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Red Earth Development of a Soil-Based Composite Using Bagasse Ash and Lime: Effects on Plasticity and Compaction Characteristics of Red Earth

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Abstract

The concept of sustainable soil composites (SSC) emerges through blending red earth with bagasse ash (BA) and hydrated lime to enhance geotechnical properties and enable productive reuse of agro-industrial waste. Red earth functions as the matrix, BA acts as a fine pozzolanic microfiller, and lime serves as the chemical binder. BA content ranges from 0% to 60%, with 10% identified as optimal; subsequent lime additions from 1% to 5% evaluate the combined influence. Laboratory investigations in accordance with IS 2720 standards determine Atterberg limits, compaction parameters, and curing-related changes at 0, 7, and 30 days. SEM imaging shows transformation from porous BA particles to a dense, interlocked matrix, and XRD confirms formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) phases, indicating early-stage pozzolanic activity. Initial BA incorporation increases the liquid limit due to high water affinity; curing decreases the value as cementitious bonds develop. BA increases Optimum Moisture Content (OMC) and decreases Maximum Dry Density (MDD) because of its low specific gravity. At optimum BA content, lime addition reduces plasticity and improves structural strength, with 3–4% lime providing the best balance between density and workability. The red earth–BA–lime composite delivers tunable engineering performance, long-term stability, and eco-efficiency, offering a practical solution for subgrade stabilization and sustainable geotechnical applications aligned with circular economy objectives.

Keywords: Soil stabilization, bagasse ash, lime, red earth, composite materials, pozzolanic reaction, compaction behavior

INTRODUCTION

The increasing demand for land due to urbanization and infrastructure development has placed immense pressure on the geotechnical capabilities of naturally occurring soils. In central India, Red Earth soil is widespread and often considered suboptimal for foundational applications due to its variability in consistency, moderate plasticity, and sensitivity to moisture fluctuations [1-2]. Classified under ferrallitic soil groups, Red Earth exhibits characteristics ranging from sandy loam to clayey loam and possesses moderate mineral content that contributes to its limited binding potential [3]. The engineering behavior of such native soils can be significantly improved through stabilization techniques that integrate supplementary materials. Among the viable solutions is the utilization of bagasse ash (BA), a byproduct of sugarcane processing, which is abundantly generated in tropical countries such as India and Brazil [4]. Its

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disposal continues to present a waste management challenge, despite its potential as a sustainable construction material due to its high silica content and pozzolanic reactivity [5-6]. BA can react with calcium hydroxide, released either from Portland cement or lime, to form calcium silicate hydrates (C–S–H), contributing to improved strength and microstructural integrity [7-8].

Lime, a traditional binder used in soil stabilization, reacts chemically with siliceous and aluminous compounds in clayey soils to form durable cementitious gels, such as C–A–H and C–S–H [9]. When used in combination with pozzolanic additives like bagasse ash, it enhances soil workability and supports long-term strength gains through progressive curing [10].

The combined use of bagasse ash (BA) and lime has been reported in multiple studies to yield superior stabilization effects compared to using either additive alone. BA, with its high amorphous silica content, reacts with lime-derived calcium hydroxide to produce cementitious gels (C–S–H and C–A–H), which densify the soil matrix and reduce plasticity [11-12]. Previous research on expansive and clayey soils has consistently shown that BA–lime mixtures improve compaction behavior, increase strength, and enhance durability under curing [13-14]. These findings provide a strong foundation for the present study, which extends this approach to red earth soil. This chemical synergy forms the basis of engineered soil-based composites. Recent advances have reframed such stabilized systems as particulate composites, where soil acts as a matrix, bagasse ash functions as a reactive microfiller, and lime behaves as a chemical binder [15-16]. The resulting ternary composite system demonstrates significant improvements in strength, water retention, volume stability, and microstructural density. This study investigates the development of a Red Earth–BA–lime composite, focusing on its plasticity and compaction behavior, supported by microstructural evidence. Through systematic variation in mix proportions and curing durations, the research aims to validate this composite system for sustainable subgrade applications.

