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Composite Behavior of Bagasse Ash Stabilized Expansive Soil with Sodium Benzophenone Under Curing Conditions

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Abstract

The present investigation examines the development of a hybrid composite using Black Cotton (BC) soil, Bagasse Ash (BA), and Sodium Benzophenone (SBP) as performance-enhancing elements. Different ratios of BA, a silica-rich agro-industrial by-product, were added to improve pozzolanic reactivity and particle size distribution (0%, 6%, and 12%). SBP was added in the range of 0–0.6% as a compatibilizer in order to enhance interfacial adhesion, particle cohesivity and moisture-assisted deterioration resistance. Composite specimens were prepared by applying controlled compaction and tested for their engineering behavior using Standard Proctor test, Unconfined Compressive Strength (UCS) tests and microstructural examination by adopting Scanning Electron Microscopy (SEM). The best packing was observed at 10% BA and 0.2% SBP, which gave the highest dry density and optimum moisture content. A more pronounced strength increase was observed according to the results of the UCS test, where the maximum value at 10%BA and 0.4%SBP after 30 days curing, exceeded over 60 per cent improvement in strength compared with untreated BC soil. SEM images showed a dense paste with fewer pores and stronger particle contact, caused by BA's pozzolanic reaction and SBP's chemical modification. These results show that blending agro-waste with chemical processing produces strong and economical composite material. This material displays excellent compaction properties, gradual strength improvement, and intact microstructure, suggesting significant promise for eco-friendly engineering and structural uses requiring increased longevity and weight-bearing capability.

Keywords: Composite materials, soil stabilization, bagasse ash, sodium benzophenone, expansive soil, pozzolanic reaction, compaction behavior, unconfined compressive strength

INTRODUCTION

Composite materials are defined as multiphase systems in which two or more constituents are combined to produce a material with enhanced physical, chemical, and mechanical properties. In such systems, the matrix phase serves to distribute stress and bind the reinforcement phase, which may be particulate, fibrous, or chemical in nature. The resulting performance depends on factors such as phase compatibility, interfacial bonding, particle dispersion, and microstructural evolution under different curing and loading conditions [1-2]. Black Cotton Soil (BCS) is a fine-grained clay formed from volcanic and basaltic rock. It contains montmorillonite, which swells when wet and shrinks when dry [3]. BCS covers nearly 15% of the landmass in India and poses a substantial material challenge due to its dimensional instability, low

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strength, and high-water sensitivity. However, its properties improve when combined with reactive fillers and chemical modifiers in a composite system [4]. In this study, BCS is modified using Bagasse Ash (BA) a pozzolanic agro-industrial by-product and Sodium Benzophenone (SBP), an organic radical-forming compound. Bagasse Ash (BA) comes from burning sugarcane residue at about 500 °C. It contains amorphous silica, which reacts with lime to form cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C-A-H) [5-6]. These compounds contribute to microstructural densification, reduced porosity, and increased load-bearing capacity. Additionally, the angular particle morphology and high surface area of BA enhances mechanical interlocking and internal cohesion [6]. Sodium Benzophenone (SBP), though primarily used in organic chemistry for solvent activation, forms benzophenone ketyl radicals upon one-electron reduction in the presence of alkali metals or water traces. These radicals alter the electrochemical environment within the matrix, potentially enhancing cation exchange, dehydration of diffuse clay layers, and interfacial bonding [7-8]. SBP is new in soil composites but offers a way to change particle surfaces and speed up early strength through radical reactions [9]. The formulation of a ternary composite system consisting of BCS (matrix), BA (filler), and SBP (chemical modifier) enables a hybrid design pathway. The study focuses on how this system behaves under different curing conditions, with an emphasis on compaction characteristics and unconfined compressive strength (UCS). The performance of such systems depends on the progressive development of hydration products, reaction-induced phase transformations, and structural refinement all of which are governed by curing duration and mix composition [10]. Traditional stabilizers such as lime, cement, and chloride salts primarily act through ionic exchange, pozzolanic gel formation, or flocculation. While effective, these methods often require high dosages, involve high carbon footprints (lime/cement), and may lose efficiency under varying moisture conditions [11-13]. In contrast, sodium benzophenone (SBP) provides a radical-mediated stabilization mechanism. Upon one-electron reduction, SBP generates benzophenone ketyl radicals, which modify the surface charge of clay minerals, dehydrate diffuse double layers, and create hydrophobic interphases that enhance moisture resistance [14-15]. This radical pathway complements the pozzolanic activity of Bagasse Ash (BA). Reactive silica from BA interacts with SBP-derived radicals, promoting early gel nucleation and microstructural densification. Such synergy is not observed with conventional stabilizers, which typically rely only on ionic flocculation or long-term hydration products. Moreover, radical-based modification has been shown in hybrid organic–inorganic composites to improve interfacial adhesion, reduce porosity, and accelerate early strength development [16-17]. These characteristics motivated the selection of SBP as a chemical modifier in the present study, aiming to introduce both rapid strength gain and durable long-term stabilization through a hybrid chemical–radical mechanism. The novelty of this research lies in exploring an organically modified pozzolanic composite system, using non-conventional chemical and mineral additives. It not only proposes a sustainable solution by utilizing industrial and agricultural waste but also advances the science of inorganic–organic hybrid composites through a microstructure-driven performance model.

