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A sustainable approach to soil stabilization: Geotechnical and microstructural insights into bagasse ash treatment

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Abstract

Expansive soils such as Black Cotton Soil pose major challenges to infrastructure due to their swelling behavior, necessitating sustainable stabilization methods using locally available industrial or agricultural waste materials. This study aims to evaluate bagasse ash (BA), an agro-industrial waste from Chittur sugar mills, as a sustainable stabilizer for improving the geotechnical properties of expansive Black cotton soil (BCS) in South India. Addressing the gap in the use of locally sourced waste for BCS stabilization, this study combines comprehensive geotechnical and microstructural analyses to enhance soil performance for infrastructure development. Laboratory and field tests revealed that untreated BCS has unfavored characteristics, such as high plasticity, low strength, and high swelling potential. Upon treatment with BA (5%, 10%, and 15% by weight), the soil exhibited improved strength, reduced plasticity, enhanced compaction characteristics, and a denser microstructure due to pozzolanic reactions. Scanning electron micrographs confirmed improved particle bonding and reduced porosity. The BA not only enhances the load-bearing capacity and durability of expansive soils but also addresses the environmental issue of waste disposal. This study provides a scientifically validated, low-cost, and sustainable alternative to conventional soil stabilizers, making it highly relevant for infrastructure development in expansive soil regions and contributing to the broader goals of green geotechnical engineering.

Keywords: Black cotton soil; Chittur; South India; Soil behavior; Geotechnical properties; Expansive soil

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1. Introduction

Black cotton soil (BCS) is highly problematic, causing severe construction issues due to its swelling and shrinking behavior. The montmorillonite clay mineral content of soil is plastic in nature, possesses low bearing capacity and poor permeability, and therefore is unsuitable for direct use in infrastructure development. BCS has geotechnical properties that can cause foundation failure, pavement spalling, and structural instability, particularly in Chittur, South India, where BCS incidents are common. BCS, characterized by montmorillonite clay minerals, exhibits expansive behavior due to mineral–water interactions. Stabilization approaches have traditionally relied on Portland cement or lime, which have high carbon footprints. Bagasse ash (BA), a byproduct of sugarcane processing, contains amorphous silica and reactive compounds that may trigger pozzolanic reactions in clay matrices. This study investigates whether BA can serve as an eco-friendly alternative stabilizer for BCS deposits. The disadvantages of BCS necessitate a thorough examination of engineering qualities to develop appropriate stabilization solutions that will improve its buildability.[1]

Black cotton soil is characterized by montmorillonite clay minerals, which account for its high plasticity and high water-retaining capacity. BCS is dark brown to black in coloration with a specific gravity of 2.5 to 2.7 (Table 1). Due to its remarkably high clay content and fine particle size, the natural water content of BCS ranges from 20% to 50%, depending on seasonal variation. The Atterberg limits of BCS are also expansive, with liquid limit ranging from 50% to 80%, plastic limit ranging from 20% to 35%, and plasticity index ranging from 25% to 45%.[2] These limits indicate a large change in response to variations in soil moisture content. The shrinkage limit of BCS is also remarkably low (8%–15%), which again verifies its high-volume instability. The compaction of BCS is low compared to other soils, with MDD of 1.3–1.7 g/cm^3 and OMC of 20%–25%. From the strength aspect, BCS has low engineering properties, with UCS of 50–150 kPa and CBR of 1%–5%, making it unable to carry heavy structural loads. BCS is also of very low permeability, with a coefficient of permeability (k) ranging from 10^{-7} to 10^{-9} cm/s, leading to poor drainage of the soil. BCS's swelling index is exceptionally high, ranging from 30% to 60%, further leading to structural instability when structures are constructed on such soil. According to SEM microstructural analysis, the soil is porous and has weak interparticle binding, making it highly water-sensitive. The aforementioned concerns need investigation into the efficiency of BA in soil stabilization due to its pozzolan properties.[3]

