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Original Article

Suitability of Bagasse Ash and Molasses for Stabilization of Expansive Black Cotton Clay Soils for Subgrade Construction in Low-Volume Rural Roads

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Abstract - *The construction and maintenance of rural roads in Africa face challenges, including limited resources, unsuitable materials, and harsh conditions. Expansive black cotton clay soils prevalent in rural Africa pose challenges for low-volume road networks, damaging sub-grades, inducing soil movement, and causing cracks and failure. Soil modification techniques to improve engineering properties have limitations due to cost and negative environmental impact. Traditional lime and cement stabilization are often infeasible due to high costs and limited availability. This study evaluates sugarcane bagasse ash (SCBA) and molasses for sub-grade improvement in expansive black cotton clay soils to determine impacts on soil properties and road performance. Laboratory tests determined engineering properties and optimized mix proportions. Soils were treated with varying amounts of molasses (0-12%) and bagasse ash (5-20%). Physical properties and classification were evaluated. Mechanical strength was assessed through Unconfined Compression Strength (UCS) and CBR testing. Results showed that soils are highly plastic, classifying as A-7-6(21). The optimum molasses content was 8%. Treated soil strength significantly increased, with treatments of 8% molasses and 10-15% bagasse ash yielding the greatest improvements, surpassing design standards. The free swell potential is significantly reduced. Findings confirm that bagasse ash-molasses blends effectively modify clay properties, indicating potential for rural roads. The optimal 8% molasses and 10% bagasse ash mixture achieved a 7-day soaked CBR of 12.5% and UCS of 475kPa. Based on these laboratory results, further field trials are recommended. This low-cost approach has significant potential for sustainably improving road infrastructure and transportation access in remote agricultural communities across Africa and similar contexts.*

Keywords - *Black cotton clay soil, Road subgrade, Sugarcane bagasse ash, Sugarcane molasses, Stabilization.*

1. Introduction

Rural roads are critical for the economic and social development of rural communities in Africa, as they provide access to markets, healthcare, education, and other basic services [1]. However, expansive black cotton clay soils prevalent in many rural areas pose significant challenges to road construction and durability [2]. As a common soil type in Africa, the treatment of these soils is crucial to ensure the safety, usability, long-term performance and durability of unpaved rural roads [1]. Black cotton clay soils experience severe volume changes with moisture fluctuations, resulting in cracking, heaving and damage, thus compromising the safety and usability of roads [3]. When wet, they severely swell and become soft and plastic with very low load-bearing capacity. At the same time, upon drying, they shrink and harden, resulting in differential settlement that leads to cracking of the pavement [4]. This reduces the overall durability for the use of the road structure [5] and has resulted in significant cost overruns in road constructions located on these soils as they exhibit many engineering problems for subgrades thus complicating road construction. The construction and maintenance of rural roads in Africa face numerous challenges, including limited financial resources, lack of suitable construction materials, and the harsh climate and soil conditions prevalent in many rural areas [1]. Since these soils are characterised by poor properties of plasticity, compressibility and very low bearing capacity [6], their swelling and shrinkage can result in general damage to the sub-base infrastructure, inducing movement in the soil mass, resulting in a deferential settlement in engineering structures, leading to cracks and subsequent failure which results in high cost of maintenance [7]. Common practices to remedy this phenomenon include changing the design to suit the site condition, removing and replacing the in-situ soil materials or through soil stabilisation [8]. The most common method used in developing countries is the replacement of poor soils [9]. However, excavating and transporting replacement soils is extremely costly and environmentally damaging [4]. This is a result of high haulage costs, increased land degradation, an increase in carbon footage and an increase in greenhouse gases, which are responsible for global warming [10]. In excavating and replacement, costs are incurred through haulage of soils with desirable engineering properties, which are often available many kilometres away from the site [11]. Other risk factors include sliding, alteration of the ecosystem, groundwater pollution and loss of arable land [11].

To improve expansive soil engineering properties, soil modification techniques are employed and these include cement stabilisation, lime stabilisation, use of geotextiles and injecting synthetic materials into the pore spaces [12]. Stabilisation is the modification or preservation of soil properties in order to improve the engineering characteristics and performance of the soil [13]. However, these conventional methods create serious environmental concerns as chemical grouts may be toxic and hazardous [8]. The production and transportation of cement and lime can have a significant impact on the environment, particularly due to the emissions of greenhouse gases and their use faces growing concerns on carbon dioxide (CO_2) emission and climate change [14]. Moreover, the use of such calcium-based additives faces growing concerns about carbon dioxide (CO_2) emission and climate change; therefore, there is a need for more sustainable soil stabilisation techniques [14].

Furthermore, the use of conventional materials for road sub-base improvement in expansive clay soils for rural roads can be expensive. It may not always be feasible due to limited access to advanced materials and technology in Africa’s rural areas [15]. Lime and cement may not be readily available in some regions, which can make it difficult to carry out stabilisation projects easily and will require a large amount of money for their transportation and storage [14]. Lime stabilisation of expansive clay soils is not durable in flood-prone areas [10], while the use of cement is not durable for soils with high clay content [16].

Research has shown that bagasse ash can improve the physical and mechanical properties of soils, making it a potentially effective stabilising agent for expansive clay soils [17]. Mixing molasses with the soil helps improve the soil's stability and resist erosion. However, the suitability of these materials for stabilizing expansive clay soils for subgrade construction is not well understood. Therefore, there is a need to investigate the effectiveness of bagasse ash and molasses as stabilizing agents for these soils. Therefore, this research investigated the feasibility of using bagasse ash and molasses for road sub-base improvement in expansive clay soils on rural roads and assessed their impact on soil properties and road performance. The objectives of this study were to determine the engineering properties of the expansive black cotton clay soil, sugarcane bagasse ash and molasses and to also assess the effect of sugarcane bagasse ash and molasses on the physical and mechanical properties of expansive black cotton clay soils for use as road subgrade.