LITERATURE REVIEW

Composite systems derived from soil matrices have gained considerable attention due to their ability to integrate industrial by-products and chemical agents for performance enhancement. Expansive soils like Black Cotton Soil (BCS) exhibit low strength and high-volume instability, making them suitable candidates for stabilization using pozzolanic fillers and chemical modifiers. Several studies have demonstrated that sodium carbonate and calcium carbonate significantly reduce the plasticity index and improve the unconfined compressive strength (UCS) of expansive soils, with sodium carbonate showing higher efficiency in controlling swelling [18]. Improved compaction and CBR values have been reported in expansive soils treated with lime and bagasse ash (BA), with 3% lime and 15% BA yielding optimal pozzolanic reactions and strength development [19]. Waste sawdust ash (WSDA) improved dry density and reduced permeability in BCS at 2% dosage, though excess ash content reduced compaction quality [20]. The incorporation of 10% BA into BCS produced significant UCS gains, particularly after 28 days of curing, emphasizing the role of time-dependent pozzolanic reactions [21]. Chemical modifiers such as sodium chloride have shown early strength improvements due to ion exchange and flocculation mechanisms [22], while chloride salts reduce the swelling potential of expansive clays through ionic surface alterations [23]. Ground granulated blast furnace slag (GGBS) has been shown to improve compaction and UCS by inducing secondary gel formation [24], and alkali-activated binders have enhanced stiffness and early strength through geopolymerization [25]. Natural pozzolans and fly ash–lime combinations have been shown to improve shear strength and reduce void ratios, correlating strength gains with microstructural densification [26-27].

Polymer-based chemical modifiers have also shown measurable gains in expansive clays. Polyacrylamide (PAM), when combined with conventional binders, improves UCS and CBR while reducing swelling by flocculating fines and forming a flexible polymer network at particle contacts. Ethylene-vinyl acetate (EVA) copolymer emulsions and proprietary polymer binders have likewise yielded higher early strength and reduced moisture sensitivity in subgrades, indicating that organic chains can supplement ionic and pozzolanic mechanisms through film formation and interparticle bridging [28]. Beyond bulk polymers, silane coupling agents improve compatibility at mineral–organic interfaces. Aminosilanes (e.g., APTES/KH550) react with surface –OH groups on clays or aggregates to form covalent siloxane bonds while presenting organophilic tails to the binder/polymer phase. Reported effects include lower water uptake, stronger interfacial adhesion, and better mechanical performance due to reduced interfacial debonding under wet conditions [29]. These results support using surface chemistry to complement pozzolanic and ionic stabilization routes.

On the chemical front, benzophenone-derived radicals have been reported to enhance interfacial bonding in hybrid materials, suggesting possible benefits in soil composites [30]. Photoinitiated free-radical systems provide a relevant analogue for SBP-type chemistry. Benzophenone and related initiators abstract hydrogen or accept electrons to generate surface-bound radicals that trigger grafting or crosslinking under mild conditions. Reviews of photoinitiated and surface-immobilized photoinitiators show that light-driven radical formation can functionalize oxide and polymer surfaces, strengthen interphases, and increase hydrophobicity mechanisms that plausibly translate to soil–ash systems when ketyl species or photo-active fragments are present [30-31]. Thermal and redox initiators further illustrate how radical pathways tailor interfacial bonding. Benzoyl peroxide (BPO) and AIBN are widely used to initiate polymerization and grafting in filled composites and molecularly imprinted polymers, improving network continuity around particles. Emerging frontal polymerization approaches exploit exothermic radical reactions to cure materials rapidly and uniformly, suggesting future routes to field-friendly hybrid binders where localized heat or chemical triggers establish robust interparticle bridges [32]. Persulfate and Fenton-type systems, though primarily used for in-situ chemical oxidation in contaminated soils, also demonstrate that radical oxidants can modify mineral/organic surfaces and pore chemistries. Studies report effective oxidation under Fe-activated or ultrasonic persulfate and classic Fe^{2+}/H_2O_2 Fenton conditions [33-34]. While the objective in remediation is contaminant destruction rather than strength gain, these works highlight controllable radical environments in soils that can, in principle, alter wettability, surface charge, and bonding, factors relevant to stabilization design.

Though Sodium Benzophenone (SBP) has not been widely studied in soil systems, its ability to generate ketyl radicals under alkaline and dry conditions implies potential for modifying particle interactions and early-stage matrix behavior. BA lime blends in silty soil have shown improvements in water resistance and strength due to long-term pozzolanic activity [35], while microsilica lime stabilization enhances modulus of elasticity and UCS by improving interparticle packing and reactivity [36]. Cement–fly ash combinations have outperformed individual binders in strength performance [37], and the reuse of industrial waste has been supported as a sustainable solution for soil stabilization [38]. Lime phosphogypsum mixtures have been found to form strength-contributing ettringite and gels [39], while lime–rice husk ash blends have demonstrated improvements in UCS, CBR, and soaked durability [40]. These studies collectively support the value of composite design in geotechnical applications and highlight a gap in the exploration of radical-modified soil systems, especially those incorporating SBP as a potential microstructure-altering agent in ternary soil composites.