In the current study, we examined the physical, mechanical, and microstructural characteristics of BCS samples at different sites of Chittur District. Various laboratory and site tests were conducted, including specific gravity tests to determine the relative density of soil grains, water-content tests to determine the soil's natural water content, and tests to assess the soil's consistency and plasticity.[4] Additionally, a light compaction test was performed to determine the optimum moisture content (OMC) and maximum dry density (MDD), and a permeability test was conducted to assess the soil's water permeability rate. BCS strength parameters were examined using the unconfined compressive strength (UCS) and California bearing ratio (CBR) tests, which are the most critical parameters for determining soil stability and load-bearing capacity. The core cutter test was used to assess *in situ* density, and scanning electron microscopy (SEM) was used to quantify microstructural composition inside the soil. Because of the complexity of BCS, , efforts have been made to improve its engineering properties through various soil-stabilizing methods, including the use of industrial and agricultural wastes, which have recently gained attention for their cost-effectiveness and sustainability.[5]

The current study investigates the potential of BA, an agro-industrial byproduct of the sugar industry, as a BCS stabilizer. BA is a pozzolanic substance that, when blended into soil, has been demonstrated to increase strength, inhibit plasticity, and improve overall soil performance. BA used in the current work was collected as waste from Chittur sugar mills and blended with soil at 5%, 10%, and 15% by weight. Test values from treated samples were compared with control samples to estimate improvements in geotechnical properties.[6] The primary objective of this research is to investigate the feasibility of using BA as a soil stabilizer to enhance the strength properties of BCS, reduce its permeability, and modify its microstructural make-up. The addition of BA to BCS is expected to increase load-carrying capacity, reduce swelling potential, and enhance environmental durability. The study's conclusions have significant implications for construction in expansive soils, such as BCS, as they offer a sustainable and low-cost stabilization solution that minimizes the reliance on conventional stabilizers, including lime and cement, which are typically resource-intensive and expensive. In addition to addressing the engineering challenges posed by BCS, this research accompanies the overall aim of promoting sustainable building practices by leveraging industrial and agricultural wastes that would otherwise contribute to environmental contamination. The primary objectives of this study are to: (i) Evaluate the effectiveness of BA in improving the geotechnical properties (strength, plasticity, permeability, and compaction) of BCS from Chittur, South India; (ii) assess the impact of 5%, 10%, and 15% BA by weight through comprehensive geotechnical tests and microstructural analysis (SEM); and (iii) assess BA's potential as a sustainable, low-cost alternative to conventional stabilizers like lime and cement for infrastructure development. The scope of this study includes laboratory and field testing of Chittur's BCS, focusing on short-term stabilization effects and their applicability to road subgrades and foundations. By leveraging locally sourced BA, our study aims to provide practical guidelines for sustainable construction in expansive soil regions, addressing both engineering and environmental challenges. The study's outcome is expected to significantly enhance the soil's strength, density, and permeability, thereby improving its suitability for construction foundations, roads, and other infrastructural developments. The study also aims to identify the optimal BA proportion that yields the best stabilization effects, making the technique efficient and viable for large-scale application. The overall applicability of this research is far-reaching, spanning sustainable construction practice and policy, as it advances the employment of alternative materials that enhance the principles of the circular economy. Lastly, research on BCS and BA stabilization is essential to developing novel, sustainable soil stabilization techniques. Through comprehensive geotechnical testing on the effects of BA on BCS, this study provides useful insight into the potential of agricultural waste materials as green soil stabilizers. The outcomes are expected to contribute to the development of improved sustainable construction practices, particularly in regions like Chittur, where expansive soils have caused engineering challenges. Through this study, soil stabilization using BA not only improves construction but also promotes the utilization of industrial and agricultural waste, contributing to more sustainable and long-lasting infrastructure.