Bagasse ash and molasses are by-products of the sugarcane industry, and they have been shown to have potential as cost-effective and environmentally friendly stabilizers for expansive clay soils [18]. Therefore, this study aimed to fill this knowledge gap by investigating the potential of bagasse ash and molasses as stabilizers for expansive clay soils. The use of bagasse ash and molasses as alternative stabilisers offers a more cost-effective and sustainable solution for road construction in these areas [4], as opposed to traditional methods of stabilising expansive clay soils, such as lime and cement stabilisation, which are relatively expensive and may not be feasible in rural areas with limited resources and infrastructure [15].

The study provides valuable information on the optimal use of these materials in rural road construction, including their effectiveness and sustainability. The results of this study are beneficial to road construction agencies, sugarcane industries, and rural communities in Africa, as well as other countries with similar soil and climatic conditions. With the current world focused on environmentally friendly solutions and investment in smart ‘green’ construction materials to reduce environmental footprint [19], utilising bagasse ash, which is a waste product for road construction, helps reduce waste disposal and promote sustainable development goals at the same time supporting the sugarcane industry and contributing to the local economy. This research contributes to the development of cost-effective and sustainable solutions for road construction in rural areas, which can enhance access, mobility, and economic opportunities for local communities.

2. Materials and Methods

2.1. Materials

The materials that were used in this study are black cotton clay soil, sugarcane bagasse ash, molasses and water. Soil samples were air-dried and crushed to pass a 4.75mm sieve, and sugarcane bagasse ash was dried and sieved through a 0.6mm sieve. All materials were stored securely in air-tight containers until use. The black cotton clay soil was obtained from the area of JKUAT, Juja. The soil was collected from diverse points that represent very well the soil of the area. Soil samples were collected from the top 300 mm of soil. The soil sample was then treated in the JKUAT civil engineering lab. The colour of the soil was observed to be dark grey and the moisture content of the soil was 6.59%. The Liquid Limit (LL) and Plastic Limit (PL) of the soil were found to be 50.51% and 29.02%, respectively, resulting in a Plasticity Index (PI) of 21.49% using methods outlined according to the British

Standard BS1377:1990. They were classified as CH (high plasticity clay) according to the Unified Soil Classification System. The sugarcane molasses and bagasse ash were purchased from Mumias Sugar Company Ltd (Kenya). The sugarcane bagasse ash was then sieved using a BS sieve of 0.6mm before being used. The water used was obtained from an onsite borehole supplying the university through the laboratory tap water to represent local conditions. Distilled water was only used for specific gravity tests to avoid ion impacts. Borehole tap water was used on tests to mimic real field soil-water interactions and produce representative geotechnical data.

2.2. Methods

Samples of sugarcane bagasse ash, molasses and black cotton clay soil were taken to the Kenya Ministry of Mining laboratory in Nairobi for chemical composition analysis. The chemical composition of the materials was obtained from an X-ray Fluorescence (XRF) analysis method. This was done to provide a deeper understanding of how molasses and bagasse ash could potentially interact chemically when blended into the local soil. To determine the engineering properties of the untreated and treated soils, physical and mechanical tests were conducted. The physical tests, included moisture content, particle size distribution, consistency limits, specific gravity and linear shrinkage and were performed according to the British Standard BS1377:1990 [20,21] for soils used in civil engineering applications. Additionally, the soil was classified using the Unified Soil Classification System (USCS) and AASHTO Classification System, in accordance with AASHTO M145-91 [22]. Mechanical strength was evaluated through unconfined compression strength testing (AASHTO T208-13) [23] and California Bearing Ratio (CBR) analysis (AASHTO T193-08) [24]. These standard procedures were used as guidance on the testing of soils for road construction engineering applications.

To assess the effect of sugarcane bagasse ash and molasses on the physical and mechanical properties of expansive black cotton clay soils for use as road subgrade, the neat soil was treated with varying amounts of molasses at 4%, 6%, 8%, 10% and 12% of the dry weight of the soil sample. The optimum amount of molasses that had the highest performance was then selected. The soil was further treated using SCBA varying at 5%, 10%, 15% and 20% blended with the optimum percentage of molasses. The treated soil samples were then subjected to Atterberg limits, compaction, and CBR testing in accordance with British Standards [20,21] for natural soil samples and stabilized samples.

3. Results and Discussion

3.1. Engineering Properties of Expansive Black Cotton Clay Soil, Sugarcane Molasses and Sugarcane Bagasse Ash

3.1.1. Chemical Properties of Natural Black Cotton Soil

The chemical composition of the expansive black cotton clay soil, sugarcane molasses, and sugarcane bagasse ash were characterized using x-ray fluorescence (XRF) analysis, as summarized in Table 1. The black cotton soil is dominated by silica (SiO_2) content of 76.14% sample by mass, consistent with its clay mineralogy [25]. A relatively high iron oxide content of 8.89% was also observed, suggesting the potential for shrink-swell behaviour due to the significant presence of swelling clay minerals such as smectite and illite that are rich in iron [26].

Table 1. Chemical composition of Soil, Molasses and SCBA

Element	Percentage (%)		
	Soil	Molasses	SCBA
MgO	0.00	11.00	3.16
Al_2O_3	11.183	--	10.86
SiO_2	76.136	--	73.95
Fe	8.887	7.00	3.63
CaO	1.479	3.40	3.39
K_2O	0.511	5.80	3.50
Ti	0.973	--	0.431
Mn	0.540	12.80	0.16
Cu	--	11.60	--
NaO	--	6.30	--
Fructose	--	12.20	--
Glucose	--	12.80	--
Sucrose	--	18.20	--

Sugarcane molasses contains significant quantities of various oxides that can influence clay soil properties through cation exchange reactions. It contained significant levels of magnesium oxide (11%), potassium oxide (5.8%), and calcium oxide (3.4%), which improve metal cations exchange that can substitute into the drained double layer of expansive clay minerals to enhance flocculation [27]. Additionally, molasses comprised of high levels of organic components including glucose, fructose and sucrose, serving as an energy source to stimulate microbial metabolisms conducive to biological cementation mechanisms [28].

The high glucose, fructose, and sucrose contents provide an energy source for bacterial activity to aid stabilisation reactions [28] and enable molasses to act as a natural binder [27]. Through cation exchange and bio-mediated processes, molasses functions as a natural soil stabilizer that promotes pore-filling within the clay fabric and the formation of organic binding agents, thereby reducing plasticity, permeability and compressibility to modify the soil structure and engineering performance [27].

