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Geotechnical Investigation of Stabilized Black Cotton Soil for Flexible Pavement Design: A Case-study of Dadin-kowa, Gombe

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Abstract

This study investigates Black Cotton Soil (BCS), classified as A-7-6 under the American Association of State Highway and Transportation Officials (AASHTO) system and the Unified Soil Classification System (USCS). The result shows that the natural BCS has a liquid limit (LL) of 80% and a plastic limit (PL) of 35.48%. When blended with 10% Ordinary Portland Cement (OPC) (90% BCS), LL and PL decreased to 55.5% and 27.14%, respectively. A comparable blend of 8% OPC, 12% Bagasse Ash (BA), and 80% BCS yielded LL and PL of 57.4% and 28.3%, respectively. The natural BCS also shows a shrinkage limit (SL) of 21.7%, which was reduced to 14.02% in a 10% BA–90% BCS blend, while the 8% OPC–12% BA–80% BCS blend lowered SL to 14.88%. For compaction properties, the natural BCS showed a maximum dry density (MDD) of 1.52 Mg/m^3 and optimum moisture content (OMC) of 18.2%. On treatment with 2% OPC, 3% BA, and 95% BCS increased MDD to a peak of 1.78 Mg/m^3, while a 10% BA 90% BCS blend raised OMC to 19.1%. For the California Bearing Ratio (CBR) values critical for pavement design, the unsoaked CBR of BCS increased from 36.49% to 42.60%, making it suitable only as a sub-base material for flexible pavements. Soaked CBR improved from 6.80% to 20.03% but remained insufficient for sub-base use.

Keywords: Black Cotton Soil, Bagasse Ash, Portland Cement, Stabilization

1. Introduction

Black cotton soil, known for its expansive clay properties, presents formidable challenges in flexible pavement design due to its high compressibility, shrinkage, and swelling characteristics [1, 2]. This soil type undergoes significant volumetric changes when exposed to moisture, a behavior primarily driven by the presence of smectite clay minerals, especially montmorillonite [3]. These repetitive swelling and shrinking cycles can cause severe damage to infrastructure, including buildings, pavements, and embankments [4]. For highway pavements, such movements lead to uneven surfaces, resulting in cracks and eventual disintegration. The instability of black cotton soil is a major cause of pavement distress and premature failure [5].

Recently, sustainable and eco-friendly solutions have gained traction in geotechnical engineering, particularly the use of industrial by-products as soil stabilizers [6, 7]. Amidst this innovation, the sugar industry offers a novel solution to the black cotton soil conundrum [8]. Sugarcane (Saccharum spp.), a perennial grass cultivated globally, is a major crop with Brazil and India leading in production [9, 10]. The sugarcane industry, while primarily focused on juice extraction for sugar production, generates significant by-products like straw and bagasse [9]. Bagasse, after juice extraction, is burnt to produce bagasse ash, which has emerged as a potent soil stabilizer [11].

This study explores the transformative potential of bagasse ash in stabilizing black cotton soil. Like a phoenix rising from the ashes, this once-discarded by-product is being repurposed to enhance the geotechnical properties of black cotton soil, creating a resilient and durable pavement design [12, 13]. The integration of bagasse ash into cement yields a harmonious blend of improved soil strength and stability, challenging traditional approaches to flexible pavement design [14, 15].

Join us on this journey as we delve into the innovative application of bagasse ash-cement stabilization, uncovering the potential for a sustainable and resilient future in geotechnical engineering. Through this exploration, we aim to shed light on how industrial waste can be repurposed to solve some of the most pressing challenges in infrastructure development.

