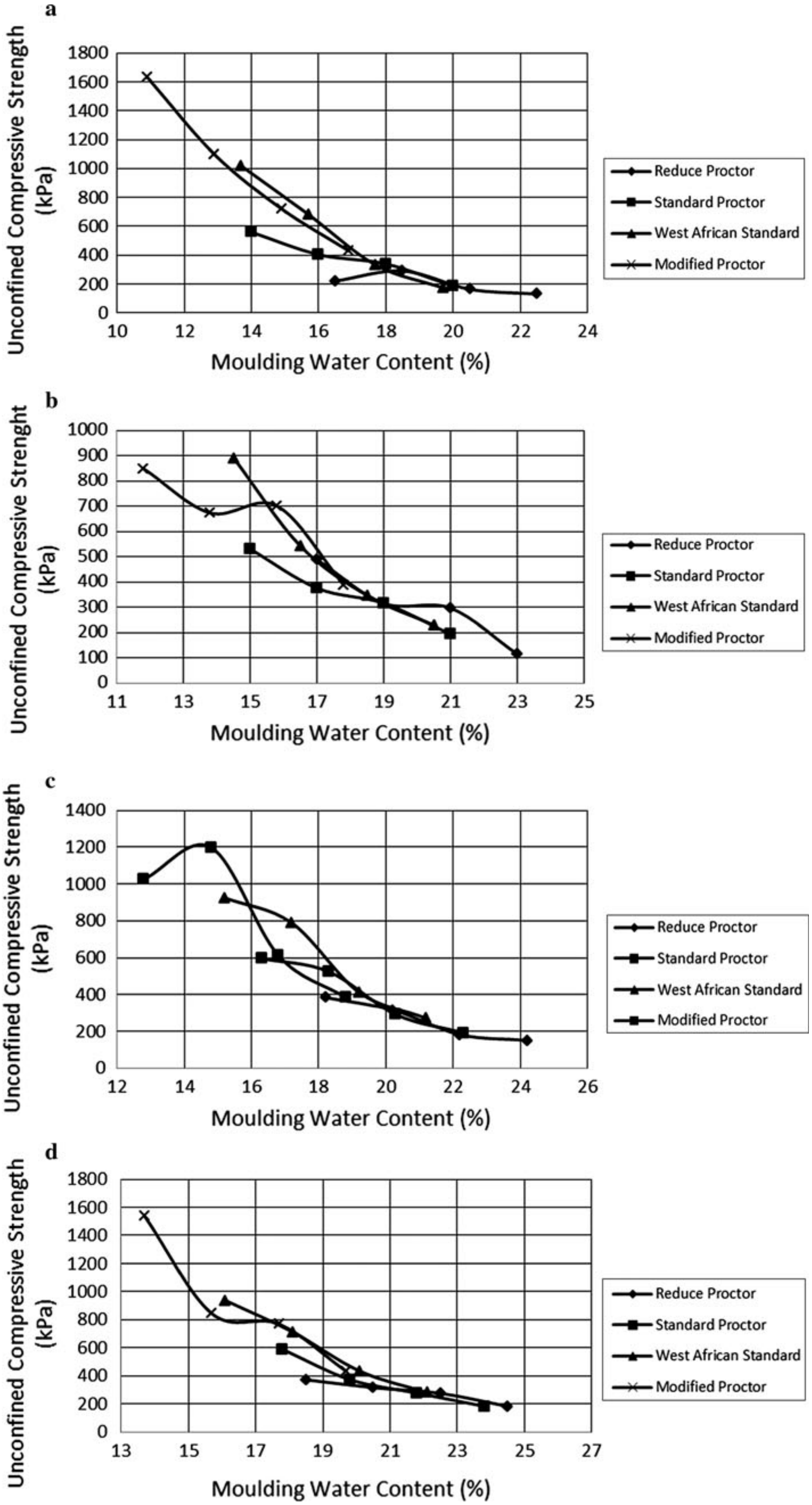

Fig. 5 Variation of unconfined compressive strength with moulding water content for **a** natural soil, **b** 4 % BAC, **c** 8 % BAC, **d** 12 % BAC