MATERIALS AND COMPOSITE FORMULATION

In the present investigation, a ternary composite system was developed using Black Cotton Soil (BCS) as the matrix phase, Bagasse Ash (BA) as a reactive mineral filler, and Sodium Benzophenone (SBP) as a chemical modifier. The main objective was to improve the compaction and shear strength characteristics of expansive soil by exploiting multi-phase interactions typical of hybrid particulate composites. The approach leverages particle rearrangement, pozzolanic gel formation, and radical-induced interfacial bonding, particularly under desiccator curing conditions. This design strategy aligns with composite behavior models, where improved matrix–filler–modifier synergy results in enhanced mechanical performance and durability [41].

The materials used in this formulation are shown in Figure 1, which includes (a) Black Cotton Soil collected from Haveri District, Karnataka, characterized by its high swelling potential, (b) Bagasse Ash obtained from sugarcane waste incineration, exhibiting pozzolanic reactivity due to its amorphous silica content, and (c) Sodium Benzophenone, a laboratory-grade organic compound used to enhance surface energy and promote radical modification in composite matrices. These materials were carefully selected for their complementary roles in the formation of a chemically and mechanically integrated composite system, suitable for expansive soil stabilization applications.

Matrix Phase: Black Cotton Soil (BCS)

The BCS used in this study was collected from Haveri District, Karnataka (14.6610° N, 75.4345° E). The soil is classified as CI (Intermediate plastic clay) based on Unified Soil Classification System (USCS). Its physical characteristics, summarized in Table 1, show a specific gravity of 2.41 and a predominantly fine-grained texture, with 65% clay and 29% silt. The soil exhibits high swelling and shrinkage behavior due to its expansive clay minerals, particularly montmorillonite, making it a poor candidate for structural applications unless stabilized. In a composite framework, such soils serve as weaker matrices, which require modification to achieve structural adequacy [42].

Filler Phase: Bagasse Ash (BA)

Bagasse Ash is obtained by controlled incineration of sugarcane bagasse at approximately 500°C. The material is lightweight, grey in colour, and contains high proportions of amorphous silica, which contributes significantly to pozzolanic activity. The physical properties of BA are listed in Table 2. It possesses non-plastic behavior, and its fine nature helps it fill micro voids between soil particles. In the composite system, BA plays a dual role: (1) as a physical filler improving the particle packing, and (2) as a chemical agent, reacting with soil calcium hydroxide to form cementitious products like calcium silicate hydrate (C–S–H), enhancing strength and durability [43-44].

Figure 1. Materials used in the experiments, (a). Black cotton soil, (b). Bagasse ash sample, (c). sodium benzophenone.

Table 1. Physical properties of black cotton soil used in this study.

Properties	Specific gravity	Particle size distribution		Unified classification
		Sand fraction (%)	*Silt & Clay*	
Black cotton soil	2.41	65%	29%	CI

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Table 2. Physical properties of Bagasse Ash (BA) including Atterberg limits and particle size distribution.

Properties	Colour pale	Specific gravity	Plastic limit (%)	Atterberg limits (%)`		Particle size distribution		
				Liquid limit (%)	*Plastic limit (%)*	*Fine sand (%)*	*Silt (%)*	*Clay (%)*
Values	Grey	1.61	Non plastic	63	Non plastic	77.20	22.80(silt & clay)	

Table 3. Physical and chemical properties of sodium benzophenone (SBP) as tested at bengaluru test house.

Property	Value
Colour	Light Yellow
Odour	Flowery
Boiling Point	582.6 °F at 760 mm Hg
Melting Point	47.8 °C
Density	1.085 at 50 °C
Flash Point	> 270 °F
Solubility in Water	<1 mg/mL
Water Solubility	137 mg/L at 25 °C
Vapor Pressure	1.93×10^{-3} mm Hg at 25 °C

Sodium Benzophenone (SBP)

Sodium Benzophenone (SBP) is a radical-generating organic compound that appears as pale-yellow crystals with a distinctive floral odor. It is soluble in organic solvents, and only marginally soluble in water. Its unique role in this composite system is due to its ability to form ketyl radicals upon reaction with alkali metals, especially under dry or curing conditions. These radicals are hypothesized to contribute to surface activation and molecular-level bonding at the soil–ash–moisture interface. The presence of SBP is expected to modify interfacial surface energies, allowing better dispersion and contact of particles in the ternary system. The physical and chemical characteristics of SBP, tested at Bangalore Test House, are presented in Table 3 [45].