2. Materials and Methodology

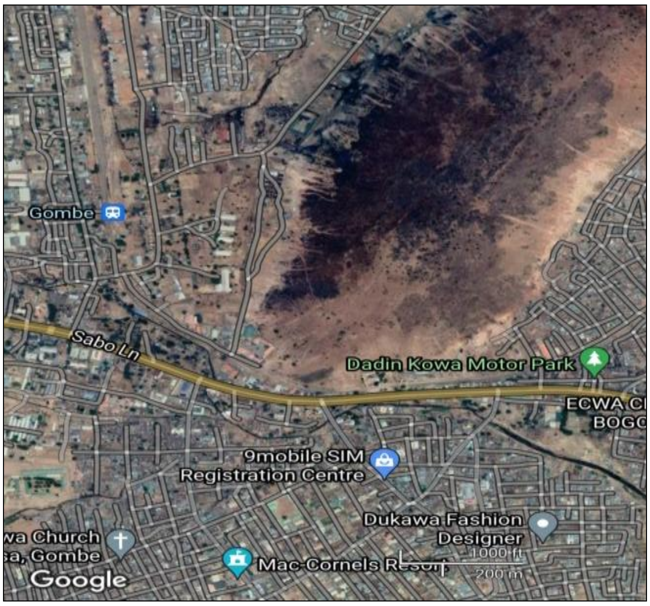
2.1 Material

2.1.1 Black Cotton Soil

The primary material used in this research is black cotton soil, obtained from Dadin Kowa in Akko Local Government Area, North-Eastern Nigeria, approximately 35 kilometers from the city of Gombe. The location coordinates are presented in Table 1. Geological and soil maps of Nigeria reveal that the parent material in this region is basic igneous rock, which, upon weathering, forms weakly developed black cotton soils.

The soil samples were collected during the dry season from an area exhibiting cracks approximately 0.25 meters wide and 2 meters deep. Akko Local Government Area experiences high temperatures, ranging from 30-32°C, and seasonal rainfall between 700-1250mm. The climate is characterized by a distinct dry season from October to May and a rainy season from June to September.

This selection of soil and the timing of sample collection provide a robust foundation for studying the unique properties and challenges posed by black cotton soil in this region, setting the stage for a comprehensive analysis and innovative solutions in soil stabilization.



Source: Google map

Fig 1: Map showing study location

Table 1: Sample location coordinate

S.No	Sample	Latitude	Longitude
1	Black Cotton Soil	10.282804	11.193318

2.1.2 Sugarcane Bagasse Ash (BA)

Sugarcane bagasse waste, sourced in large quantities from Zaria City, Kaduna state, and completely sun-dried for 3-4 days and then burnt into ash in an open-air setting under atmospheric conditions. To achieve a consistent particle size, the ash was sieved locally to remove larger particles before final sieving with a No. 200 sieve (75µm aperture). Finally, the processed ash was stored in an airtight container to prevent moisture absorption during storage.

2.1.3 Cement

The ordinary Portland cement (OPC) used in the study was purchased from an open market at Samaru Market in Zaria, Kaduna State, Nigeria. Zaria is a major city in the northern part of Nigeria, known for its vibrant markets and commercial activities. The Samaru Market is a popular local market located in the town, where a wide variety of goods, including construction materials like cement, are sold. The OPC obtained from this market was the specific type of cement used in the research project being documented in the journal.

2.2 Methods

2.2.1 Determination of Index Properties

The properties of both natural and stabilized Black Cotton Soil (BCS) were thoroughly evaluated following BS 1377 and BS 1924 standards. Various mixtures were tested, including combinations of 10% cement with 90% BCS and 10% bagasse ash (BA) with 90% BCS. Additionally, cement percentages of 0%, 2%, 4%, 8%, and 10% were mixed with incremental BA amounts of 0%, 3%, 6%, 9%, and 12% by the dry weight of the natural soil. This rigorous process aimed to enhance the soil's structural integrity.

2.2.2 Compaction

Appropriate quantities of BCS were separately blended with cement and were further admixed with various amount of BA to obtain the Cement/BA stabilized BCS blends (See. 2.2.1). A 3000g soil sample was divided into five parts, mixed with water, and placed into a 1000cm³ cylindrical mold. Each part was compacted in five layers with 25 evenly distributed blows from a 4.5kg rammer with a 50mm diameter, dropped from 450mm above the soil's surface. The mold, fitted with a detachable collar, was trimmed level after compaction. The weights of the mold with (W2) and without soil (W1) were recorded. Two samples for moisture content were taken from the top and bottom. The soil was crumbled, re-pulverized, mixed with the remaining soil, and 125ml of water was added. This process was repeated, increasing water content until the mold's weight dropped. Finally, the bulk density (ρb) was determined by weighing the mold and taking a small soil sample for moisture content.