The elemental composition of sugarcane bagasse ash was dominated by silica and alumina, making 76.1% and 11.2%, respectively. These constituent oxides indicate that the ash possesses pozzolanic properties through which it can undergo hydration reactions in the presence of water and calcium ions to form cementitious calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels [15]. The appreciable quantities of additional oxides such as potash, calcium oxide and iron oxide refine these pozzolanic reactions while improving the clay structure. Potassium oxide aids flocculation by filling voids between layers to increase porosity, whereas calcium oxide acts as a coagulant cation and intermediate for cementitious bonding [29].

When combined with the organic components and carbonates present in molasses, these compounds impart the ash with capabilities for pore-filling, ion substitution, cementation and aggregate-like behaviour, thereby enhancing the engineering performance of problematic expansive clays through modification of their microstructure and macroscopic properties. Sugarcane molasses exhibited high organic carbon content above 40%, providing a carbon source for microbial metabolism and cementitious compound formation upon reaction with bagasse ash [28].

3.1.2 Physical and Mechanical Properties of Natural Black Cotton Soil

Table 2 below summarizes the key physical and mechanical characteristics and properties of natural untreated expansive black cotton clay soil.

Table 2. Engineering properties of the soil

Property	Value
Colour observations	Dark grey
Moisture Content	6.59%
Classification (AASHTO)	A-7-6
Liquid Limit (LL)	50.51%
Plastic Limit (PL)	29.02%
Plasticity Index (PI)	21.49%
Linear Shrinkage	14.86%
Specific gravity	2.23
Free-swell	105%
Maximum Dry Density	1.388g/cm³
Optimum Moisture Content	25.5%
Soaked CBR (4 days soaking)	1.42%
UCS	98.53kPa

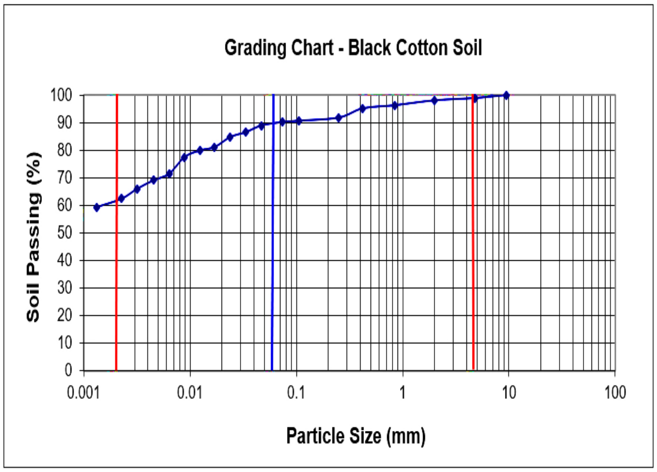

Fig. 1 Particle size distribution (grain size distribution curve of the soil)

Colour Observation

The soil was observed to be dark grey in colour in its neat state and gave a black colour when water was added. Darker colours often indicate higher contents of clay minerals and/or organic matter [30]. The change to black upon the addition of water suggests that organic compounds in the soil are released into the water, staining it dark. This indicates a significant presence of organic matter [31].

Particle Size Distribution

The particle size analysis conducted on the soil sample is presented in Figure 1. Based on the characteristics exhibited from the tests, the soil was classified under A-7-6 as per the AASHTO system. Soils belonging to this category are predominantly fine-grained with high clay content, rendering them problematic in engineering applications. Owing to their shrink-swell nature and tendency to degrade upon moisture fluctuations, untreated A-7-6 soils perform poorly in supporting pavement structures [27].

Consistency Limits

The liquid limit and plastic limit tests resulted in values of 50.51% and 29.02%, respectively, giving a plasticity index of 21.49%. According to the USCS [22], soils with a plasticity index greater than 7 and liquid limit less than 50 are classified as CL - low plasticity clay. However, since the liquid limit of this soil is marginally above 50, it falls into the CH category, indicating high plasticity clay. These consistency limit values indicate that the soil has significant plasticity and a moderately high clay content. The higher liquid limit shows that the soil is more susceptible to expansion upon wetting [32]. The wider plasticity indices correspond to higher clay content and swelling potential. The consistency limit results imply that the soil studied is of a high plasticity clay type, which would produce properties like high swelling potential, low strength and susceptibility to moisture variation [33]. The liquid limit, plastic limit and plasticity index values confirm that the soil is of an expansive nature, making it unsuitable for direct use as subgrade material for road construction without appropriate modification and stabilisation.

Linear Shrinkage

The linear shrinkage test yielded a value of 14.86% for the soil; according to ASTM D427, soils with linear shrinkage greater than 10% are considered highly expansive. The high linear shrinkage of 14.86%, therefore, confirms that this soil exhibits significant shrinkage behaviour and is of an expansive nature. The high linear shrinkage is consistent with the soil's high plasticity, as indicated by its liquid limit, plastic limit and plasticity index values, making it unsuitable for direct use as subgrade material without proper modification.

Specific Gravity

The specific gravity of the soil was determined to be 2.23 based on a pycnometer. A specific gravity above 2 is considered high for mineral soil, and values over 2.6 are more typical for organic soils with significant organic matter content [34]. Therefore, the specific gravity of 2.23 suggests that the soil contains some notable quantity of organic matter in addition to the inorganic mineral content. The specific gravity corresponds to a lower density relative to typical inorganic mineral soils with values around 2.7 [35]. The lower density, aligning with the high specific gravity, indicates that the soil has lower packing and arrangement efficiency due to the clay minerals [3]. This, therefore, means that this soil has higher specific gravity and will exhibit greater compressibility, elasticity and water absorption.

Free-swell

The swell index was used to determine the general swelling characteristics of the soil and the test yielded a value of 105% for the soil. This considerably high swell index is associated with clay which could swell considerably when wet. According to [35] a free swell value over 50% is considered severely swelling, while over 100% is very severely swelling. Therefore, a value of 105% places this soil in the very severely swelling category. The extreme swelling potential suggests that even small increases in moisture content could cause massive volume changes and disruption within the soil [35]. This would lead to significant heave, structural damage and performance issues.