Composite Design Strategy and Mechanistic Interpretation

The experimental matrix was designed to evaluate the composite behavior of the BCS BA SBP system under different curing conditions. The investigation was carried out in two phases. In the first phase, BCS was blended with 5%, 10%, 15%, and 20% BA by weight and tested for compaction and UCS behavior. Based on optimal strength gain, 10% BA was selected as the optimum content. In the second phase, SBP was added to the BCS + 10% BA system in 0.2%, 0.4%, 0.6%, and 0.8% dosages and tested under immediate, 7-day, and 30-day desiccator curing to evaluate its radical enhancement effect on strength development. The testing followed IS:2720-Part VII (Compaction) and Part X (UCS) procedures [46].

Experimental Testing and Curing Protocol

Two primary tests were conducted on each composite mix:

- Standard Proctor Compaction Test (IS 2720 Part VII) to determine MDD and OMC
- Unconfined Compressive Strength (UCS) (IS 2720 Part X) to assess shear strength

Specimens were cast in cylindrical molds (38 mm diameter × 76 mm height) and subjected to three curing regimes:

- Immediate Testing (0 days)
- Short-Term Curing (7 days)
- Long-Term Curing (30 days)

Table 4. Experimental program showing mix proportions, test types, and curing periods.

S n	Mix configuration	Tests conducted	Curing period (days)
1	BCS (control)	Compaction, UCS	0, 7, 30
2	BCS + 5–20% BA	Compaction, UCS	0, 7, 30
3	BCS + Optimum BA + 0.2–0.8% SBP	Compaction, UCS	0, 7, 30

Table 5. Results of optimum moisture content and maximum dry density of different combinations of bagasse ash, black cotton.

Combination	Dry density (g/cc)	Optimum moisture content (%)
BCS Alone	15.3	23.25
BCS + 5% BA	14.7	28.67
BCS + 10% BA	14.7	26.59
BCS + 15% BA	13.8	30.72
BCS + 20% BA	14.3	30.57

Curing was performed in sealed desiccators at controlled room temperature to allow hydration and radical-based interaction to evolve with time. A summary of the experimental program is given in Table 4.

This formulation strategy enables the study of how multi-phase interactions, especially radical-induced bonding and pozzolanic reactivity, influence the macro-mechanical behavior of the soil composite system.

RESULTS AND DISCUSSIONS

This section discusses the effect of Bagasse Ash (BA) and Sodium Benzophenone (SBP) on the compaction behavior and strength performance of Black Cotton Soil (BCS), considering both immediate and time-dependent effects. Composite mechanisms such as filler densification, chemical reactivity, and radical modification are used to interpret the experimental results.

Compaction Characteristics of BCS with Bagasse Ash

The compaction behavior of Black Cotton Soil (BCS) was examined by blending it with varying percentages of Bagasse Ash (BA) specifically 5%, 10%, 15%, and 20% by dry weight to evaluate its influence on Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). These parameters are crucial for assessing compaction efficiency and structural suitability. Standard Proctor compaction tests were conducted as IS 2720 (Part VII). The results are presented in Table 5, and the trends are graphically illustrated in Figure 2.

As observed from Table 5, there is a progressive reduction in dry density with increasing BA content. This trend is attributed to the lower specific gravity of BA (1.61) compared to that of BCS (2.41). The inclusion of BA leads to a dilution effect, which reduces the unit weight of the compacted mixture. Notably, at 10% BA, the dry density stabilizes, indicating a potential optimum for particle rearrangement and interfacial compatibility between the BA and BCS particles. Beyond this point, further addition of BA increases internal voids due to poor particle packing, thereby reducing the density. On the other hand, OMC increases consistently with higher BA content. This behavior is due to the high porosity and surface area of BA particles, which absorb more water. Additionally, BA requires more water for lubrication during compaction, enhancing its workability but also increasing moisture demand.

From a composite material standpoint, BA functions as a reactive particulate filler, which influences the porosity, packing density, and moisture absorption characteristics of the blend. These findings are consistent with composite densification theories, where the introduction of a low-density, high-porosity filler alters the compaction response through physical interaction and surface chemistry effects [47]. Figure 2 visually presents the variations in MDD and OMC across the different BA percentages, further supporting the observations discussed above.