2. Materials and methods

Bagasse ash used in this study was sourced as an agro-industrial byproduct from sugarcane processing at sugar mills in Chittur, South India. During sugarcane juice extraction, the fibrous residue (bagasse) is combusted for energy, producing BA, a fine, light-grey to dark-grey powder with a specific gravity of 1.46 (Table 2). Chittur's sugarcane-rich economy ensures abundant BA availability, making it a cost-effective and locally accessible material for soil stabilization. The BA was oven-dried at 105 °C, crushed, and sieved through a 75 µm sieve to ensure uniformity and compatibility with BCS particles. Its high silica content (60–70% silicon dioxide [SiO_2]) imparts pozzolanic properties, enabling reactions with BCS's clay minerals to form cementitious compounds, such as calcium silicate hydrate (CSH), which enhance soil strength and reduce plasticity. BA was selected over conventional stabilizers, such as cement or lime, due to its low cost, local availability, and environmental benefits, including reduced landfill waste and lower carbon emissions compared to resource-intensive alternatives. The choice of 5%, 10%, and 15% BA by weight was informed by prior studies,[7] which indicated optimal pozzolanic activity within this range for expansive soils. This selection aligned with the study's objective to develop a sustainable, low-cost stabilization method for BCS, addressing both engineering and environmental challenges in Chittur's infrastructure development. Strength parameters were ascertained using the UCS test and the CBR, yielding vital information on soil stability and load-carrying capacity. A core cutter test was also conducted in the field to determine the *in situ* soil density. In addition, SEM analysis was performed to examine the microstructural properties of the soil, including particle orientation, pore structure, and interparticle bonding.

The experimental program was designed in accordance with Indian Standard specifications and comprised the following components: permeability and microstructural variations in BCS to examine its potential as an eco-friendly and cost-effective stabilizer. Samples were collected from different sites across Chittur District, where BCS deposits were prevalent. This multi-site approach ensured representative characterization of regional soil properties. Samples were air-dried, crushed to pass through a 4.75 mm sieve, and stored in sealed containers to prevent moisture loss. SEM micrographs of the untreated soil exhibited a highly porous structure with poor interparticle bonding, which accounts for its expansive nature and sensitivity towards moisture.

Table 1. Properties of black cotton soil

Properties	Value
Specific gravity	2.55
Maximum dry density	1.65 g/cc
Optimum moisture content	21%
California bearing ratio	2.52%
Liquid limit	63%
Plastic limit	36%
Plasticity index	28%
Color	Black

Table 2. Properties of bagasse ash

Properties	Value
Specific gravity	1.46
Maximum dry density	1.26 g/cc
Optimum moisture content	35%
Plastic nature	Non-plastic
Color	Dark Black

3. Results and discussion

From an environmental perspective, using BA as a stabilizer diverts agro-industrial waste from landfills, reducing disposal costs and environmental pollution. Compared to conventional stabilizers like cement, which have high carbon footprints due to production processes, BA requires only drying and sieving, minimizing energy use. This approach conserves natural resources and supports sustainable construction practices by repurposing waste materials. SEM analysis, a sophisticated method not commonly used in BCS stabilization studies, revealed significant microstructural changes in BA-treated samples. Untreated BCS exhibited a dispersed microstructure with large voids and weak interparticle bonding, contributing to its poor load-bearing capacity and water sensitivity. With 5% BA, void spaces were reduced as fine ash particles filled the interspaces between clay platelets, improving packing. At 10% BA, SEM images confirmed the formation of cementitious compounds (CSH and calcium aluminate hydrate [CAH]) that enhanced particle cohesion. The 15% BA sample exhibited a highly dense microstructure with minimal porosity and strong bonding due to sustained pozzolanic reactions, correlating with increased UCS (178 kPa) and CBR (7.96%). These findings underscore SEM's critical role in elucidating the mechanisms behind BA's stabilization efficacy. The pozzolanic reaction of BA with BCS clay minerals is responsible for the creation of cementitious phases, which enhance soil strength over a period of time.