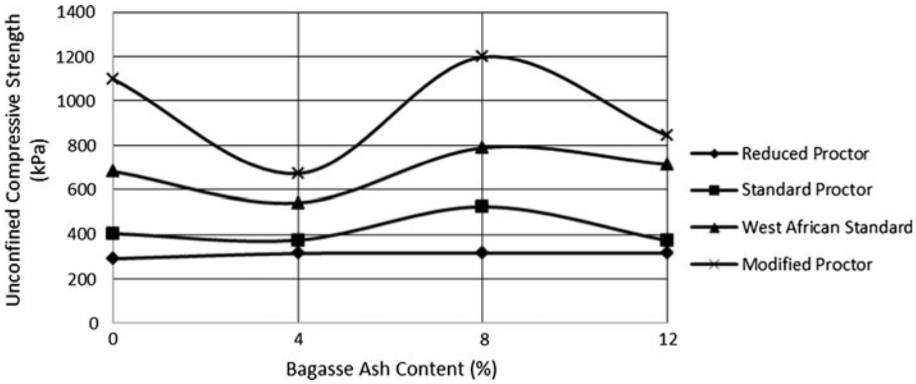

Fig. 6 Variation of unconfined compressive strength with bagasse ash content at the optimum moisture content

reactive silica or alumina, or both when they were present in the soil to from insoluble calcium silicates or aluminates and other pozzolanic products from time-dependent reactions. These pozzolanic products bonded together the clay particles or clusters of clay particles (or clay minerals) and created a new bonded, stronger matrix of soil [10, 34, 35, 57]. At 10 % bagasse treatment, the UCS values reduced for samples compacted at the different energies. The increase in UCS between 8 and 10 % could have been due to excess bagasse ash content being available for the pozzolanic reaction thereby, changing the soil matrix by altering the soil into a more friable state (less clayey) thus resulting in reduction in UCS.

4.5 Volumetric shrinkage

The variation of VSS with moulding water content is shown in Fig. 7. Generally, VSS increased with higher moulding water content. Specimens compacted at higher moulding water content shrunk more during drying, which is consistent with the results reported [6, 19, 20]. This was so because drying shrinkage in fine-grained soils depends on particle movement as a result of pore water tension developed by capillary menisci [36]. If two samples of given clay are at the same initial water content but different fabrics (textural state), the clay sample that is more deflocculated and dispersed will shrink most. This is due to average smaller pore sizes, allowing greater capillary stresses with easier relative movement of particles and particle groups. Furthermore, samples compacted at higher moulding water contents have more water in their void spaces that would result in higher shrinkage on drying since volumetric shrinkage is proportional to the volume of water leaving the pore spaces as explained by Haines [26] describing the drying process of saturated soils.

For the natural soil compacted at moulding water contents in the range −2 to +4 % of the OMC for modified Proctor compactive effort, VSS values are <4 %. The maximum VSS value of 4 % was obtained at 17.8, 18.7 and 19.12 % for West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 7a). On treatment with 4 % bagasse ash, the regulatory maximum VSS value of 4 % was obtained at 16.7, 18.7, 17.9 and 19.4 % moulding water contents for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 7b). At 8 % bagasse ash treatment, the recommended maximum VSS value of 4 % was obtained at 17.6, 20.14 and 20.4 % moulding water contents for West African Standard, standard Proctor and reduced Proctor compaction energies, respectively (see Fig. 7c). At 12 % bagasse ash treatment, the maximum permissible VSS value of 4 % was obtained at 19.8, 19.8, 20.9 and 20.52 % moulding water contents for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 7d). Generally, VSS decreased with higher compactive effort probably due to lesser amount of water contained in the voids of specimens compacted at higher compactive efforts.

The effect of bagasse ash content on VSS at the OMC is shown in Fig. 8. Generally, VSS increased with higher bagasse ash treatment due to the increase in fines with larger surface area present in the soil mixture that required more water at the corresponding OMC for reaction. Consequently, this resulted in higher shrinkage during drying. The increase in VSS can also be attributed to physico-chemical reactions (ion exchange) within the soil-bagasse ash mixture.