LITERATURE REVIEW

Numerous investigations have confirmed the efficacy of agro-industrial waste in geotechnical enhancement. Studies [17] demonstrated the viability of bagasse ash as a partial stabilizer in expansive soils, where its amorphous silica content played a vital role in reducing plasticity and improving strength. Similarly, work reported in [18] established the influence of waste-based amendments in creating more compactable and cohesive soil matrices. A materials-science perspective on stabilized soils has further confirmed their classification as particulate composites. Author [19] evaluated eggshell lime as a sustainable binder, highlighting improvements in matrix densification and strength under prolonged curing. Findings in [20] reported enhanced mechanical behavior in lime-stabilized soil composites through controlled hydration kinetics. Studies [21-22] confirmed that high-reactivity pozzolans, including BA, contribute to the development of composite microstructures by forming secondary cementitious phases. In clayey soils treated with lime and reactive ash, strength development correlates with the formation of C–S–H and C–A–H gels that enhance cohesion and reduce permeability [23]. Furthermore, references [24] emphasized that mineralogical transformations in treated soils can lead to semi-permanent enhancements in geotechnical properties. Evidence from [25] supported SEM and XRD-based internal restructuring of lime–ash–soil systems. These findings support the premise of this study that soils treated with bagasse ash and lime can be considered sustainable composites exhibiting tailored engineering properties suitable for modern geotechnical applications.

MATERIALS AND COMPOSITE FORMULATION

The experimental program involved preparing a composite material system using red earth as the matrix, bagasse ash (BA) as the pozzolanic filler, and hydrated lime as the chemical binder. The materials were characterized for their physical and chemical properties prior to mix formulation. The matrix–filler–binder system was studied by varying the BA content from 0% to 60% by weight of red earth in increments of 10% (i.e., 0%, 10%, 20%, 30%, 40%, 50%, and 60%). Based on preliminary tests, 10% BA was identified as the optimum dosage. At this optimum BA level, lime was added in incremental percentages ranging from 1% to 5% (i.e., 1%, 2%, 3%, 4%, and 5%) to assess its effect on composite behavior [26-27].

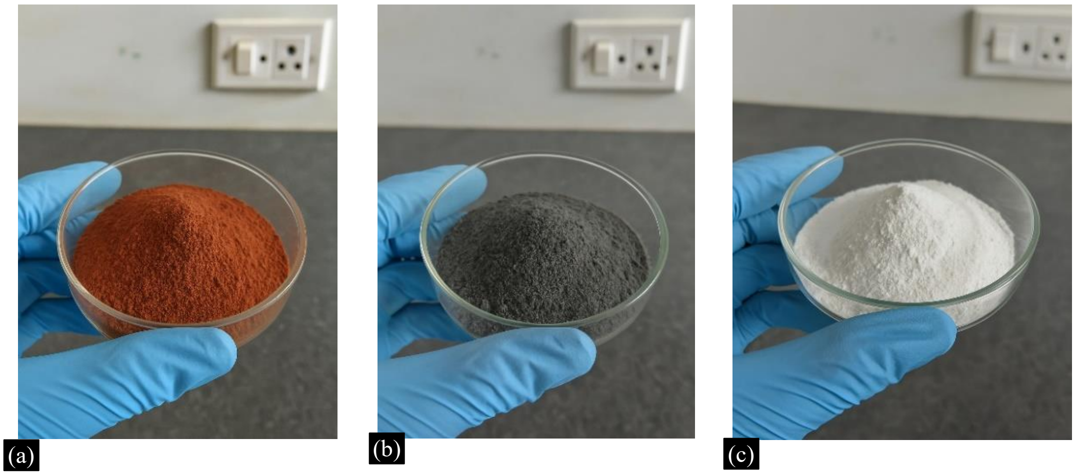

Figure 1. Materials used in the experiments, (a). Red earth sample, (b). Bagasse ash sample, (c). Lime sample.

The red earth was collected from Yelahanka, Karnataka, exhibiting a reddish hue due to high iron oxide content and was classified as a CI-type soil based on its Atterberg limits and grain size distribution. The key physical properties of the red earth and bagasse ash are summarized in Table 1, which highlights differences in specific gravity, grain size distribution, and plasticity behavior. BA was obtained from Mandya Sugar Factory and exhibited a high silt-size fraction and low specific gravity (1.8), contributing to its high-water absorption and pozzolanic reactivity. Hydrated lime, sourced from Vasa Scientific, Bengaluru, was used for its high $Ca(OH)_2$ content (>90%). The detailed chemical composition of the lime is presented in Table 2, emphasizing its purity and minimal impurities, which ensure strong chemical reactivity in the composite matrix. All materials pictures taken in the laboratory showed in Figure 1.