2.2.3 Atterberg Limits

This investigates soil's reaction to water using the Casagrande apparatus to estimate the liquid limit, plastic limit, and plasticity index for both natural and treated soils. The tests were conducted following BS 1377 (1990) Part 2 and BS 1924 (1990) standards, ensuring precise and reliable results. These measures help us understand the soil's consistency and its suitability for various engineering applications.

2.2.4 California Bearing Ratio (CBR)

Appropriate quantities of Black Cotton Soil (BCS) were individually mixed with cement and subsequently combined with varying amounts of Bagasse Ash (BA) to create the Cement/BA stabilized BCS blends (See 2.2.1). The test followed BS 1377 (1990) standards. The sample was passed through a 20mm IS sieve and retained on a 4.75mm IS sieve. Natural and cemented CBR samples were thoroughly mixed with water, and the extension collar and base plate were attached to the mold with the disc mounted on top. The samples were compacted in five layers, each receiving 62 blows from a 4.5kg rammer dropped from a height of

450mm. The collar was then removed, and excess soil was trimmed to level with the mold. The mold was turned over, and the base plate and disc were removed. The mold was weighed to determine bulk and dry density, and cured in a tied polythene bag for 24 hours. After curing, the samples were mounted on the penetration test unit with the surcharge weight, and the penetration piston was centered on the specimen. The load and displacement dial gauges were set to zero, and the machine applied a load to the penetration plunger at a rate of 1.25mm/min. Load readings were recorded at specified intervals for both top and bottom. The samples were then immersed in water for 24 hours, and load readings were recorded again for the soaked samples.

2.2.5 Free swell test

Approximately 10 grams of soil passing through a BS No. 40 sieve (425µm aperture) was oven-dried and allowed to cool in a desiccator. The sample was then gradually poured into a 100cm³ measuring cylinder filled with water, which was agitated to form a homogeneous soil-water mixture. After allowing the mixture to swell for 24 hours, the swell volume was recorded. This comprehensive assessment provided invaluable insights into the effectiveness of the stabilization techniques employed.

3. Results and Discussions

3.1 Index Properties

The test results on the natural Black Cotton Soil (BCS) are shown in Table 2. The soil was classified as A-7-5(26) and clay (CL) under the AASHTO and USCS classification systems, respectively. The characteristics of the soil include a natural moisture content of 8.53%, a specific gravity of 2.60, a liquid limit of 80%, a plastic limit of 35.42%, and a plasticity index of 44.58%, with 90.25% of particles passing through the BS No. 200 sieve.

Table 2: Properties of Natural BCS

Properties		Quantities
% passing BS sieve no. 200		90.25%
Liquid Limit (LL) (%)		80
Plastic Limit (PL) (%)		35.42
Plasticity index (PI) (%)		44.58
AASHTO classification		A-7-6
USCS		CL
Group index		26
Specific gravity		2.6
Natural moisture content (%)		8.53
Color		Greyish black
Optimum moisture content (%)		18.8
Maximum dry density (mg/m³)		1.49
CBR	Unsoaked %	36.46
	Soaked %	6.80

Similarly, Gidigasu and Gawu [16] classified the soil as sandy-clay and silty-clay, reporting liquid limits ranging from 28% to 190% and plasticity indexes from 14% to 145%. Free swell varied between 50% and 220%. According to the AASHTO system, the soil is classified as A-7-5 and A-7-6, with group index values from 13 to 89. In the USCS, it is classified as CH and CL. These soils typically plot above the A-line on the Casagrande chart, indicating inorganic clay with low to very high plasticity. The CBR values of unsoaked samples are relatively high, but soaking significantly reduces these values.