4.6 Acceptable zones

An acceptable zone for each of the three design parameters (hydraulic conductivity, k, shear strength, VSS) described by Daniel and Benson [18]. “This procedure requires establishing compaction moisture content—dry density ranges needed to achieve the permissible, and then

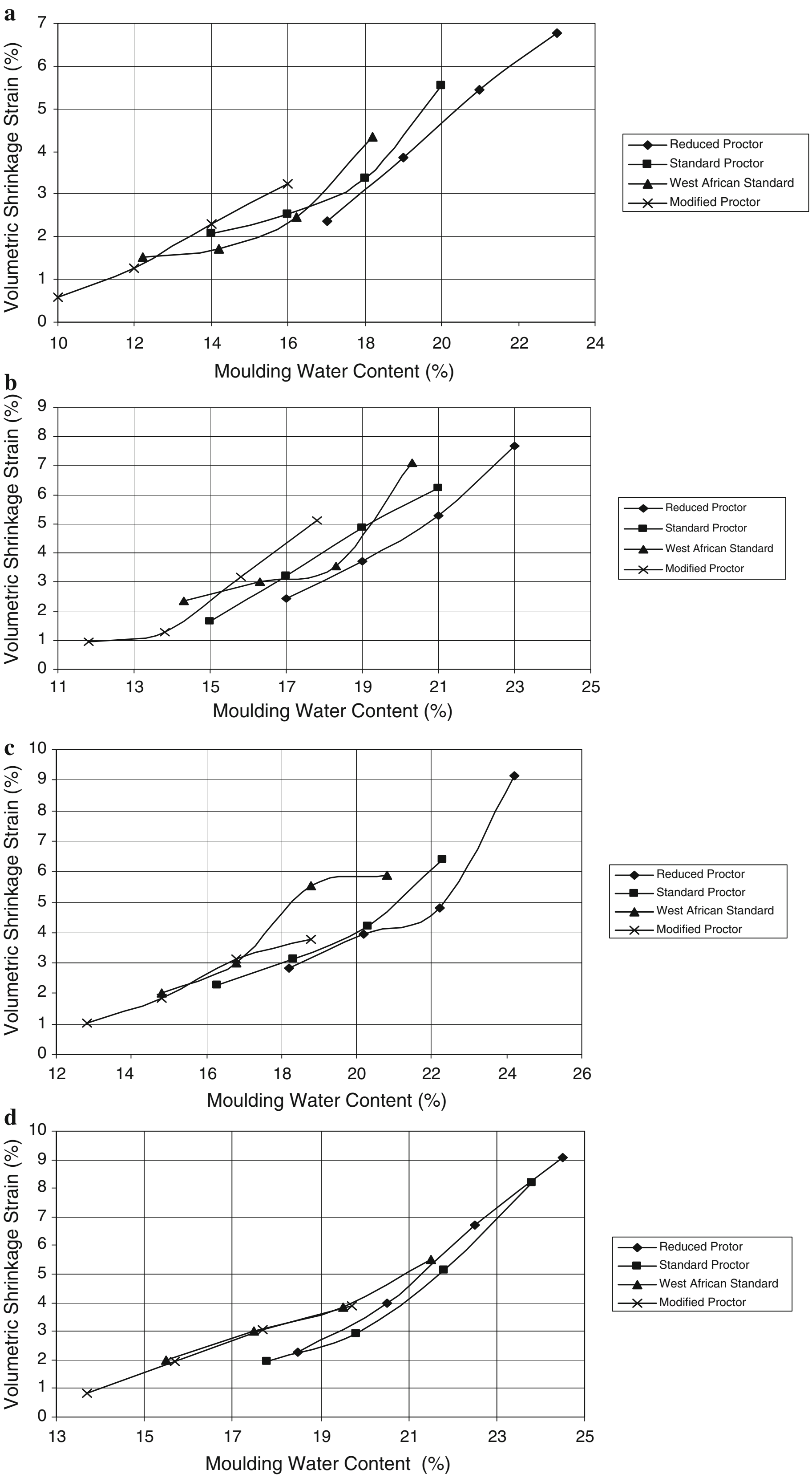

Fig. 7 Variation of volumetric shrinkage strain versus moulding water content for **a** the natural soil, **b** at 4 % BAC, **c** at 8 % BAC, **d** at 12 % BAC

