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PERFORMANCE OPTIMIZATION OF SUSTAINABLE RAMMED EARTH BLOCKS REINFORCED WITH JUTE AND LIMESTONE CALCINED CLAY CEMENT (LC³)

Randeep*, Sanjay Srivastava, V. Soamidas

Department of Civil Engineering, Dayalbagh Educational Institute (Deemed to be University), Agra, India

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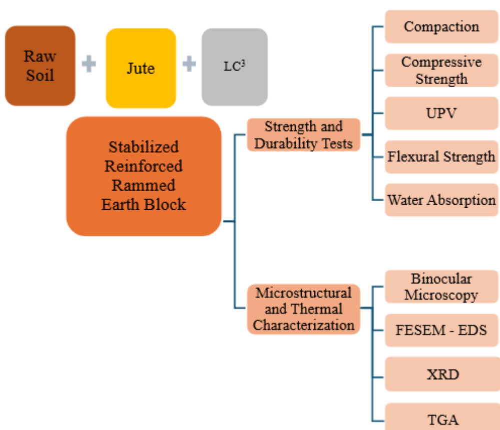
*Corresponding author
randeeplohra@dei.ac.in

Graphical abstract



Abstract

Rammed earth blocks (REBs) are attracting renewed attention as sustainable building materials due to their low embodied energy and use of locally sourced soil, yet their limited tensile strength and moisture sensitivity restrict wider structural applications. This study investigates a dual enhancement approach, combining natural jute fiber reinforcement (0.25–1.25% by weight) with 10% Limestone Calcined Clay Cement (LC³) stabilization. To evaluate performance, mechanical tests, including compaction, compressive strength (dry and wet), flexural strength, ultrasonic pulse velocity (UPV), and water absorption, were performed. Microstructural evolution was examined through binocular microscopy, FESEM-EDS, XRD, and TGA analyses. Results indicated that 1% jute fiber provided the best balance of strength and ductility, while LC³ contributed to matrix densification and improved durability. The combined system achieved a compressive strength of 4.32 MPa, a flexural strength of 1.17 MPa, and reduced water absorption to 13.18%. Microstructural observations confirmed the formation of pozzolanic products and a refined pore network, highlighting the potential of this composite for durable, low-carbon, and cost-effective construction.

Keywords: Jute Fiber Reinforcement, Limestone Calcined Clay Cement Stabilization, Rammed Earth, Durability, Microstructural Analysis

1.0 INTRODUCTION

In response to the escalating climate crisis, the construction sector faces increasing pressure to transition toward sustainable materials and practices. Conventional Portland cement and concrete account for nearly 8% of global CO_2 emissions (1,2), highlighting the urgent need to develop low-carbon alternatives. REBs have gained renewed interest for their minimal embodied energy, thermal efficiency, and use of locally available soils, making them a viable option for low-cost, environmentally conscious construction, particularly in resource-limited or rural areas. Despite their environmental promise, REBs are constrained by inherent material limitations. Their low compressive strength, poor tensile performance, and susceptibility to moisture-induced degradation hinder structural applications and long-term durability (3,4). Addressing these deficiencies requires targeted interventions that not only improve mechanical behavior but also preserve sustainability and cost-effectiveness.

Natural fiber reinforcement has gained traction to improve the ductility and toughness of earthen composites. Jute fiber offers several advantages: high tensile strength, biodegradability, affordability, and widespread availability in tropical regions (5). When embedded in an earthen matrix, jute acts as a micro-reinforcement, bridging cracks, delaying failure, and increasing energy absorption capacity (1,6,7). Recent studies further indicate that jute fibers contribute to matrix densification and promote crack arrest mechanisms at the microstructural level, as confirmed through SEM and EDS analyses (8). However, the literature remains limited in evaluating the quantitative impact of varying jute content on both mechanical and microstructural performance in raw-soil REBs, leaving critical gaps in material optimization and design.

To complement the reinforcing effects of jute, Limestone Calcined Clay Cement (LC^3) has emerged as a promising stabilizer in earthen construction. Composed of clinker, calcined clay, limestone, and gypsum, LC^3 can partially replace traditional cement, reducing emissions while contributing to early strength development and moisture resistance (9,10). Pozzolanic reactions between LC^3 components and soil minerals result in the formation of calcium silicate hydrates (C-S-H) and carboaluminate phases, which enhance matrix bonding and durability (11,12). Nonetheless, LC^3-stabilized composites often exhibit brittle failure modes under flexural and tensile loading, limiting their deformation capacity. Here, natural fibers like jute can play a compensatory role by enhancing toughness and controlling crack propagation, presenting a dual approach as in (13). Despite the potential synergy between LC^3 and jute fibers, research on their combined use in rammed earth systems remains scarce, with most studies focusing on each material individually (14).