3.2 Atterberg Limit Characteristics

The reduction in the liquid limit with higher percentages of cement and bagasse ash can be attributed to the decrease in free silt and clay in the soil, caused by cation exchange and the flocculation of clay particles. The lowest liquid limit observed was 57.4% at 8% ordinary Portland cement (OPC) and 12% bagasse ash (BA) with 80% black cotton soil (BCS). This is likely due to the pozzolanic properties of bagasse ash, which increase water demand at higher ash contents. Brajesh (2013) also noted a decrease in the liquid limit with the addition of cement/BA blends.

The plastic limit decreased from 35.42% for natural BCS to 28.3% at 8% OPC and 12% BA, possibly due to cation exchange reactions causing flocculation and releasing water from outer layers. The plasticity index of BCS reduced significantly from 44.58% after stabilization with BA and OPC. Lokesh *et al.* [18] observed a similar trend, with the plasticity index decreasing and falling into the range of moderate plasticity as the content of bagasse ash and lime increased.

The cement and black cotton soil blend reduced the shrinkage limit of the soil from 21.7% for the natural soil to 14.02% at 10% cement and 90% black cotton soil content, the cement, bagasse ash and black cotton blend, close to the lowest value is 8%CE, BA12% & 80% BCS, which is 14.88% as shown in the table.

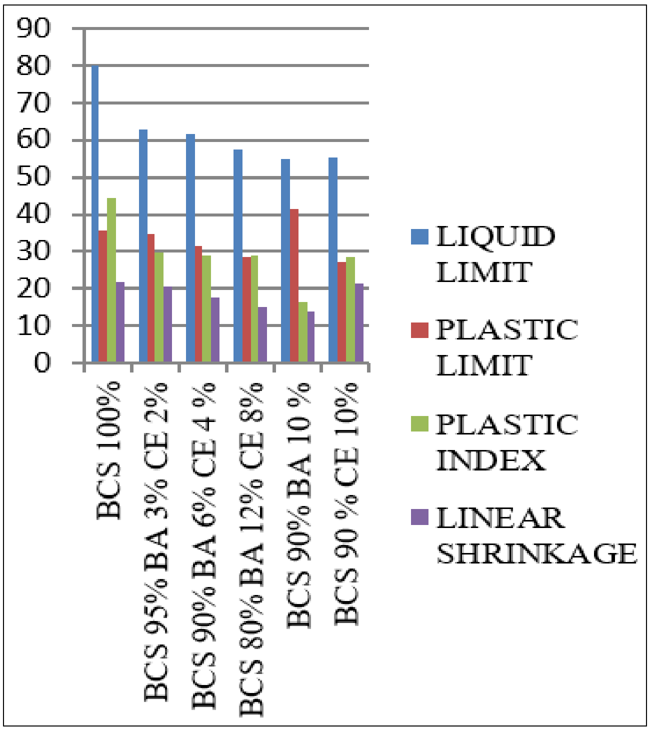


Fig 2: Effect of Bagasse Ash (BA) and Cement (CE) Stabilization on Atterberg Limits of Black Cotton Soil (BCS)

3.3 Compaction characteristics

The variations of OMC with OPC/BA blends of the British heavy energy levels are shown in Fig 2. There was an initial increase in OMC with an increase in cement/bagasse ash blend. The initial increment could have been as a result of increasing demand for water by various cations and the clay mineral particles to undergo a hydration reaction. The subsequent drop could have resulted from a cation exchange process that generated clay particle flocculation. The maximum dry density of the untreated soil was found to decrease with the addition of SBA-cement mixtures due to their light weight [19]. The optimum moisture content (OMC) increased while the maximum dry density (MDD) decreased with increasing bagasse and cement content.