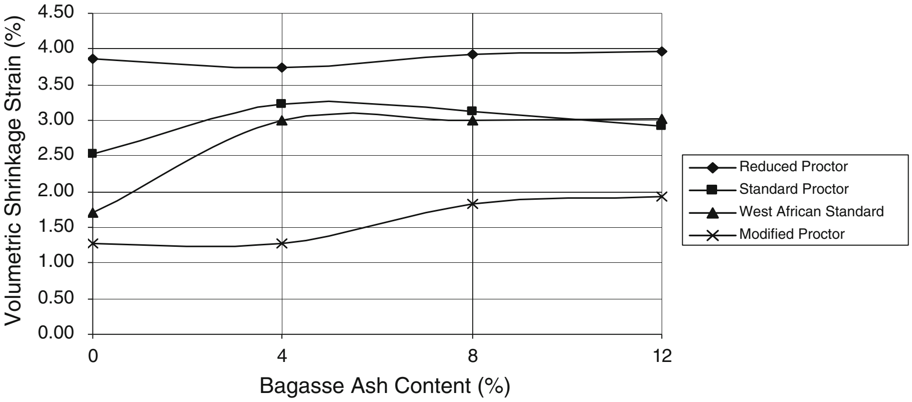

Fig. 8 Variation of volumetric shrinkage strain with bagasse ash content at the optimum moisture content

modifying these ranges to account for other factors such as volumetric shrinkage and shear strength. First, the measured hydraulic conductivity obtained from laboratory results is plotted as a function of moulding water content for the various compactive effort used. Secondly, the dry unit weight water content points showing specimens that had hydraulic conductivities greater than the maximum acceptable values and specimens with hydraulic conductivities less than or equal to the maximum acceptable value. Thirdly, the acceptable zone is finally drawn to cover data points representing test results meeting or exceeding the design criteria ($k \leq 1 \times 10^{-9}$ m/s). Engineering judgment is necessary in constructing the acceptable zone". The acceptable zone is further modified based on the other design consideration (i.e. VSS $\leq$ 4 %; UCS $\geq$ 200 kPa). Furthermore, after an acceptable zone was defined for each design parameter, an overall acceptable zone was obtained by superimposition to obtain a zone that satisfied all the three design parameters.

4.7 Hydraulic conductivity

For the natural soil, acceptable hydraulic conductivity plane was achieved at moulding water contents ranging from 10.8 to 17.1, 12.2 to 18.3, 14.7 to 20.1 and 17.3 to 23 % for specimens compacted at modified Proctor, West African Standard, standard Proctor and reduced Proctor energies, respectively (see Fig. 9). At 4 % bagasse ash treatment, hydraulic conductivity values less than 1×10^{-9} m/s were recorded from 11.7 to 17.9, 14.2 to 20.4, 14.9 to 21.2 and 17.9 to 23.6 % moulding water contents for the four compactive efforts from the highest to the lowest, respectively (see Fig. 10).

For 8 % bagasse ash treatment, the plane of acceptable hydraulic conductivity values were obtained from 12.7 to 19, 15.2 to 21.3, 16.2 to 22.4 and 18.5 to 24.8 % moulding water contents for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 11). At 12 % bagasse ash treatment, the acceptable plane of hydraulic conductivity values was recorded at moulding water contents that ranged from 13.6 to 19.8, 16 to 22.2, 17.7 to 23.9 and 18.7 to 24.8 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 12).