3.1. Specific gravity

The specific gravity test was also conducted on the soil samples to examine the ratio of the weight of a specified volume of soil to that of an equal volume of water. This characteristic is important in geotechnical engineering because it affects soil properties, such as compaction, permeability, and shear strength.[8] Specific gravity of BCS was 2.55, which is a common value of fine-grained soils with comparably dense structures to other soils. Incorporation of BA as a stabilizer in varying percentages resulted in a specific gravity with a gradual decrease. The specific gravity of BCS + 5% BA was 2.49, which decreased to 2.44 in the case of BCS + 10% BA and to 2.42 in BCS + 15% BA. It can be observed that the specific gravity decreased because of the low specific gravity of BA (1.41).[9] The inclusion of BA in the mixture replaced some of the heavier soil particles, thereby lowering the overall specific gravity of the soil. A reduction in specific gravity is also evidence of increased stabilization, as it can reduce swelling and shrinkage, two of the most common problems associated with BCS. The results indicate the promising potential of BA as a cost-effective and environmentally friendly stabilizer for problematic soils in sustainable soil improvement processes. The test results are presented in Table 3.

Table 3. Specific gravity of black cotton soil (BCS) with bagasse ash

Bagasse ash (%)	Specific gravity
0% (untreated BCS)	2.55
5%	2.49
10%	2.44
15%	2.42

The low specific gravity of BA also results from its lower density than soil particles. As a light agro-industrial waste, when incorporated into soil, it can reduce the unit weight of BCS. This reduction in soil unit weight is useful for applications requiring low-density material; therefore, sub-grade layers and embankment layers are not capable of withstanding heavy loads due to settlement.[10]

3.2. Water content

The water content was determined based on the percentage of water in the soil sample by weight.[9] The initial water content of BCS was 22.6%, characteristic of expansive soils and reflects their high moisture retention capacity. The water content of the resulting mixes increased moderately with increasing BA percentages in BCS. Water content in mix BCS + 5% BA was 24.3%, while the mixtures at BCS + 10% BA were increased to 25.7%. BCS + 15% BA showed the highest water content of 27.1% (Table 4). The increase in water content after incorporating BA could be due to the ash's absorptive nature, which retains moisture throughout the stabilization process.[11] While the rise is modest, it suggests that the BA had minimal impact on soil water retention. Therefore, incorporating BA could improve the engineering properties of BCS without significantly altering its water retention characteristics.

3.3. Liquid, plastic, and shrinkage limits

Liquid, plastic, and shrinkage limit tests were conducted to investigate the plasticity properties of BCS and the impact of BA as a stabilizer. The liquid limit of the native BCS was 62%, indicating high plasticity and a significant potential for volumetric change with variations in moisture content. The plastic limit of BCS were 37%, with a plasticity index of 29%. This suggests that BCS tends to deform significantly under stress. When BA was added to BCS in different proportions, significant variations in plasticity were observed. For BCS + 5% BA, the liquid limit and plastic limit decreased to 59% and 36%, respectively, with the plasticity index decreased to 23%. At 10% BA, the liquid limit further decreased to 56%, while the plastic limit increased to 39%, further reducing the plasticity index to 16%. Lastly, for BCS + 15% BA, the liquid limit was decreased to 52%, the plastic limit increased to 43%, and the plasticity index decreased to 11% (Table 5). These results indicate that the addition of BA has significantly reduced the plasticity index and liquid limit, soil parameters that reflect workability and plasticity.[12] This suggests that the soil became less water-absorbing, thereby becoming more stabilizable and controllable for construction. Additionally, the shrinkage limit improved with the incorporation of BA, indicating that the volume change behavior of the soil under dry conditions would not be extreme, further enhancing its applicability to infrastructure projects.

Table 4. Water content test

Bagasse ash	Water content (%)
0% (untreated black cotton soil)	22.5%
5%	24.3%
10%	25.7%
15%	27.1%

Table 5. Liquid limit, plastic limit, and shrinkage limit

Bagasse ash	Liquid limit	Plastic limit	Shrinkage limit
0% (untreated black cotton soil)	62%	37%	29%
5%	59%	36%	23%
10%	56%	39%	16%
15%	52%	43%	11%