All materials were characterized according to IS 2720 standards before composite mix preparation. The combination ratios were based on incremental BA and lime percentages ranging from 0% to 60% and 1% to 5%, respectively. Table 1 presents the physical and chemical properties of red earth and bagasse ash used in the study. The data provides a basis for understanding the material characteristics that influence their suitability and performance in the experimental program. Table 2 summarizes the chemical properties of lime used as a stabilizing agent. These properties are essential for evaluating its reactivity and role in improving the engineering behavior of the treated materials.

Table 1. Properties of red earth and bagasse ash.

Properties	**Red earth**	**Bagasse ash**
Colour	***Red***	***Pale grey***
Specific Gravity	2.55	1.8
Particle size variation.		
Sand (%)	15.78	77.2
Silt (%)	68.22	22.80(silt + clay)
Clay (%)	16	-
AITERBERG'S limits	45	63
LL (%)	21	Non-Plastic
PL (%)	14	-
UCS (Kpa)	210	-
Unified classification	CI	-
Compaction characteristics		
Maximum Dry Density (kN/m^3)	17.77	10.59
Optimum moisture content (%)	19	45

Table 2. Chemical properties of lime

Component	Content (%)
$Ca(OH)_2$	≥ 90.00
Chloride (Cl)	0.04
Sulphate (SO_4)	0.40
Arsenic (As)	0.0004
Lead (Pb)	0.004
Insoluble Matter	1.00