Compaction

The optimum moisture content and maximum dry density of the soil were determined to be 25.5% and 1.388 g/cm³, respectively, using a standard Proctor compaction test. The high optimum moisture content of 25.5% indicates that the soil requires a significant amount of water to achieve maximum compaction. This is because the soil has a high clay and organic matter content that absorbs large quantities of moisture. The maximum dry density of 1.388 g/cm³ is considered very low for mineral soil since typical mineral soils have maximum dry densities in the range of 1.6 to 2.0 g/cm³ [36]. Combined, the high optimum moisture content and low maximum dry density signify that the soil particles are not well graded or arranged, leading to low density even at high moisture levels. This corresponds to properties like lower strength, lower durability and higher compressibility [36].

California Bearing Ratio (CBR)

The CBR test yielded a value of 1.42% for the soil, indicating that it has a severe deficiency of strength to function as a subgrade material in pavement structures. According to the AASHTO classification system [37], CBR values below 3% correspond to very poor soil support and the inability of the soil to provide any significant load-bearing capacity. Thus, the CBR value of 1.42% conclusively shows that in its current untreated condition, the soil fails to meet even the most minimal requirements for use as a subgrade. Even light traffic volumes would cause excessive deformation, rutting and instability in pavements constructed on soil with such a low CBR [38].

Unconfined Compressive Strength (UCS)

The unconfined compressive strength (UCS) test yielded a value of 98.53kPa for the untreated soil. This strength is considered very low according to the Kenya Road Design Manual for roads and bridges Part III [44]. With the prevailing low UCS and CBR values, the untreated soil possesses inadequate load transfer and subgrade support capabilities. Even light traffic loads are expected to cause significant deformation and plastic failure in pavements constructed over this expansive black cotton soil [38].

3.2. Effects of Molasses on the Physical and Mechanical Properties of Expansive Black Cotton Clay Soils

3.2.1. Effects of Molasses Stabilisation on the Consistency Limits of Black Cotton Soil

As shown in Figure 2, the Atterberg limits testing revealed that the addition of sugarcane molasses reduced the plasticity index (PI) of the expansive black cotton clay soil. As the molasses content increased from 0% to 12% by dry mass, PI decreased from an initial value of 21.49% down to 16.06%. Liquid limit (LL) initially reduced slightly at lower molasses proportions of 2-6%, likely due to the coating effect of molasses reducing clay particle interactions and stickiness [27]. However, from 8-12% molasses, plastic limit (PL) saw a small rise, suggesting that optimal flocculation and agglomeration of soil grains are reached at these ratios through binding [39]. The pronounced drop in both LL and PI with increasing molasses can be attributed to physico-chemical modifications within the double diffuse layer and clay lattice structure [27]. Binding soil particles together, pore-filling, and ion exchange mechanisms improve the clay fabric and reduce plasticity. The transition of PI from 21.49% in untreated soil to 17.55-18.42% with 8-10% molasses treatment indicates an adjustment of the material classification from highly to moderately expansive.