3.4. Compaction characteristics of black cotton soil

Maximum dry density and OMC of BCS and the mixture with BA were assessed using compaction tests. It is one of the most critical parameters for evaluating the soil's ability to achieve adequate densification under applied compaction energy, thereby influencing its strength and stability in construction applications. The MDD of untreated BCS was 1.54 g/cc, with OMC of 19.7%. This indicates that the soil is fine-grained and expansive, exhibiting relatively low compaction property and a high moisture content at its densest state.[13] The inclusion of BA markedly altered the compaction behavior. At 5% BA, the MDD decreased to 1.51 g/cc, and OMC increased to 21.4%. With 10% BA mixture, MDD was further decreased to 1.48 g/cc, and the OMC was further increased to 23.1%. At 15% BA, MDD was lowest (1.44 g/cc), and the OMC was highest (24.7%) (Table 6).

Table 6. Compaction test

Bagasse ash	Maximum dry density	Optimum moisture content
0% (Untreated black cotton soil)	1.54 g/cc	19.7%
5%	1.51 g/cc	21.4%
10%	1.48 g/cc	23.1%
15%	1.44 g/cc	24.7%

3.5. Permeability test

The permeability test was conducted to measure the extent to which water permeates through the soil mixtures.[14] As permeability is a vital property for estimating drainage behavior, the soil's capacity to hold water indicates its stability in construction.[14] Untreated BCS is characterized by high clay content and small particle size, resulting in poor drainage. Untreated BCS had a coefficient of permeability (k) of approximately 1.07×10^{-6} cm/s, indicating highly restricted water movement through the soil. Such low permeability causes water to be retained in the soil, gradually reducing its strength due to repeated swelling and shrinkage. There was a marginal rise in permeability upon the incorporation of BA. At 5% BA, the coefficient increased to 1.23×10^{-6} cm/s, with a marginal rise in water movement. The permeability further increased to 1.39×10^{-6} cm/s with 10% BA. While for 15% BA, it was 1.55×10^{-6} cm/s (Table 7). This indicates that the addition of BA increases permeability, albeit marginally.[15]

Table 7. Permeability test

Bagasse ash	Permeability value (cm/s)
0% (Untreated black cotton soil)	1.07×10^{-6}
5%	1.23×10^{-6}
10%	1.39×10^{-6}
15%	1.55×10^{-6}

3.6. Unconfined compressive strength test

The UCS test was performed to investigate the strength parameters of BCS prior to and after stabilization using BA, as shown in. UCS is among the most important parameters in geotechnical engineering.[16] It defines the soil's capability to resist axial compressive loads without lateral confinement. A relatively low UCS of 84 kPa was observed in untreated BCS. This may be due to poor particle bonding, high moisture retention, and expansiveness. This relatively low strength has rendered BCS unsuitable for direct construction under the designed and approved loading conditions. As a result, excess deformation and structural stability issues arise in various structures, such as roads and foundations. Upon stabilization with BA, there was a substantial increase in UCS values. UCS increased to 112 kPa at 5% BA through enhancement by pozzolanic reactions between the silica in BA and the clay minerals in BCS. An additional increase in BA content from 5 to 10% further improved UCS to 149 kPa, indicating better cohesion and lower moisture sensitivity. The UCS value at 15% BA was the highest, at 178 kPa (Table 8). This value confirms that the stabilizer binds soil particles, reduces soil shrinkage, and improves soil bearing capacity. The increase in UCS with the addition of BA may be due to the cementing compounds that develop and reduce plasticity as interparticle bonding increases in the soil.

3.7. California bearing ratio

The CBR test is crucial for determining subgrade soil load-bearing capacity, particularly in foundation and pavement design.[17] Swelling and shrinkage are intrinsic characteristics of BCS, with typical CBR values that are too low for direct use in road construction. We conducted the CBR test for untreated BCS and BCS stabilized with different percentages of BA—5%, 10%, and 15%—to assess the strength and load resistance. Untreated BCS exhibited a CBR of 2.13%, demonstrating low bearing capacity and low resistance to traffic loads. At 5% BA, the CBR increased to 3.46%, indicating improved soil cohesion and thereby reducing water absorption. Increasing the BA content to 10% resulted in a CBR value of 5.88%, attributed to the formation of pozzolanic reaction products. These reaction products enhanced interparticle bonding, leading to a further increase in CBR to 7.96% at 15% BA, indicating an optimal level of stabilization (Table 9). The stabilized BCS is resilient, non-compressible, and resistant to deformation under loading at this state. The increase in CBR by incorporating BA is based on pozzolanic reactions, which fill voids in the soil and increase the density and compactness of the aggregate. However, stability in the soil is not ensured by more than 15% content, as such ashes deteriorate the clay content and the cohesion between them. These findings show that BA markedly enhances the CBR value of BCS and thus can be utilized effectively in road subgrades and foundation works.