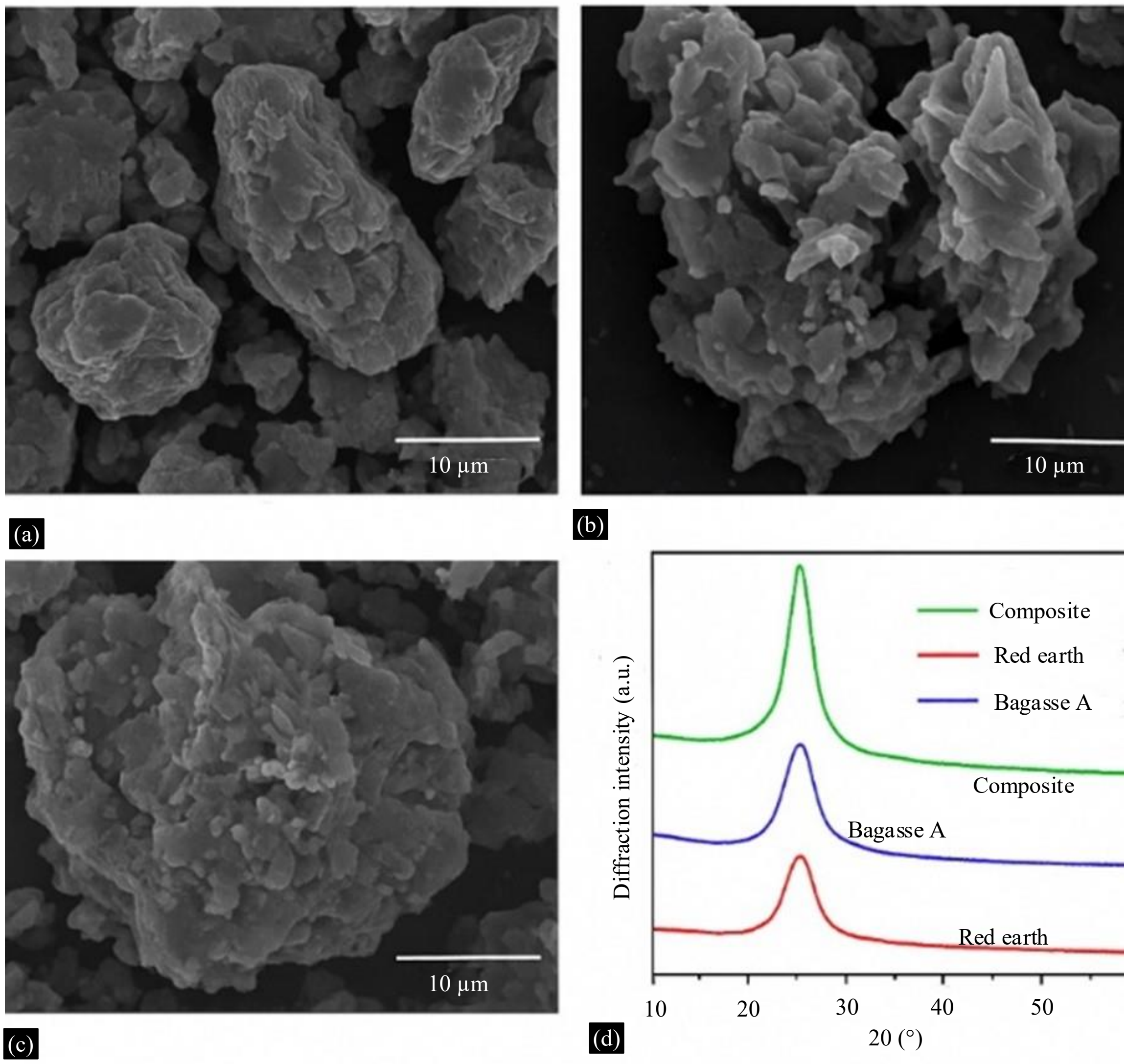

Figure 2. Microstructural and mineralogical analysis of red earth and BA composites. (a) SEM of red earth showing compact angular particles; (b) SEM of BA showing porous, irregular morphology; (c) SEM of red earth–BA composite showing interlocking and early pozzolanic bonding; (d) XRD patterns indicating formation of calcium silicate hydrate (C–S–H) phases after curing.

Standard geotechnical procedures in accordance with IS 2720 (Parts 5 and 7) were employed to determine the liquid limit (LL), plastic limit (PL), and compaction characteristics such as maximum dry density (MDD) and optimum moisture content (OMC) for each composite mix. Each combination was prepared, mixed thoroughly, and compacted using the Standard Proctor method. Tests were conducted in triplicate to ensure accuracy and reproducibility. The curing periods applied were 0 days (immediate), 7 days, and 30 days, enabling evaluation of the short-term and time-dependent behavior of the composite material. Curing was done in sealed desiccators to minimize moisture loss and simulate realistic field conditions where chemical bonding reactions continue over time.This methodology enables the evaluation of the soil composite system as a function of particle interactions, filler content, and curing-driven chemical bonding, thereby offering valuable insight into the engineering performance of matrix–filler–binder systems for sustainable ground improvement.

RESULTS AND DISCUSSIONS

The following section presents detailed results on plasticity reduction and compaction behavior of red earth treated with BA and lime, supported by curing-dependent trends and microstructural evidence.

Microstructural Analysis of Composite Components

The microstructural characteristics of red earth, bagasse ash, and their composite blend were analyzed using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) and it presented. These techniques help reveal morphological and mineralogical features that influence the composite behavior and pozzolanic reactivity of the material system.

Figure 2. Microstructural and mineralogical analysis:(a) SEM image of red earth shows compact, angular particles with a relatively dense packing arrangement, indicating low porosity. (b) SEM image of bagasse ash displays a highly porous and irregular morphology with spherical and fragmented particles, typical of ash residue from combustion. This microstructure contributes to high surface area and enhances water absorption. (cller interlock between ash and soil particles, indicating early-stage pozzolanic bonding. (d) XRD patterns show distinct mineral phases in red earth (e.g., kaolinite, quartz) and bagasse ash (e.g., amorphous silica). In the composite, the emergence of a broad hump near $2\theta = 30°$ suggests the formation of amorphous calcium silicate hydrate (C–S–H) phases, validating the onset of pozzolanic reactions during curing.

Table 3. Liquid limit of red earth treated with various percentages of bagasse ash.

Combination	**Liquid limit (%)**		
Curing days	***0 days***	***7 days***	***30 days***
Red Earth alone	45	45	45
BA Alone	63	63	63
RE + 10% BA	53	50	49
RE + 20% BA	56	54	51
RE + 30% BA	61	57	53
RE + 40% BA	63	59	54
RE + 50% BA	65	61	55
RE + 60% BA	68	64	57

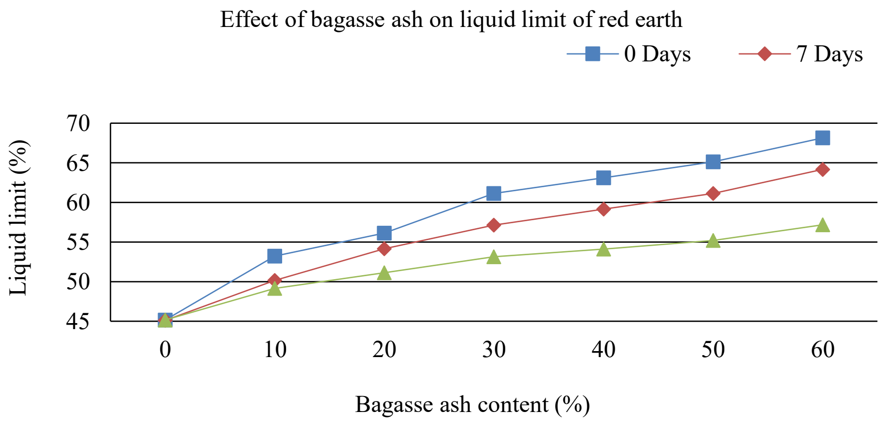

Figure 3. Variation in liquid limit (%) of red earth with different bagasse ash (BA) contents under curing periods of 0, 7, and 30 days.