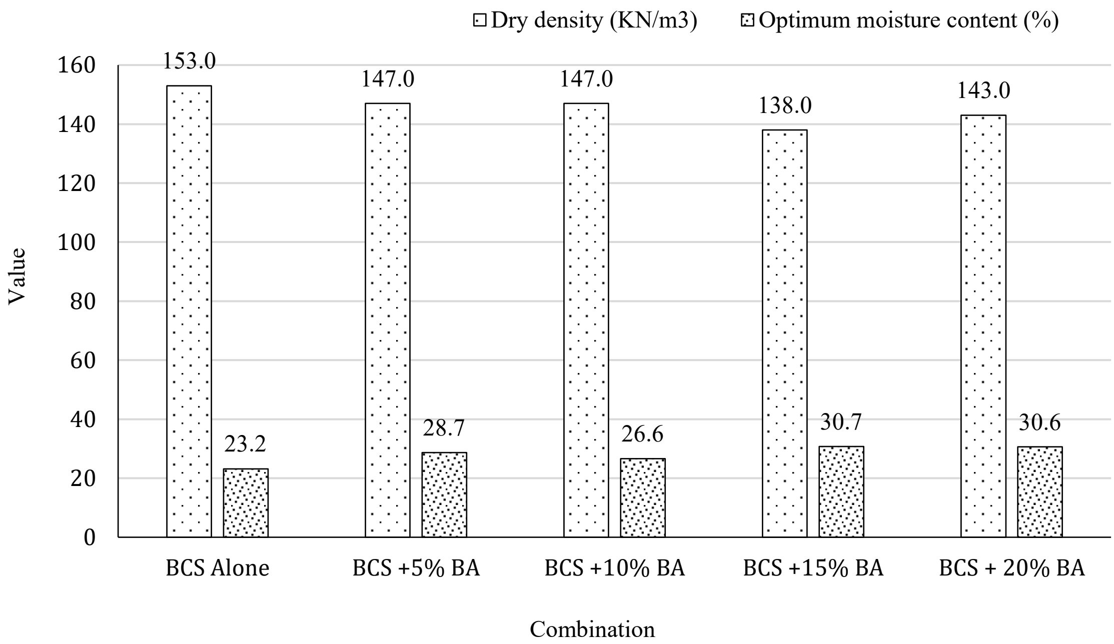

Figure 2. Variation of maximum dry density (MDD, g/cc) and optimum moisture content (OMC, %) for black cotton soil with different bagasse ash (BA) contents.

Table 6. Compaction characteristics of BCS + 10% BA with varying SBP.

Combination	Dry density (g/cc)	Optimum moisture content (%)
BCS Alone	15.3	23.25
BCS + 10% BA (Optimum BA)	14.7	26.59
BCS + 10% BA + 0.2% SBP	14.0	31.00
BCS + 10% BA + 0.4% SBP	14.4	26.12
BCS + 10% BA + 0.6% SBP	13.9	25.42
BCS + 10% BA + 0.8% SBP	14.0	23.83

Effect of Sodium Benzophenone on Compaction Characteristics (with Optimum BA)

In this phase of the study, black cotton soil (BCS) was first blended with the optimum dosage of bagasse ash (BA) at 10%, and then further modified with varying percentages of sodium benzophenone (SBP) specifically 0.2%, 0.4%, 0.6%, and 0.8%. The objective was to observe how SBP, acting as a chemical modifier, affects the compaction characteristics of the soil–ash matrix, particularly the maximum dry density (MDD) and optimum moisture content (OMC). The results of this investigation are summarized in Table 6 and illustrated in Figure 3.

The results show a non-linear influence of SBP on both dry density and moisture content. When 0.2% SBP was introduced, there was a sharp decline in dry density and a noticeable spike in OMC. This suggests that at lower dosages, SBP may temporarily disrupt the interparticle bonding or alter the hydration dynamics, possibly due to incomplete interaction or weak surface bonding within the matrix. However, as the SBP dosage increased to 0.4% and 0.6%, an improvement in dry density was observed along with a reduction in moisture content. This trend, evident from Table 6, indicates enhanced interfacial bonding and more effective packing of particles, likely facilitated by SBP radicals promoting better contact and microscale stabilization. The combination with 0.6% SBP particularly exhibited favorable compaction behavior, implying it to be the most effective dosage in terms of enhancing soil structure and reducing water demand. Beyond this point, at 0.8% SBP, no significant improvement in compaction was observed; in fact, the values stabilized or slightly declined, suggesting a possible saturation of active bonding sites or chemical interference in the pozzolanic activity.

The variation in compaction behavior is further clarified in Figure 3, which presents a comparative bar graph of dry density and OMC across all combinations. The graph highlights the inverse relationship between the two parameters and visually reinforces the trend that SBP has a peak performance around the 0.6% dosage. From a composite materials perspective, the addition of SBP does more than physically alter the soil structure; it actively influences the surface chemistry and energy states within the BCS–BA system. The observed changes affirm that compaction characteristics in chemically treated soils are driven not just by mechanical interaction, but also by complex interfacial reactions, which can be optimized for better engineering performance.

Effect of Bagasse Ash On Strength Behavior of Black Cotton Soil

To evaluate the contribution of Bagasse Ash (BA) to the strength development of black cotton soil (BCS), unconfined compressive strength (UCS) tests were conducted on BCS treated with varying percentages of BA 5%, 10%, 15%, and 20% over three curing periods: 0, 7, and 30 days. These tests were performed in accordance with IS 2720 Part X. The inclusion of BA introduces a reactive pozzolanic phase into the soil matrix, facilitating the formation of secondary cementitious gels over time. This mechanism enhances interparticle bonding and densifies the soil structure as curing progresses. The strength values obtained for each combination are summarized in Table 7.