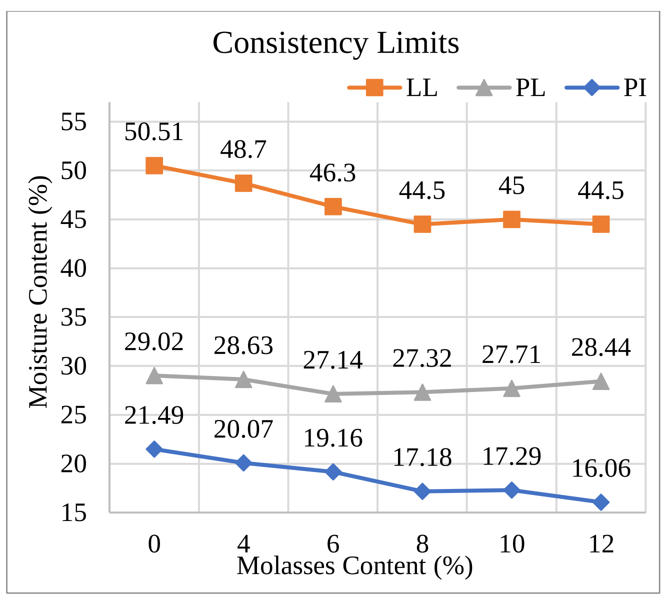

Fig. 2 Effects of varying molasses content on consistency limits

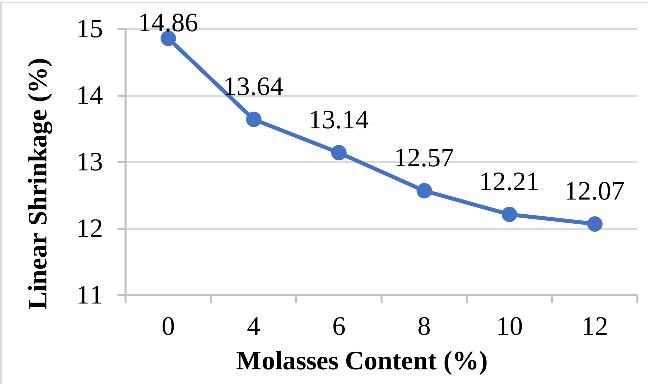

Fig. 3 Linear shrinkage of soil treated with varying molasses content

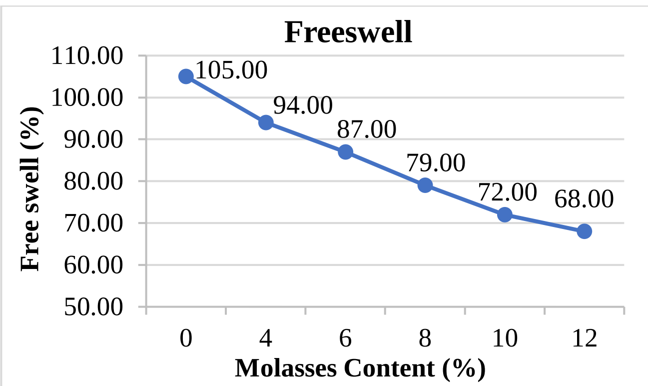

Fig. 4 Free-swell of soil treated with varying molasses content

3.2.2. Linear Shrinkage

Linear shrinkage testing revealed that as molasses content increased from 0% to 12% by dry mass, linear shrinkage was observed to reduce progressively from 14.86% down to 12.07%. This trend can be explained by the physicochemical interactions of molasses within the expansive clay fabric [27]. Molasses contain organic constituents, including sugars that adsorb onto clay particle surfaces via van der Waals forces, disrupting the oriented water film between layers and replacing it with a thin molasses coating [5]. This alters the microstructure by increasing interlayer spacing, preventing close contact and impeding shrinkage-swelling upon moisture fluctuations [27]. At higher molasses contents from 10-12%, linear shrinkage values approached the suitable design limit of 12-15% recommended for rural road subgrades [44], indicating mitigation of the problematic volume changes.

3.2.3. Free-swell

Free swell tests revealed that the untreated expansive clay soil exhibited an extremely high value of 105%, classifying it as severely expansive [35]. In addition to sugarcane molasses from 0-12% by dry mass, free swell was observed to decrease significantly. At higher molasses contents from 10-12%, free swell approached more suitable levels between 50-70% stipulated in design standards [40]. This trend can be explained by the physicochemical interactions imparted by molasses at the clay soil-water interface [27]. The hydrophilic organic components of molasses, such as sugars, adsorb onto external clay surfaces through van der Waals forces, disrupting the oriented water film and densifying the double diffuse layer. This alters the microstructure by increasing interlayer spacing within the clay lattice, impeding full expansion and restricting the mobility and dispersion of clay particles during hydration [5, 27].

3.2.4. Compaction

The influence of sugarcane molasses on the compaction characteristics of the expansive black cotton clay soil was evaluated through Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) testing.

As shown in Figures 5 and 6, OMC decreased while MDD increased with rising molasses concentrations from 0-12% by dry mass, indicating modification of the compaction curve. The reduction in OMC can be attributed to the hygroscopic nature of molasses, whereby its hydrophilic constituents, such as sugars, absorb free water that would otherwise be retained within the soil pores [27]. This lowers the water demand for equivalent compaction. Meanwhile, the upward trend in MDD correlates to the lubricating effect imparted by molasses at the solid-liquid interface, allowing for increased packing and densification of soil grains under compaction and leading to an improved packing arrangement [5].