Variation in Liquid Limit with Bagasse Ash Content

Figure 3 illustrates the variation in liquid limit (LL) of red earth blended with incremental percentages of bagasse ash (BA) over different curing periods (0, 7, and 30 days). The data presented in Table 3 reflects the evolution of plasticity characteristics in response to both physical filler effects and chemical pozzolanic interactions. These results provide insight into the temporal behavior of the red earth–BA composite under controlled curing conditions, simulating short-term and long-term stabilization potential.

As shown in Table 3, the liquid limit of the untreated red earth remained consistent at 45% across all curing intervals. Upon introduction of bagasse ash, LL exhibited a progressive increase, peaking at 68% with 60% BA in the uncurated state. This initial rise can be attributed to the microstructural properties of BA, its porous texture and finer particle size increase the composite's water-holding capacity, thus elevating plasticity. However, as the curing period extends to 7 and 30 days, a consistent decline in LL is observed, especially prominent in the 10%–30% BA range. This decline signifies the activation of pozzolanic reactions, where the amorphous silica in BA reacts with calcium ions in the soil to form stable cementitious compounds such as calcium silicate hydrate (C–S–H). These compounds reduce pore space and limit the free water content, thereby lowering the LL. The balance between initial plasticity and long-term strength enhancement highlights the composite nature of this stabilized soil system. The 10%–30% BA range appears optimal for maximizing the dual benefits of workability in the fresh state and strength development upon curing. These findings emphasize the efficacy of BA as a sustainable stabilizing agent, promoting improved engineering performance while utilizing industrial by-products.

Table 4. Liquid limit of red earth with optimum percentage of bagasse ash and various percentages of lime.

Combination	Liquid limit (%)		
Curing days	***0 days***	***7 days***	***30 days***
Red Earth alone	45	45	45
BA Alone	63	63	63
1% Lime	51	47	45
2% Lime	49	45	42
3% Lime	48	43	40
4% Lime	45	41	38
5% Lime	42	39	37

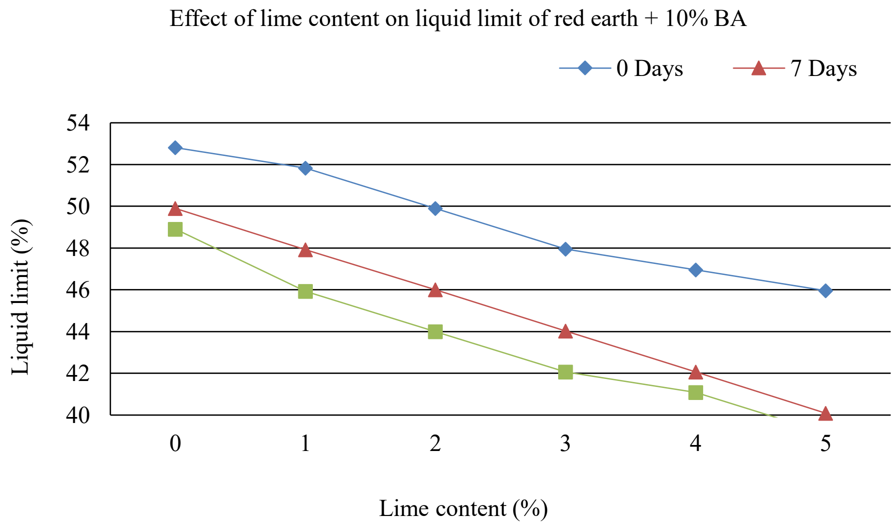

Figure 4. Effect of lime content (1-5%) on the liquid limit (%) of red earth stabilized with 10% bagasse ash (BA) at 0, 7, and 30 days of curing.