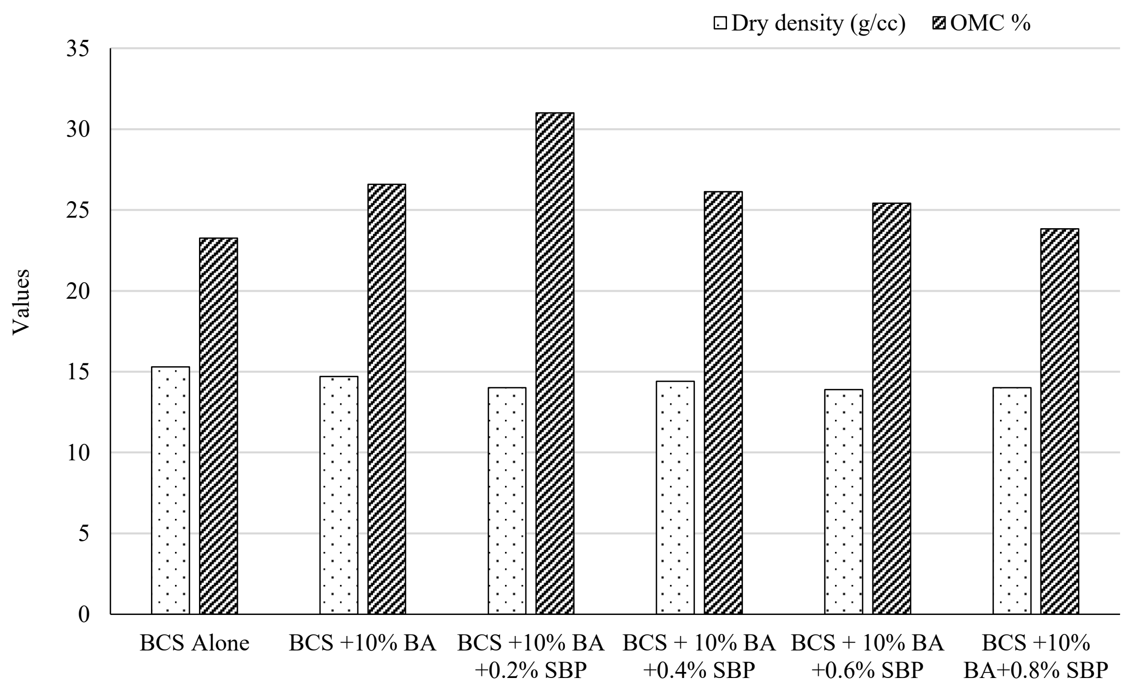

Figure 3. Effect of sodium benzophenone (SBP) dosage on maximum dry density (MDD, g/cc) and optimum moisture content (OMC, %) for BCS + 10% BA system.

Table 7. Unconfined compressive strength (UCS, kPa) of black cotton soil stabilized with different bagasse Ash (BA) contents at 0-, 7-, and 30-days curing.

Combination	UCS (kPa) - 0 days	UCS (kPa) - 7 days	UCS (kPa) - 30 days
BCS Alone	313.2	313.2	313.2
BCS + 5% BA	313.3	753.0	504.66
BCS + 10% BA	826.2	1204.0	663.48
BCS + 15% BA	491.1	552.4	317.23
BCS + 20% BA	235.6	637.4	292.83