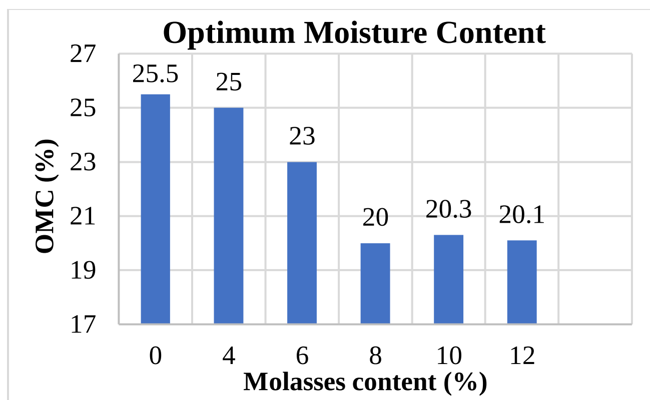

Fig. 5 OMC of soil treated with varying molasses content

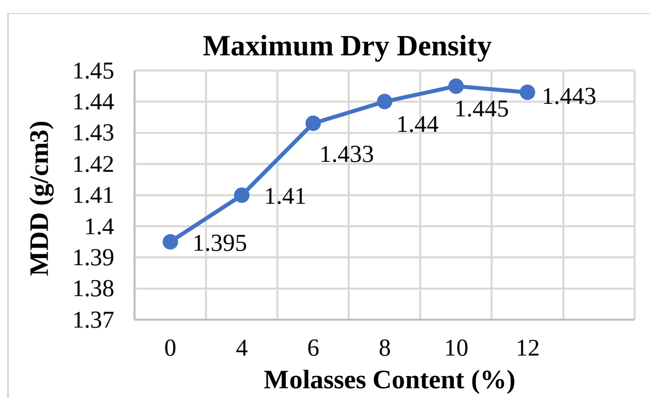

Fig. 6 MDD of soil treated with varying molasses content

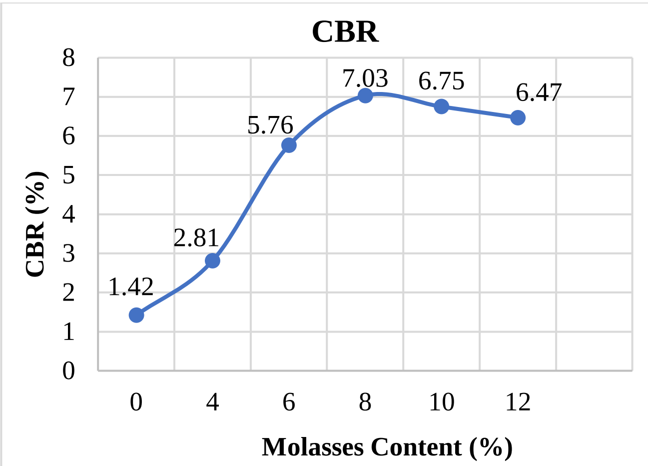

Fig. 7 CBR of soil treated with varying molasses content

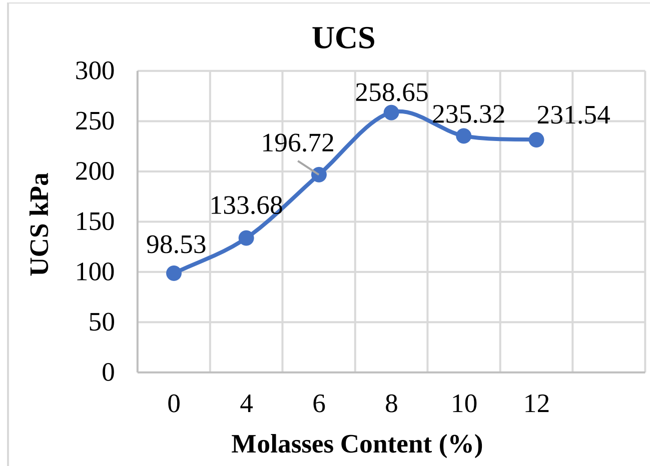

Fig. 8 UCS of soil treated with varying molasses content

3.2.5. California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test, which evaluates a soil's load-bearing capacity relevant to pavement design, was used to evaluate the strength characteristics of the soil. The neat soil had a very low CBR of 1.42%, making it weak and unstable for supporting road loads [41]. However, with the addition of only 4% molasses, there is a significant increase in CBR to 2.81%. Further increase of molasses to 6-8% shows even higher CBR values of 5.76% and 7.03%, respectively, indicating a substantial improvement in load-bearing capacity [38]. The CBR attains a maximum of 7.03% at 8% molasses content. Beyond this addition, there is a slight decrease observed in CBR values at 10% and 12% molasses. This could be attributed to the filler effect, where excess molasses acts more as a lubricant rather than a binding agent at higher levels [27]. Therefore, optimal modification of the expansive soil's engineering performance was achieved through physico-chemical interactions at 8% molasses dosage.

3.2.6. Unconfined Compressive Strength (UCS)

The unconfined compressive strength (UCS) test results showed that the strength of the black cotton soil increased with the addition of molasses up to 8% content. The UCS of the neat soil was 98.53 kPa; when 4% molasses was added, the UCS increased to 133.68 kPa. At 6% molasses content, there was a further increase in UCS to 196.72 kPa. The maximum UCS of 258.65 kPa was observed with 8% molasses addition. With the increase in molasses content, the soil exhibited improved cohesive properties as the axial strain increased considerably.

This increasing trend in UCS with increasing molasses content of up to 8% can be attributed to cation exchange and flocculation/agglomeration reactions. However, excessive molasses coating of individual soil grains beyond an optimum threshold led to a reduction in UCS values, possibly by acting as a lubricant weakening the interparticle bonds within the soil structure. Thus, molasses contents had a significant influence on the engineering properties of the untreated expansive soil.

3.3. Effects of Molasses and SCBA on the Properties of Expansive Black Cotton Clay Soils

The physical and mechanical properties and behaviour of the expansive black cotton clay soil after stabilisation with 8% by mass of sugarcane molasses and varying percentages from 0 – 20% of sugarcane bagasse ash (SCBA) are discussed in this section.

3.3.1. Consistency Limits

The LL of the soil increased from 44.51% to 48.10% with the addition of SCBA from 0 – 10% (Figure 9). This indicates that the cohesiveness of soil particles increases with the addition of SCBA by up to 10% due to static reactions between SCBA, molasses and clay [25]. The molasses coating clay surfaces within interlayers facilitated closer contact for reaction with SCBA. However, LL slightly decreased above 10% SCBA, likely due to pore filling limiting further flocculation [15]. Plastic limit (PL) steadily rose from 27.32% to 33.86% over 0-20% SCBA, reflecting cementitious bonds formed between hydrated SCBA polymers, clay and molasses coatings.

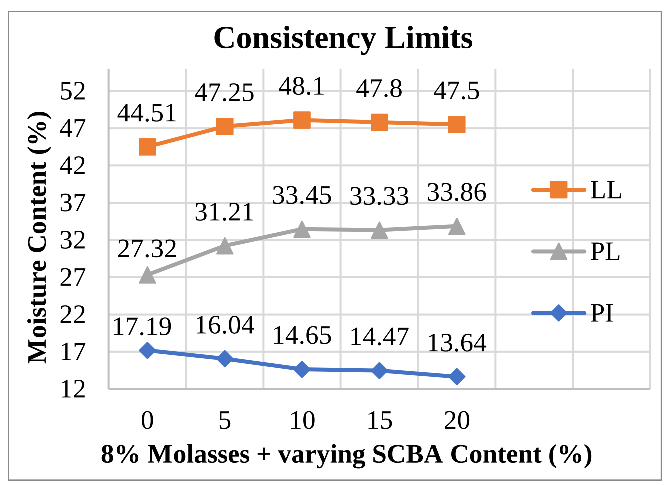

Fig. 9 Consistency Limits of soil treated with 8% Molasses and varying SCBA content

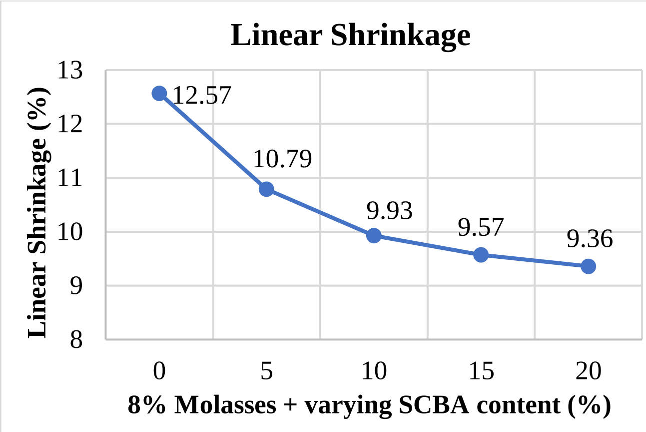

Fig. 10 Linear shrinkage of soil treated with 8% Molasses and varying SCBA content

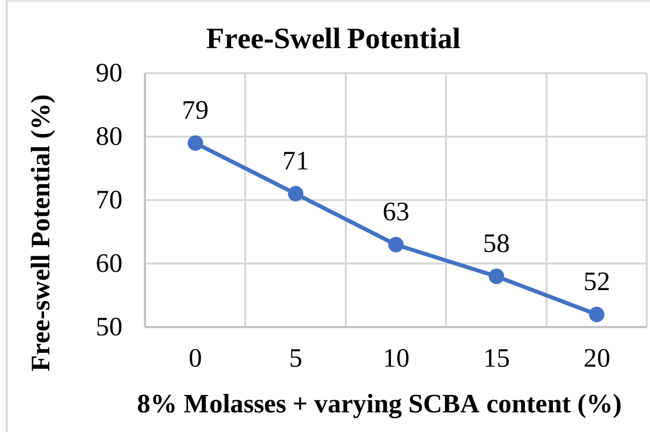

Fig. 11 Free swell of soil treated with 8% Molasse and varying SCBA content

Consequently, the plasticity index (PI) was reduced, signifying enhanced consistency for workability conferred by the synergistic geotechnical modifications [39]: modifying particle interactions and mineralogy through physicochemical mechanisms remediated expansion potentials. Therefore, the addition of 8% molasses along with 5-15% sugarcane bagasse ash is effective in modifying the consistency properties of expansive black cotton soil towards optimum ranges for the construction of low-cost rural roads.