Effect of Lime on Liquid Limit at Optimum BA Content

This section examines the influence of lime addition on the liquid limit (LL) of red earth stabilized with the optimum bagasse ash (BA) content determined previously as 10%. Lime was added incrementally from 1% to 5% by dry weight of soil. The results were recorded over curing periods of 0, 7, and 30 days, and are presented in Table 4.

The addition of lime to the 10% BA-treated red earth further reduced the LL across all curing intervals. At 0 days, a steady decline in LL is observed as lime content increases, indicating an immediate flocculation and agglomeration of soil particles. The reduction becomes more prominent with curing, where the pozzolanic reaction between lime and silica/alumina in both soil and BA generates additional C–S–H and calcium aluminate hydrate (C–A–H) gels.

This reaction binds the particles into a more cohesive matrix, limiting water adsorption and plastic deformation. By 30 days, LL values decreased from 49% (no lime) to 39% (5% lime), showing a 20.4% reduction. The results confirm that lime, in synergy with BA, significantly improves soil stability by reducing its plasticity. The initial LL of the natural Red Earth (RE) was established as 45%. Upon treatment with BA at the optimal ratio of 10%, the LL exhibited an increase to 49% following a 30-day curing period. Subsequent introduction of lime at concentrations ranging from 1% to 5% led to an initial decrease in LL, transitioning from 49% to 42%. This decrease was correlated with an ascending lime content. With the progression of curing days, a notable reduction in LL values was observed, ultimately reaching 37%. This trend signifies that LL values are inversely proportional to the duration of curing, indicating the potential for enhanced material behavior over time and it is shown in the Figure 4.

Compaction Characteristics and MDD/OMC Results

This section analyzes the influence of bagasse ash (BA) additions on the compaction behavior of red earth, focusing on variations in Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Measurements were taken for different BA dosages (0%–60%) after 0 and 30 days of curing. To ensure clarity and eliminate redundancy, the original field-measured MDD values (in kN/m³) are now integrated alongside the laboratory results (in g/cc) in a unified format shown in Table 5.

The results presented in Table 5 reveal that with increasing BA content, there is a steady increase in OMC and a corresponding decrease in MDD. This trend is attributed to the porous and lightweight nature of bagasse ash, which demands more water to reach compaction and reduces the overall density of the soil matrix. After 30 days of curing, a further increase in OMC is noted, especially at higher BA contents. This can be linked to pozzolanic reactions leading to matrix restructuring, which increases water demand for reorientation. Concurrently, the continued decline in MDD highlights the reduced unit weight of the stabilized matrix due to the ash's lower specific gravity and increased internal voids.

The optimal compaction performance appears between 10% and 30% BA, where the balance between improved moisture retention and manageable density reduction supports enhanced workability and compaction effort. This also coincides with the trends observed in liquid limit behavior, indicating the reliability of this composite formulation.

Table 5. Compaction characteristics of red earth with varying bagasse ash content (lab and field values)

BA content (%)	OMC (%) – 0 days	MDD (g/cc) – 0 days	OMC (%) – 30 days	MDD (g/cc) – 30 days
0 (Red Earth)	18.2	1.72	18.2	1.72
10%	20.5	1.68	21.0	1.66
20%	21.8	1.63	22.3	1.61
30%	23.0	1.60	23.8	1.58
40%	24.2	1.57	25.0	1.55
50%	25.5	1.54	26.2	1.52
60%	26.8	1.51	27.5	1.49