Table 8. Unconfined compressive strength test

Bagasse ash	Compressive strength (kPa)
0% (Untreated black cotton soil)	84
5%	112
10%	149
15%	178

Table 9. California bearing ratio test result

Bagasse ash	California bearing ratio (%)
0% (Untreated black cotton soil)	2.13
5%	3.46
10%	5.88
15%	7.96

3.8. Core cutter test

The core cutter test is a site test conducted *in situ* across the soil to determine moisture content and density, which are key to assessing compaction efficiency and load-carrying capacity. As BCS has high shrinkage and swelling susceptibility and high moisture retention capacity, its natural density is extremely low, and stabilization of the soil with additives such as BA is usually necessary to improve its compaction behavior. The core cutter test was conducted in this study on untreated BCS and BCS stabilized with 5%, 10%, and 15% BA to determine the change in field density. The bulk density of untreated BCS was initially 1.44 g/cc, hence loose in nature and not compactible to a great extent. Bulk density increased to 1.57 g/cc after 5% addition of BA. The addition of BA increased soil compaction through the filler action of ash particles. In the case of 10% BA, the density increased to 1.74 g/cc due to the pozzolanic reaction, which increased the bonding among soil particles. The maximum bulk density of 1.89 g/cc was achieved at 15% BA (Table 10), marking the stabilization point at which the soil structure was highly dense and resistant to volume change.[18] The soil density increased with the addition of BA due to improved particle arrangement, since the finer ash particles filled the gaps between soil grains, thereby minimizing pores.

Additionally, the pozzolanic character is responsible for the cementation, thereby improving the soil stability.

Table 10. Core cutter test result

Bagasse ash	California bearing ratio (g/cc)
0% (Untreated black cotton soil)	1.44
5%	1.57
10%	1.74
15%	1.89

3.9. Scanning electron microscopy analysis

Scanning electron microscopy is a powerful method for studying the microstructural properties of soil and its alteration after stabilization. In this study, the fine imaging on the structure and bonding of the soil particles and their pore structure was established, as well as how BA influences the BCS microstructure.Because BCS has a high content of montmorillonite, it has a loose, porous microstructure consisting of weakly bonded particles; therefore, it swells and shrinks easily, as shown in Figure 1. The incorporation of BA, a pozzolanic material, alters the aforementioned property, thereby improving the microstructural stability of BCS. SEM analysis showed that the untreated BCS sample contained a dispersed microstructure with notable voids, and interparticle bonding was weak, which accounts for its poor load-bearing capacity and water sensitivity. 5% BA inclusion led to a significant reduction in void space because the fine ash particles occupied the space between the clay platelets, thereby improving the packing density. In 10% BA, SEM images revealed the formation of cementitious compounds, including CSH and CAH. For the 15% BA, the microstructure appeared highly dense, with minimal porosity and soil particles well bonded by pozzolanic reactions that continued to take place.