4.8 Shear strength

For the natural soil, the acceptable zone for shear strength was achieved by compacting at moulding water contents ranging from 10.8 to 17, 12.1 to 18.3, 13.8 to 20.2 and 16.5 to 20.2 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor energies, respectively (see Fig. 9). At 4 % bagasse ash treatment, acceptable compaction plane for shear strength was attained at moulding water contents ranging from 11.7 to 17.9, 14.2 to 20.4, 14.8 to 21.2 and 16.9 to 22.7 % for the four compactive efforts in decreasing order, respectively (see Fig. 10). Acceptable compaction plane at 8 % bagasse ash treatment was achieved at moulding water contents from 12.7 to 18.9, 15.2 to 21.4, 16.3 to 21.8 and 18.2 to 21.8 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor energy levels, respectively (see Fig. 11). At 12 % bagasse ash treatment, the acceptable plane was obtained at moulding water contents ranging from 13.4 to 19.8, 16 to 22.2, 17.8 to 23.9 and 18.4 to 24.4 % for the four compactive efforts in decreasing order, respectively (see Fig. 12).

4.9 Volumetric shrinkage strain

The compaction plane on which acceptable VSS for the natural soil was obtained was achieved for moulding water contents that ranged from 10.8 to 1, 12.2 to 18.3 and 14.6 to 18.9 % for modified Proctor, West African Standard and standard Proctor energy levels, respectively, while at

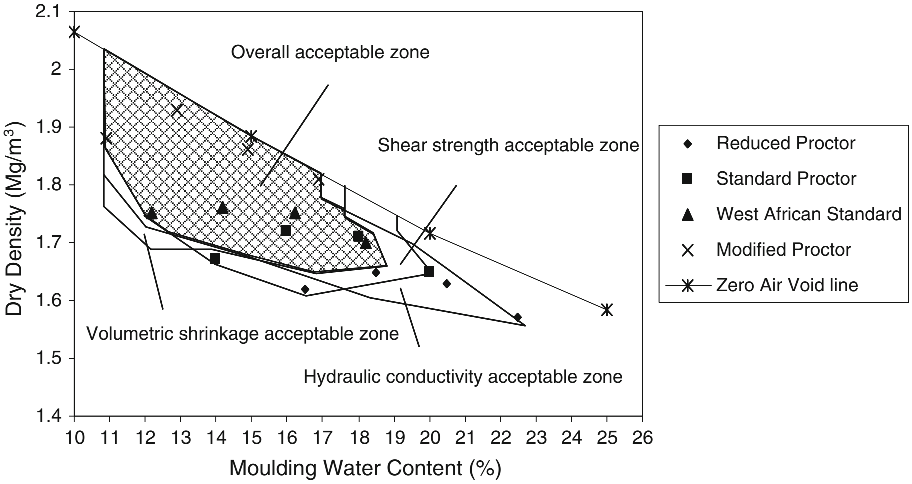

Fig. 9 Overall acceptable zone for the natural soil (0 % bagasse ash treatment)