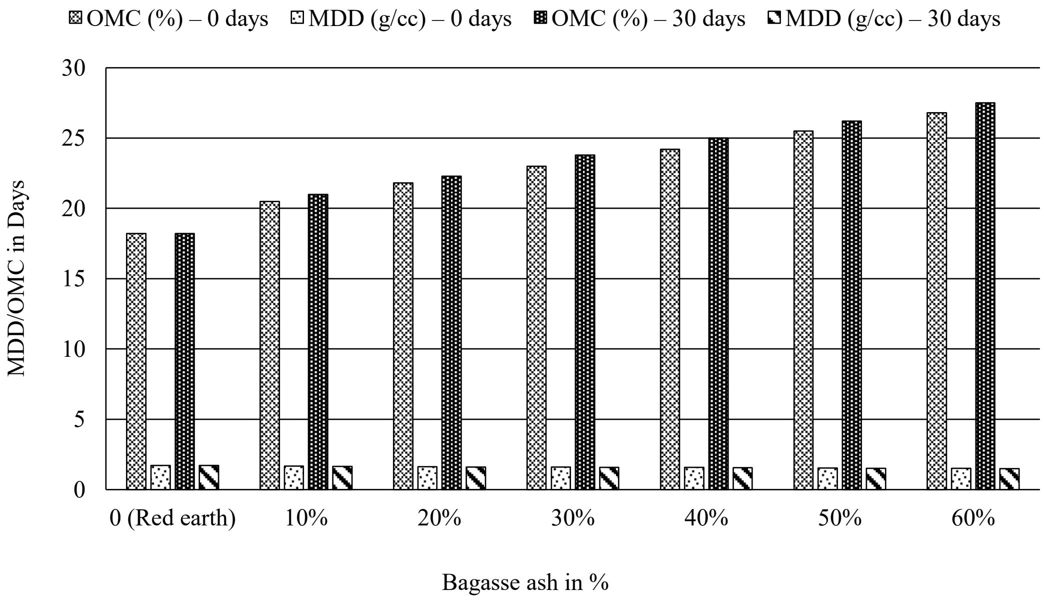

Figure 5. Influence of bagasse ash (BA) content on optimum moisture content (OMC, %) and maximum dry density (MDD, g/cc) of red earth at 0 and 30 days of curing.

Table 6. Compaction characteristics of red earth treated with optimum bagasse ash and varying percentages of lime (0 and 30 days).

Combination	MDD (kN/m³) – 0 days	OMC (%) – 0 days	MDD (kN/m³) – 30 days	OMC (%) – 30 days
Red Earth alone	17.7	19	17.5	18
Red Earth + Optimum BA + 1% Lime	15.55	21	15.40	20
Red Earth + Optimum BA + 2% Lime	15.55	25	15.25	24
Red Earth + Optimum BA + 3% Lime	14.3	30	14.1	28
Red Earth + Optimum BA + 4% Lime	14.4	29	14.2	27
Red Earth + Optimum BA + 5% Lime	15.6	20	15.4	19

Effect of Lime on Compaction Characteristics

This section presents the compaction characteristics of red earth soil treated with the optimum dosage of bagasse ash (10%) and varying lime contents ranging from 1% to 5% over curing durations of 0 and 30 days. Table 6 summarizes the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) values. These results demonstrate the influence of lime on the densification and water demand behavior of the stabilized soil composite at both early and extended curing stages, as visually illustrated in Figure 6. These results demonstrate the influence of lime on the densification and water demand behavior of the stabilized soil composite at both early and extended curing stages.

Table 6 presents the compaction behavior of red earth stabilized with an optimum 10% bagasse ash (BA) and varying lime contents (1% to 5%) under 0-day and 30-day curing periods. The data show notable changes in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), reflecting how lime addition affects the soil structure over time. At 0 days, increasing lime content causes a progressive increase in OMC from 21% to 30%, accompanied by a decline in MDD from 15.55 to 14.3 kN/m³ at 3% lime. This trend is attributed to lime's flocculation effect, which opens up the soil structure and increases water demand for effective compaction. By 30 days, the OMC slightly decreases across all lime percentages, while the MDD shows a modest recovery. This behavior results from pozzolanic reactions that densify the soil matrix by forming calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels. These cementitious products gradually bind the particles, reducing internal voids and lowering water absorption requirements.