3.3.2. Linear Shrinkage

The linear shrinkage of the soil treated with molasses only at 8% was 12.57%. With the addition of SCBA at 5%, 10%, 15% and 20%, respectively, the linear shrinkage decreased to 10.79%, 9.93%, 9.57 and 9.36% (Figure 10). This decrease is attributed to the pore-filling effect of ash particles and the interactions between SCBA and molasses-coated clay particles.

In addition, this could have been a result of the hydrated cementitious products forming from reactions between SCBA silica/alumina and metal ions released by molasses, which filled pores and improved the clay lattice planes [39]. Simultaneously, molasses's surface-absorbed configuration on clay facilitates closer packing and densification during cementation [27]. By filling voids and altering the micro fabric, geotechnical modifications result in desirable stability for subgrade applications where volume changes can induce structural damage, even without fixed shrinkage criteria [10].

3.3.3. Free-Swell

The free swell of soil treated with 8% molasses was measured to be 79%. With the addition of 0 – 20% SCBA, the free swell decreased to 52% (Figure 11), demonstrating the reduction in the expansive behaviour of the soil. According to [29], ash additions provide a pore-filling action that impedes clay swelling as the static reaction between SCBA and the binding effect by molasses coats and rigidifies clay particle surfaces [16].

At the same time, molasses organics absorbed into clay disrupt the oriented water layer and facilitate closer packing [27]. These mechanisms densify the double layer, fill voids within the fabric, and impede clay lattice expansion. By modifying mineralogy and restricting water intrusion/orientation, the geotechnical additives sufficiently reduced swelling to ≤70%, satisfying the design criterion for stable support applications in rural roads as per the Kenya Road design manual for roads and bridges Part III [44]. Thus, the optimized 8% molasses and 10-20% SCBA treatment demonstrate effectiveness at solving this problematic volume-change tendency.

3.3.4. Compaction

Compaction characteristics of the 8% molasses-stabilized expansive black cotton clay soil were evaluated through optimum moisture content (OMC) and maximum dry density (MDD) testing with variable sugarcane bagasse ash (SCBA) additions. OMC decreased from 20% to 18% with 0-10% SCBA (Figure 12), likely due to the combined effects of molasses' hygroscopic nature and static bonding from ionic reactions between SCBA and free ions from molasses, which reduce moisture demand [27,33]. Above 10% SCBA, OMC rose marginally, potentially attributed to ash dominance interfering with the soil-binding capabilities of molasses as its role shifts from modification to aggregate filler.