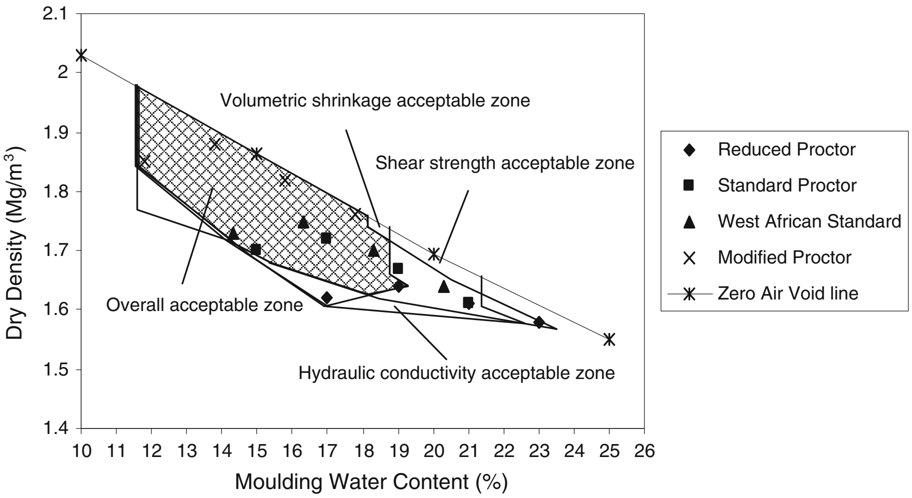

Fig. 10 Overall acceptable zone for 4 % bagasse ash treatment

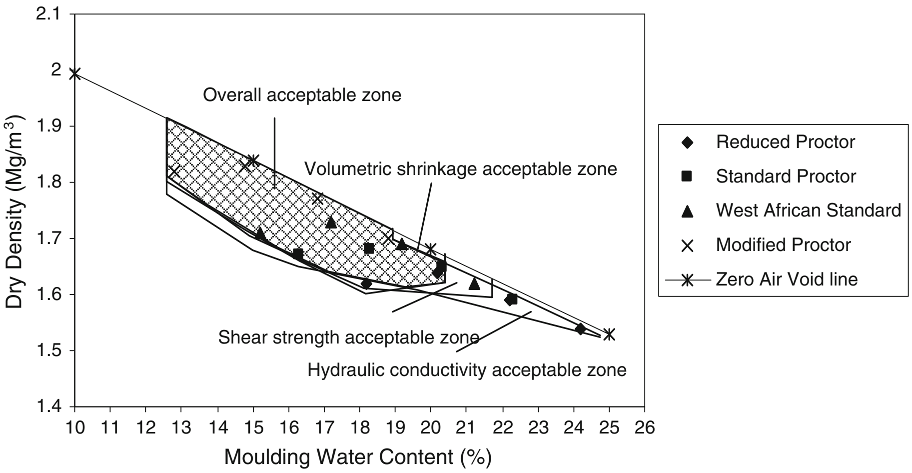

Fig. 11 Overall acceptable zone for 8 % bagasse ash treatment

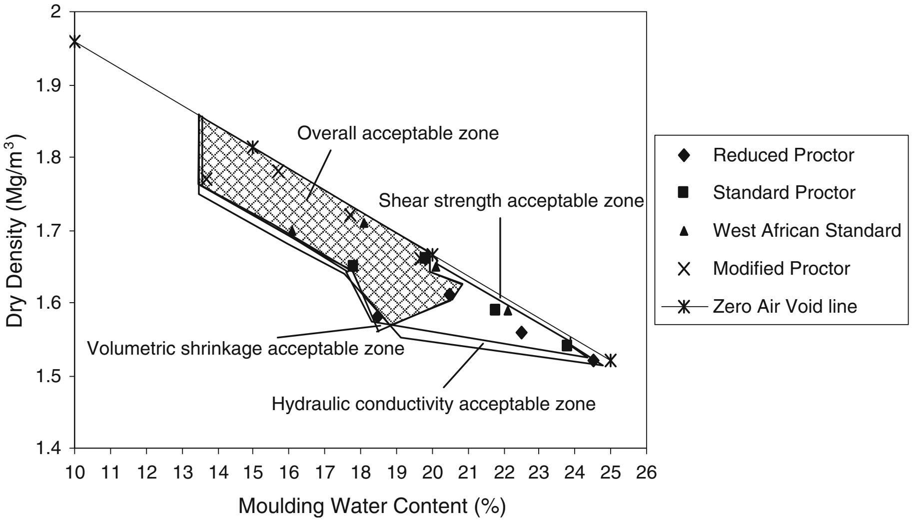

Fig. 12 Overall acceptable zone for 12 % bagasse ash treatment

reduced Proctor effort, no specimen was on this plane (see Fig. 9). At 4 % bagasse ash treatment, it was achieved at moulding water contents in the range 11.7–18, 14.2–18.4, 14.9–18.8 and 16.9–19.1 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 10). Treatment with 8 % bagasse ash produced VSS acceptable compaction plane that was obtained at moulding water contents that ranged from 12.7 to 18.9, 15.2 to 20.4, 16.2 to 20.4 and 18.7 to 20.4 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactive efforts, respectively (see Fig. 11). At 12 % bagasse ash treatment, VSS acceptable compaction plane was achieved at moulding water contents ranging from 13.7 to 19.8, 16 to 19.9, 17.8 to 19.9 and 18.4 to 20.7 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor compactions, respectively (see Fig. 12).