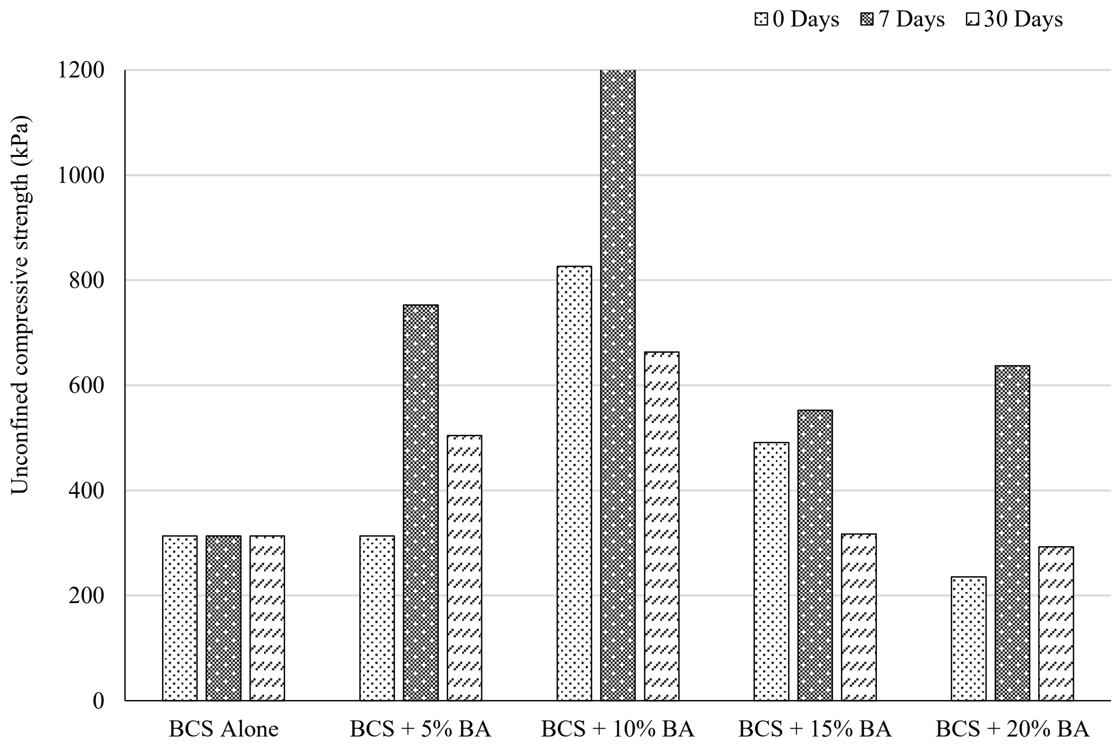

Figure 4. Unconfined compressive strength (UCS, kPa) of BCS stabilized with bagasse Ash (BA) at different curing periods (0, 7, and 30 days).

The UCS results indicate a clear time-dependent strength gain due to the pozzolanic reaction between the amorphous silica present in BA and the free lime in the soil as shown in figure 4. The untreated BCS (control mix) showed a constant UCS of 313.2 kPa across all curing periods, reflecting its inherently weak structure and lack of reactive components. With the addition of BA at 5% and 10%, there is a substantial improvement in strength. The mix with 10% BA achieved the highest UCS of 1204.0 kPa at 7 days, which indicates an optimal balance between the filler effect and pozzolanic reactivity. The early strength of 826.2 kPa at 0 days for this mix is likely due to improved particle packing and densification, while the significant gain by 7 days can be attributed to the formation of calcium silicate hydrate (C–S–H) gel, which effectively fills voids and bonds particles together.

However, beyond 10% BA particularly at 15% and 20% the UCS begins to decline, especially after 30 days. This reduction is explained by the dilution effect: higher ash content leads to an overabundance of non-cohesive fines that weaken the matrix continuity. Additionally, the pozzolanic reaction becomes limited due to insufficient calcium availability, resulting in incomplete binder formation. Therefore, although BA acts as a dual-phase material first as a filler improving compaction, and later as a reactive pozzolan enhancing long-term strength its effectiveness is highly dosage-sensitive. The trend is visually captured in Figure 4, where the UCS progression for each BA content and curing period is presented. The figure clearly highlights the superior performance of the 10% BA mix and the diminishing returns beyond this percentage. From a composite material perspective, the results underscore the importance of balancing physical and chemical interactions to achieve optimal performance in soil stabilization systems [34].

Effect of SBP on Strength (with Optimum BA)

To further improve the performance of the 10% BA–BCS blend, SBP was added in varying dosages (0.2% to 0.8%). UCS was measured for each ternary mix at different curing intervals, as shown in Table 8.

Table 8. UCS of BCS + 10% BA + Varying % of SBP.

Combination	UCS (kPa) - 0 Days	UCS (kPa) - 7 Days	UCS (kPa) - 30 Days
BCS Alone	313.2	313.2	313.2
BCS + 10% BA + 0.2% SBP	261.87	467.39	610.37
BCS + 10% BA + 0.4% SBP	588.79	423.70	527.11
BCS + 10% BA + 0.6% SBP	474.27	763.10	781.04
BCS + 10% BA + 0.8% SBP	445.97	512.69	613.34

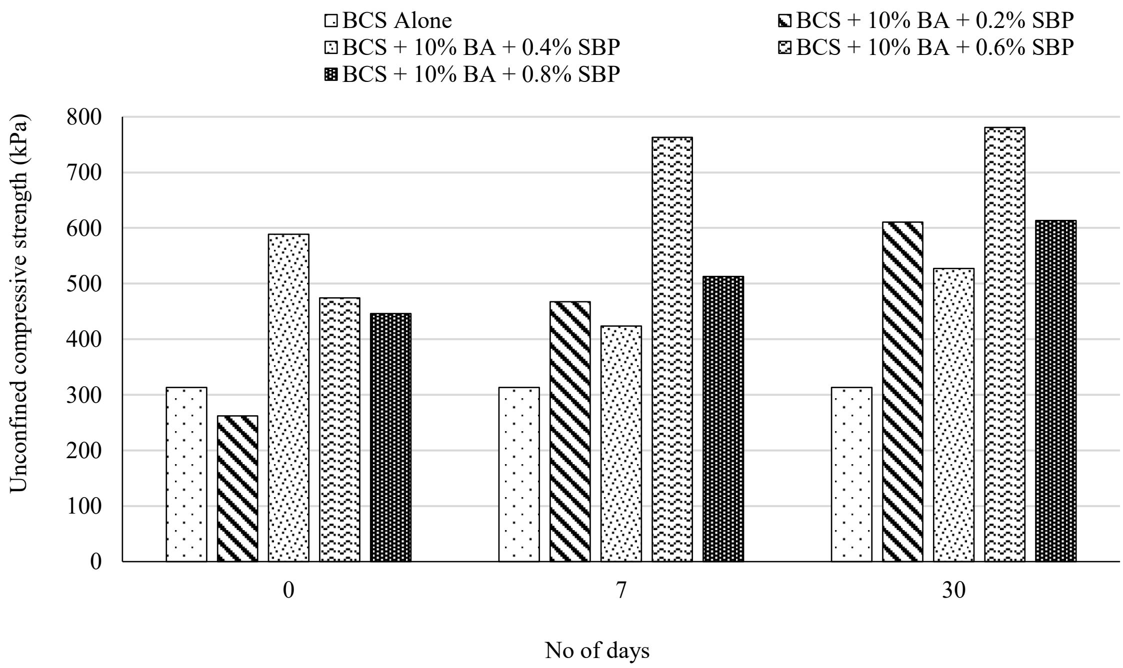

Figure 5. Unconfined compressive strength (UCS, kPa) of BCS + 10% BA with varying sodium benzophenone (SBP) contents under different curing periods (0, 7, and 30 days).