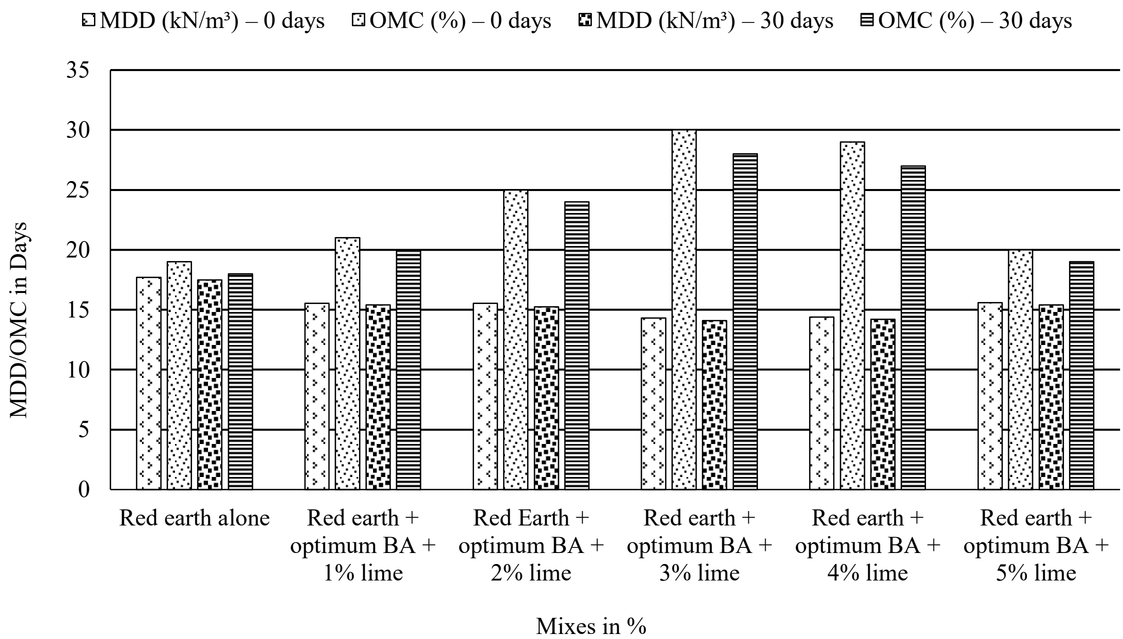

Figure 6. Influence of lime content (1-5%) on optimum moisture content (OMC, %) and maximum dry density (MDD, kN/m³) of red earth with 10% BA, measured at 0 and 30 days of curing.

Figure 6 explore the lowest MDD (14.1 kN/m³) and highest OMC (28%) occur at 3% lime content after 30 days, beyond which the trends begin to reverse. At 5% lime, MDD increases and OMC drops, indicating a more compact and efficient soil matrix due to over-stabilization. This data suggests that 3%–4% lime in combination with 10% BA provides a favorable balance between workability and density, especially after extended curing. These observations affirm the synergistic role of lime and bagasse ash in enhancing the geotechnical performance of expansive soils through sustainable stabilization techniques.

The improvement in the plasticity and compaction characteristics of red earth treated with bagasse ash (BA) and lime can be explained by combined physical and chemical mechanisms. Physically, BA particles act as lightweight fillers with a porous morphology, which initially increases water absorption and reduces the maximum dry density of the soil. Their fine size and high surface area help fill voids between soil grains, thereby altering the soil fabric and improving particle interlock. Chemically, the high amorphous silica content of BA reacts with calcium hydroxide released from lime hydration to form secondary cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These gels progressively bind soil particles, densify the matrix, and reduce the availability of free water, leading to lower plasticity indices. Over curing time, flocculation of clay minerals due to lime addition and pozzolanic bonding from BA-lime reactions together create a denser, more stable composite microstructure. This dual mechanism-physical modification by BA and chemical stabilization by lime explains the observed reductions in liquid limit and improvements in compaction behavior. The SEM and XRD results further validate this theoretical framework by showing particle interlock and the presence of C-S-H phases in the cured samples.

CONCLUSIONS

- This study explores the development of a sustainable soil-based composite material by incorporating bagasse ash (BA) and lime into red earth, with a specific emphasis on its potential as a low-cost engineered composite. The combined action of physical microfiller effects from BA and the pozzolanic activation driven by lime addition has yielded a stabilized matrix with optimized geotechnical properties and promising internal structural cohesion.

- The observed enhancement in compaction characteristics, specifically the reduction in Maximum Dry Density (MDD) and increase in Optimum Moisture Content (OMC), reflects the lightweight and porous nature of BA, which behaves as a reactive filler. Microstructural analysis via SEM confirmed the formation of a dense, interlocked matrix, while XRD analysis showed the evolution of secondary cementitious phases such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C-A-H). These hydrated gels contribute significantly to the internal matrix strengthening and moisture regulation.
- The synergy between BA and lime leads to time-dependent restructuring of the composite's internal framework. As curing progresses, a refined granular skeleton and increased particle bonding density emerge, mimicking behavior observed in other cementitious or alkali-activated composites. This behavior validates the classification of the stabilized red earth–BA–lime mixture as a true geocomposite material, engineered through sustainable means.
- From a composite materials perspective, this bio-silica and lime-based system exhibits essential features of engineered composites, namely tailored performance, multi-phase interaction, and long-term durability. Moreover, the approach aligns with circular economic principles by converting agricultural and industrial waste into high-performance construction materials. Thus, the findings demonstrate that soil composites designed with bagasse ash and lime possess the potential for scalable application in subgrade layers, embankments, and green infrastructure, while contributing to sustainable material science advancements.

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