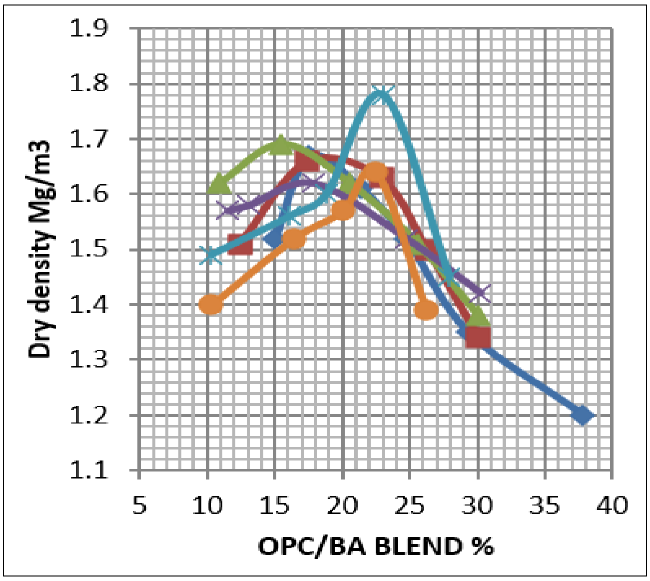


Fig 2: Variation of OMC with BA for various cement contents

3.4 California Bearing Ratio (CBR)

The CBR value is a vital measure of a soil's capacity to sustain loads. Accurate assessment of CBR is essential, as overestimation can cause pavement failure while underestimation leads to excessive and costly pavement design [20]. CBR testing is critical for evaluating the suitability of soil used in subgrades, capping, sub-bases, or base layers. To simulate how soil behaves in various conditions, CBR tests were conducted in both soaked and unsoaked conditions, in accordance with BS 1377-part 4. The results of this test are presented in Table 3.

Table 3: Deductions from CBR test

S. No	Description of Sample	CBR (%)	
		Unsoaked	Soaked
Control	BCS	36.49	6.80
2	BA 3% + CE 2%	37.43	6.71
3	BA 6% + CE 4 %	34.87	12.38
4	BA 12% + CE 8%	26.38	12.44
5	BA 10 %	17.95	3.99
6	CE 10%	42.60	20.03

Table 3 reveals a substantial increase in CBR values for both unsoaked and soaked. While the addition of bagasse ash enhanced the unsoaked strength, peaking at 37.43% with a 2% cement and 3% bagasse ash ratio, the soaked samples exhibited a significant strength reduction. Although neither condition met base course criteria (requiring a minimum CBR of 80%), specific mixtures (3% bagasse ash with 2% cement and 6% bagasse ash with 4% cement) exceeded the subgrade standard of 30% as outlined in Federal Ministry of Works and Housing guidelines [21].

4. Conclusion

1. The OPC/BA mixture influenced the index characteristics of the black cotton soil, but not enough to significantly reduce the liquid limit due to the high swelling properties of this particular black cotton soil.
2. Reactions similar to those of cement were observed from the strength gain, which showed improvements with increasing bagasse ash content.
3. The unsoaked CBR values 36.49%, 37.43%, 34.87%, 26.38% and 42.60% can be accepted as being adequate to satisfy the Nigerian General Specification (1997) as recommended for sub-base materials.
4. We can effectively use a cement/bagasse ash blend for the black cotton soil stabilization.

5. Recommendation

Based on the research findings, the following unsoaked values for cement, bagasse ash, and black cotton soil blends can be recommended as sub-base material in flexible pavement construction:

- 3% cement, 2% bagasse ash, 95% black cotton soil: CBR value of 36.49%
- 6% cement, 4% bagasse ash, 90% black cotton soil: CBR value of 37.43%
- 8% cement, 12% bagasse ash, 80% black cotton soil: CBR value of 34.87%
- 10% cement, 90% black cotton soil: CBR value of 42.60%

These blends demonstrate sufficient strength and can be effectively used as sub-base material, as the lower layers of flexible pavement are subjected to lower stress magnitudes, allowing for the use of lower-quality materials (Patel *et al.*, 2019). For future studies, further improvement could be achieved by increasing the amount of OPC/BA blend.

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