SBP demonstrates a complex but effective modification mechanism. The maximum long-term strength (781.04 kPa) was obtained at 0.6% SBP after 30 days, making it the optimum dosage as shown in figure 5. SBP likely enhances interparticle bonding through radical activation at the clay-filler interface. The ketyl radicals generated in the alkaline environment bond with free ions or reactive silica, forming stable crosslinks and hydrophobic layers that resist moisture reabsorption and promote curing. Lower dosages (0.2%) underperform initially due to insufficient radical density, though long-term performance improves. At 0.4%, early UCS is high, possibly from fast-set interactions, but lacks sustained gel growth. Beyond 0.6%, SBP begins to interfere with hydration reactions and weakens the gel phase due to radical oversaturation or reduced pH, a common behavior observed in chemically modified hybrid composites. These observations align with composite system theory, where strength enhancement relies on achieving a balance between matrix–filler–modifier interactions. Too little SBP underutilizes the system's potential, while too much destabilizes hydration and interfacial adhesion [48-49].

Interpretation of Composite Mechanism

The improvement in mechanical performance of the treated Black Cotton Soil (BCS) results from the synergistic interactions between the matrix phase (BCS), mineral filler (Bagasse Ash, BA), and chemical modifier (Sodium Benzophenone, SBP). Each component plays a specific functional role that contributes to the overall behavior of the ternary composite system, particularly under varying curing conditions. Bagasse Ash acts as a reactive pozzolanic filler, supplying amorphous silica that reacts with calcium ions liberated from the soil matrix to form secondary cementitious compounds, primarily calcium silicate hydrate (C–S–H) gels. These gels not only enhance particle bonding but also densify the soil structure by filling micropores and improving interparticle friction. This explains the substantial strength gain at 10% BA, especially after 7 days of curing, when pozzolanic reactions are most active.

Sodium Benzophenone contributes to strength development via chemical surface modification. Upon exposure to an alkaline and low-moisture environment, SBP generates ketyl radicals that modify clay particle surfaces by altering their electrochemical charge and promoting the formation of hydrophobic polymer-like layers. This mechanism improves interfacial bonding between the fine soil particles and the ash filler, contributing to improved strength and durability, particularly at 0.6% dosage. Furthermore, SBP may assist in reducing moisture ingress during curing, thereby promoting stable gel formation and delaying structural degradation. The evolution of strength across curing periods confirms the time-dependent nature of composite hardening. The optimal performance is governed by:

- Particle-packing optimization through fine ash particles improving matrix density,
- Hydration-induced pozzolanic reactions forming durable binder gels (C–S–H),
- Radical surface activation by SBP enhancing interfacial adhesion and hydrophobicity,
- And phase synergy under controlled curing, which aligns well with hybrid composite theory, where phase compatibility, dispersion, and interfacial transition zones (ITZs) dictate mechanical behavior [50].

These findings collectively validate the composite approach for soil stabilization, where filler reinforcement and chemical functionalization can be tailored to optimize geotechnical performance. The improved compressive strength and densification of the ternary blend confirm that BA–SBP–BCS systems behave as reactive particulate composites rather than simple additive mixtures.

CONCLUSIONS

- In summary, the addition of Bagasse Ash (BA) to Black Cotton (BC) soil led to increased strength, reaching an optimal concentration of 10% BA. Beyond this threshold, soil strength declined. This enhanced strength may result from a pozzolanic reaction or BA acting as a filler material, making 10% BA the ideal stabilization percentage.
- Furthermore, the introduction of Sodium Benzophenone (SBP) to BC soil treated with the recommended BA dosage revealed intriguing trends. Optimal moisture content and maximum dry density decreased as SBP content increased. This change may be due to alterations in soil structure or potential reactions between SBP and soil moisture.
- Additionally, investigating the combined effect of SBP with the ideal BA concentration revealed that soil strength increased, peaking at 0.6% SBP, with an initial boost at 0.4% SBP. This phenomenon could be attributed to cluster formation within the soil matrix, enhancing immediate strength. Over time, with curing, soil bonding strength improved until a critical point was reached, causing cluster breakage and reduced strength.
- In conclusion, combining BA and SBP effectively enhances BC soil strength and stability. Further research into the interaction mechanisms, including pozzolanic reactions and cluster formation, is needed to refine soil stabilization techniques for practical applications.

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