5. Limitations and future research

The present investigation has several inherent limitations that should be acknowledged. The BA content was limited to a maximum of 15% by dry weight of soil, so the behavior of BCS at higher BA dosages (for example, 20–25%) remains unknown, including the possibility of diminishing returns or adverse effects at elevated replacement levels. Additionally, long-term performance was not evaluated, as all tests were conducted over relatively short curing periods without monitoring under in-service conditions; consequently, the response of BA-treated BCS to extended exposure and aging cannot be confirmed. In a previous study, the addition of BA produced maximum immediate (58.3%), early (20.7%), and delayed (32.7%) strength gains, and strength and stiffness increased significantly over several months.[19] Related to this, durability under cyclic environmental loading was not assessed in the current study because wet–dry and freeze–thaw cycles were not performed; the resilience of the stabilized soil to repeated moisture and temperature variations remains unresolved. Cyclic wetting–drying strongly affects the swelling and degradation of stabilized expansive clays.[20] The study is also geographically constrained, being based on BCS from a single locality, so the findings and the identified "optimum" BA content may not be generalizable to soils with different mineralogical or organic characteristics in other regions. In addition, our work did not include a parallel program using conventional stabilizers, such as lime or cement, so a direct comparison of strength gain, durability, cost, and carbon footprint is unavailable within the same experimental framework. For example, a previous study used BA in place of ordinary Portland cement in expansive soils.[21]

From a geotechnical design perspective, only index, compaction, and compressive strength parameters were determined; fundamental shear strength parameters, such as cohesion and internal friction angle, were not investigated in this study. This limits the direct application of the results to bearing capacity and stability analyses

Field validation was limited to *in situ* density measurements using the core cutter method, and no field strength or stiffness tests (such as dynamic cone penetrometer or plate load tests) were conducted. Therefore, the correlation between laboratory performance and actual field behavior remains to be established. In addition to laboratory results, further field trials are recommended, such as using a dynamic cone penetrometer to assess field strength.[22] The influence of BA's initial moisture condition, which is inherently hygroscopic, on mixing homogeneity, compaction response, and subsequent strength development was not systematically investigated, even though this factor may be important under varying site conditions. In a previous study, OMC increased from 13.5% to 19.1% (fly ash) and 15.26% (BA) at up to 12.5% addition.[23]

Environmental aspects were also outside the scope of the current study: leaching characteristics, heavy metal mobility, and compliance with environmental regulations were not examined. Therefore, the long-term environmental safety of BA-stabilized BCS cannot be fully assured. Leaching characteristics and environmental performance are increasingly regarded as critical for

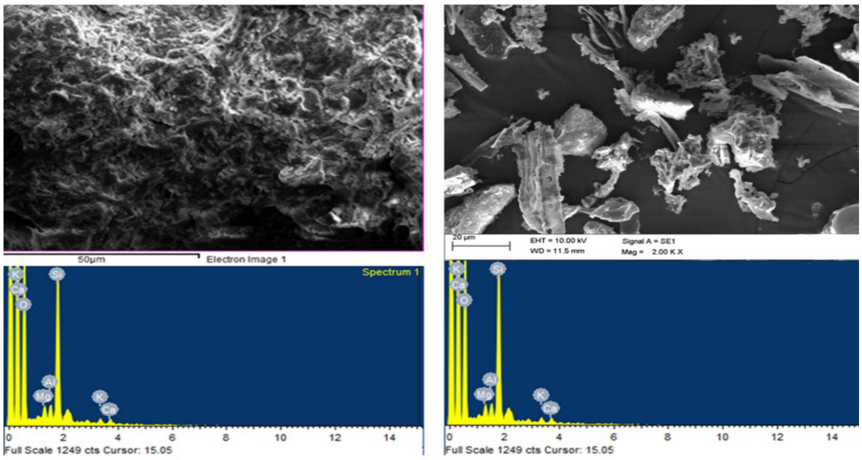

Figure 1. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses of black cotton soil samples. (A) SEM image of raw soil. Scale bar: 50 µm; magnification: 500 ×. (B) SEM image of raw soil. Scale bar: 10 µm; magnification: 1,000 ×. (C) EDS spectrum from raw soil (spectrum 1); key elements: oxygen, silicon, aluminium, and iron. (D) EDS spectrum from raw soil (spectrum 2); confirming composition consistency.

waste-derived binders.[24] Practical construction aspects, such as workable time after mixing and the impact of delayed compaction, were not studied. Therefore, guidance on handling and placement windows in site conditions is not available from the current data. Mixing, transport, and compaction delays can influence the field performance of pozzolan-stabilized soils.[2] The BA was used in a single, sieved condition, and no parametric study on particle size distribution was undertaken; therefore, the relative roles of filler effects versus pozzolanic reactivity as a function of BA grading are not resolved. Sugarcane BA particle size resulted in 50% acceleration of the pozzolanic reaction, while fineness strongly influences the reaction kinetics.[25]

The entire program was conducted at laboratory scale, without pilot or full-scale trial sections, leaving open questions about constructability, quality control, and performance under real traffic and loading conditions.