4.10 Overall acceptable zone

The overall acceptable zones in which the material can be compacted based on superimposition of the acceptable zones of all three design parameters previously established are shown as the hatched areas in Figs. 9, 10, 11 and 12. The natural soil should be compacted within moulding water content that ranges from 10.8 to 19 % in order to satisfy the three criteria (see Fig. 9), while at 4 % bagasse ash treatment, it should be compacted between 11.7 and 19.3 % moulding water contents (see Fig. 10). Treatment with 8 % bagasse ash gives the range of moulding water content within which all three established criteria are satisfied as 12.7–20.4 % (see Fig. 11), while at 12 % bagasse ash treatment, the soil should be compacted between 13.7 and 20.9 % moulding water content to satisfy all three design parameters (see Fig. 12).

From the plots of overall acceptable zones, it is observed that 8 % bagasse ash treatment of the natural soil recorded the highest number of specimens (i.e. 11 out of 16 samples) that satisfied the various design parameters. The soil at this treatment should be compacted at moulding water contents that range from 12.6 to 19, 15 to 20.4, 16.2 to 20.4 and 18.4 to 20.4 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor energy levels, respectively, in order to serve as an effective hydraulic barrier material.

4.11 Field application

The conventional field approach in compaction for roadway bases, structural fills, embankments and earthen dams is to specify the dry density of the compacted soil to be greater than or equal to a percentage of the maximum dry unit weight from a laboratory compaction test. This is achieved in the field through repeated number of passes by the compaction equipment over soil with controlled moisture content along with quality control checks such as in situ density; the engineer is able to achieve the specified compaction dry density.

Similarly, with the specified moulding water contents obtained for the various treatment and compactive efforts from the overall acceptable zone, compaction in the field can also be achieved through predetermined passes in trial pads with strict adherence to the specified moisture range and also adhering to the compaction dry densities specified within the overall acceptable zone.

Furthermore, good quality control and quality assurance are important in the application of the above recommendation in the field, because of the sensitivity of hydraulic conductivity which is a key for the barrier material to changes in moulding water contents and dry densities. Also good construction practices such as thorough mixing of soil, effective bonding of various compaction lifts, and proper protection of compacted lifts from desiccation induced shrinkage along with proper supervision by qualified personnel are necessary.

5 Conclusion

The treatment of a reddish-brown lateritic soil with up to 12 % bagasse ash, using four compaction energies (i.e. reduced Proctor, standard Proctor, West African Standard, and modified Proctor) at four moulding water contents (i.e. −2, 0, 2 and 4 % of the OMC), respectively, to assess its suitability in waste containment barrier application showed improved properties. Soil index properties improved as reflected in decreases in plasticity index and LS, while OMC increased and MDD decreased with higher BAC.

The hydraulic conductivity values of specimens generally decreased with higher moulding water content and compactive efforts; 4 % bagasse ash treatment of soil recorded the lowest hydraulic conductivity value at the OMC. The UCS decreased and increased with higher moulding water content and compactive efforts, respectively. Peak UCS values were recorded at the OMC for soil treated with 8 % bagasse ash content irrespective of the compactive effort used. Volumetric shrinkage increased with higher moulding water content and decreased with higher compactive effort. The volumetric shrinkage increased with higher bagasse ash treatment at the OMC irrespective of the compactive effort used.

The plots of acceptable zones show that 8, 12 and 8 % bagasse ash treatments recorded optimum results for hydraulic conductivity, shear strength and volumetric shrinkage, respectively. Based on overall acceptable zones for all bagasse ash treatment, 8 % bagasse ash treatment recorded optimum results. The soil at this level of treatment should be compacted at moulding water content in the range 12.6–19, 15–20.4, 16.2–20.4 and 18.4–20.4 % for modified Proctor, West African Standard, standard Proctor and reduced Proctor energy levels, respectively, in order to be used as an effective hydraulic barrier material.

Summarily, these results show that lateritic soil treated with up to 12 % bagasse ash can effectively be used as a hydraulic barrier in waste containment systems (liners and covers) with optimum results at 8 % treatment. This finding will also help in solving some of the environmental problems created by bagasse generated from the sugar industry and an economic means of disposal.

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