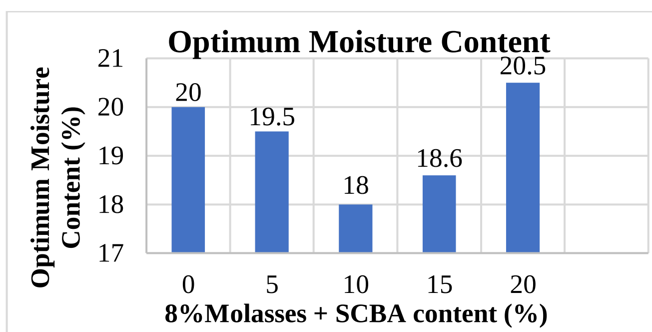

Fig. 12 OMC of soil treated with 8% Molasse and varying SCBA content

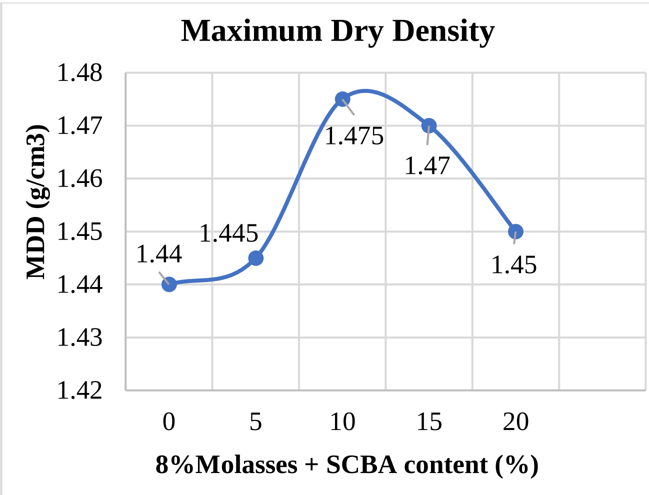

Fig. 13 MDD of soil treated with 8% Molasse and varying SCBA content

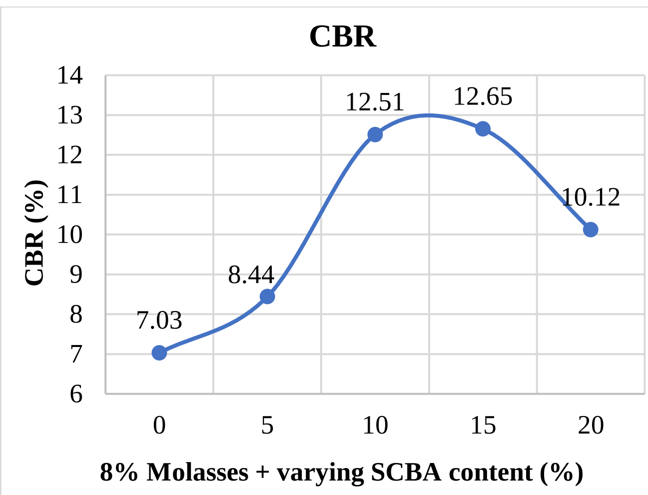

Fig. 14 CBR of soil treated with 8% Molasse and varying SCBA content

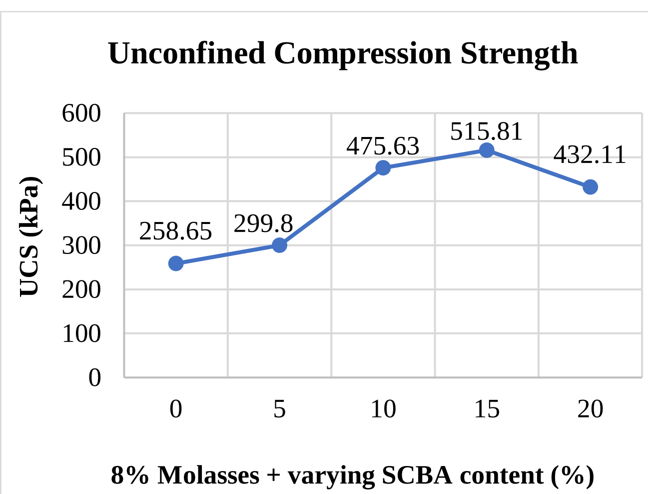

Fig. 15 UCS of soil treated with 8% Molasse and varying SCBA content

The increase in OMC could also be because of the high amount of ash particles that are contributed by ash; therefore, at higher ash percentages, OMC will increase [15]. MDD increased initially from 1.44 g/cm3 to a peak of 1.475 g/cm3 at 10% SCBA due to improved packing facilitated by ash particle coatings on molasses-amended clays (Figure 13). Above 10% SCBA, MDD levelled off up to 15% but decreased at 20%, indicating ash overabundance may disrupt optimized treatment effects on compaction [42].

3.3.5. California Bearing Ratio (CBR)

The California bearing ratio (CBR) test results as shown in Figure 14, soil treated with only 8% molasses exhibited a CBR of 7.03%. In contrast, the addition of 5% SCBA further improved strength to 8.44% due to synergistic static reactions between SCBA and molasses-treated clay minerals [39]. CBR peaked at 12.65% with 15% SCBA supplementation, exceeding standards for subgrade design by the Kenya Road design manual for roads and bridges PartIII [44] and these are attributed to cation exchange, flocculation/agglomeration and carbonation modifications from reactions between metal ions from molasses and SCBA within the stabilized matrix [25].

Higher CBR values between 10-15% SCBA signify mechanical improvements arising from the densification and rigidification of the clay fabric by hydrated cementitious bonding compounds [27]. However, CBR declined slightly above 15% SCBA, potentially due to hindered pore-filling and bonding at excessive ash contents [43]. By modifying mineralogy and pore structure through physico-chemical mechanisms imparted by the optimized 8% molasses-10-15% SCBA treatment, load-bearing capacity was sufficiently improved to support traffic loads per design specifications in Kenya [44].

3.3.6. Unconfined Compressive Strength (UCS)

The significant increase in UCS value (Figure 15) is likely due to reactions between SCBA, molasses, clay soil and water. As discussed above, the cation exchange reaction and adhesive property of molasses are responsible for increasing the compressive strength of the soil in addition to static bonds and some pozzolanic reactions from SCBA. Soil stabilised with 8% molasses had a UCS of 258.65 kPa. At 5% SCBA along with 8% molasses, the UCS improved to 299.8 kPa. A considerable rise in strength was observed at 10% SCBA content, achieving the UCS value of 475.63 kPa. This significant gain in strength with higher SCBA can be attributed to the reaction between SCBA, calcium ions from molasses and clay minerals. These compounds infill voids and cement soil particles. The maximum value was observed at 15% SCBA with a UCS of 515.81kPa. However, beyond the 15% SCBA, excess unreacted ash particles at 20% content may have caused dilution and reduction in coordination modulus, lowering UCS to 432.11 kPa.

4. Conclusion

This study sought to determine the suitability of sugarcane bagasse ash and molasses for the stabilisation of expansive black cotton clay soils for subgrade construction of low-volume rural roads.

This study determined an optimum combination of sugarcane molasses and bagasse ash to stabilize expansive black cotton clay soil for use as subgrade material to be 8%Molasses and 10%SCBA by dry weight of the soil. The soil investigated was sampled from the site and characterized as predominantly clay-rich through particle size analysis and high plasticity indices from tests on its liquid and plastic limits and classified as A-6-7 according to the American Association of State Highway and Transportation Officials system, which delineates soils as being of poor quality with poor engineering performance under changing environmental conditions.

The results determined that treating the natural soil with 8% molasses by weight optimized its mechanical properties when evaluated through Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests. The UCS and CBR values increased to 258.65kPa and 7.03%, respectively, with the 8% molasses treatment - representing improvements over the untreated soil.

However, the stabilized subgrade did not fully meet the design requirements for strength as specified by CBR and UCS thresholds. Test results revealed that treatment with 8% molasses and 10% bagasse ash provided the optimum performance, with the stabilized soil meeting specifications. At this proportion, unconfined compression testing yielded a strength of 475.63kPa while the California bearing ratio reached 12.51%, surpassing the required thresholds.

Additionally, the free swell potential was significantly reduced to 63% through physicochemical modifications induced by this co-stabilizer treatment. By achieving the target mechanical properties and reducing volume change as specified in Kenyan road design standards, the 8% molasses + 10% bagasse ash combination proved effective at stabilizing the problem soil.

This confirms the viability of an agricultural waste-based approach for soil remediation and sustainable road construction. The combination of sugarcane molasses and bagasse ash was found to be effective in stabilizing the problematic expansive black cotton clay soil through physicochemical modification mechanisms.

Molasses coats clay particles, disrupt the structured water layer, and enables closer packing through surface bonding. It also provides metallic ions that react with bagasse ash's silica and alumina, binding the soil. Together, molasses and bagasse ash densify the soil fabric through flocculation, pore-filling, cation exchange, and cementation reactions. This reduces plasticity, shrinkage, swelling, and permeability.

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