Swelling pressure, a critical parameter for expansive soils, was not measured in the current study. Therefore, the extent to which BA treatment can control heaving under restrained conditions remains uncertain.

6. Conclusion

This investigation of BA as a stabilizer for BCS from Chittur District, Tamil Nadu, demonstrates significant potential for practical application and environmental sustainability. The key findings of this study are as follows:

Using BA as a stabilizer provides a sustainable, low-cost solution to improve the geotechnical properties of BCS, making it suitable for infrastructure projects such as roads and foundations in expansive soil regions. This approach supports circular economy principles by repurposing agro-industrial waste and reducing reliance on resource-intensive stabilizers like cement. Based on experimental investigations of BA-stabilized BCS, significant improvements in geotechnical characteristics were observed, suggesting it as a viable option for construction. The specific gravity of untreated BCS was 2.55; adding 15% BA reduced it to 2.42 because the ash had a lower density than the soil particles. The moisture content also increased with the addition of BA, from 22.5% to 27.1%, due to BA's higher moisture retention property. The BA-stabilized BCS showed improved plasticity and workability, with a low risk of shrinkage. The liquid limit, which was 62% for raw BCS, decreased to 52% with 15% BA replacement, whereas the plastic limit increased from 37% to 43%. The shrinkage limit was also significantly reduced from 29% to 11%, which is useful for minimizing volumetric variance caused by changes in moisture content. The decrease in plasticity characteristics is a beneficial component of soil management and behavior. The compaction behavior was analyzed, in which it was observed that as the BA content increased, MDD decreased from 1.54 g/cc to 1.44 g/cc due to the lower density of BA particles. Conversely, the optimum moisture content (OMC) increased from 19.7% to 24.7% as BA content increased, reflecting the greater water demand of the mixture and its improved workability during compaction. The permeability profile also improved slightly, with the value increasing from 1.07×10^{-6} cm/s to 1.55×10^{-6} cm/s, indicating better drainage and a lower risk of waterlogging. Strength parameters also improved to a greater extent, as the stabilized soil had a higher bearing capacity. UCS values increased significantly from

84 kPa to 178 kPa, indicating a tighter, more compacted soil matrix. CBR also increased from 2.13% to 7.96%, indicating greater soil strength and stability. Field density tests also indicated enhanced compaction, with the bulk density rising from 1.44 g/cc to 1.89 g/cc. BA demonstrates promise as an eco-friendly stabilizer for BCS, offering economic and environmental benefits. However, the realization of large-scale infrastructure applications requires systematic investigation of long-term durability, regional generalizability, and comprehensive performance characteristics as detailed above. The sustainability potential is significant: utilizing agricultural waste while reducing cement demand aligns with circular economy principles and India's environmental commitments.

Taken together, the incorporation of BA at weights of 5%, 10%, and 15% in BCS led to an enhancement in the soil characteristics. The plasticity of soil reduces, thus lowering its shrink–swell capacity and strengthening its stability. The compaction properties improve as MDD increases and OMC decreases. Increased load-carrying capacity is reflected in the strength parameters; UCS and CBR also increased significantly, which improved the soil's suitability for construction. The permeability of the soil further decreases as there is less opportunity to retain excess water, thereby improving its strength.SEM indicates that the treated soil possesses a more compact microstructure with reduced porosity and improved interparticle bonding strength. As a low-cost stabilizer, it can also improve the geotechnical properties of BCS, thereby making infrastructure development easier in the Chittur area.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

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Availability of data

Data are not openly available. Data are available upon request.

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