This study presents a novel dual-modification approach, integrating jute fiber reinforcement (0.25-1.25% by weight) and 10% LC^3 stabilization to enhance both mechanical performance and internal microstructure of REBs. The research is structured in two phases: first, to identify the optimum jute dosage that balances strength gain with matrix integrity; second, to evaluate the synergistic effect of LC^3 incorporation at this optimal fiber level. Mechanical properties were assessed through compaction behavior, dry and wet compressive strength, flexural strength, ultrasonic pulse velocity (UPV), and water absorption tests. These were complemented by a suite of microstructural techniques, including binocular microscopy, FESEM-EDS, XRD, and TGA, to establish structure-property relationships. The novelty of this work lies in its systematic evaluation of fiber–binder synergy in REBs, with a focus on optimizing composite performance for low-cost, climate-resilient housing. By bridging the current gap between natural fiber reinforcement and low-carbon stabilization, this study contributes to the advancement of sustainable, structurally viable earthen construction technologies.

2.0 METHODOLOGY

2.1 Materials

Soil plays a vital role in determining the structural and environmental performance of rammed earth blocks (REBs). For this study, soil was collected from the outskirts of Agra, India, and analyzed for particle distribution and plasticity. The soil consisted of 72.69% sand, 11.53% silt, and 15.78% clay, with a plasticity index of 8.28%, placing it within the ideal range for REB applications. Such a composition ensures a balance between workability and mechanical stability. Binocular microscopy (Figure 1a) showed the compacted raw soil had a uniform particle arrangement and cohesive matrix, which contributes to better compaction and load transfer, essential for producing durable and structurally sound blocks, supported by references (15–17). These characteristics confirm its appropriateness for use in stabilized and fiber-reinforced REB systems.

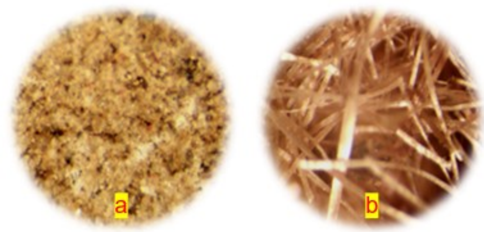


Figure 1 (a) Compacted raw soil, (b) Jute fibres

Jute fibers are biodegradable, high-tensile reinforcements abundantly available in tropical regions, making them an eco-friendly choice for enhancing earthen construction. In rammed earth, they function as natural crack arrestors by bridging micro-cracks and distributing tensile stress, thereby improving ductility and delaying failure. For this study, untreated jute fibers with a diameter of 1.0 to 1.5 mm, were procured commercially and manually cut to a uniform length of 40 mm as this length provides an effective balance between enhancing strength, ensuring good soil–fibre bonding, and maintaining ease of mixing and compaction. Shorter fibers tend to offer limited reinforcement, while longer ones can lead to balling, uneven dispersion, and reduced compaction quality (18–20) and it was varied 0.25% to 1.25% to identify the optimum reinforcement content (21–23). Their fibrous morphology is illustrated in the microscopic image shown in Figure 1b. As observed in the EDS analysis, carbon and oxygen were the dominant elements detected. This aligns with the known chemical composition of jute fibres, which typically contain around 72% cellulose, 12.8% hemicellulose, and 8.1% lignin, as reported by (24).

LC^3 is a low-carbon binder composed of clinker, calcined clay, and limestone, capable of replacing up to 50% of clinker in conventional cement, thereby reducing CO_2 emissions and energy demand significantly. In this study, 10% LC^3 by weight was used for stabilizing rammed earth blocks, a proportion supported by previous research demonstrating its effectiveness in improving the strength and durability of both rammed earth and soil blocks (25,26) Its influence on compressive strength, water absorption, and microstructural development was assessed after a 28-day curing period to evaluate its long-term performance benefits.

2.2 Methods

This study employs a laboratory-based methodology to investigate the compaction behavior, mechanical properties, durability, and microstructural characteristics of rammed earth blocks (REBs) reinforced with jute fibers and stabilized with 10% LC^3 cement. To ensure uniform fiber dispersion and avoid clumping, jute fibers were thoroughly dry-mixed with soil before gradually adding water. The compaction characteristics were determined using the Standard Proctor Test in accordance with (27) to establish the optimum moisture content (OMC) and maximum dry density (MDD). All the specimen were compacted at corresponding OMC-MDD as mention in Table 1, followed by a 28-day curing period, under wet gunny bags covered with a polythene sheet to retain moisture, at approximately 27 ± 2 °C and above 90% relative humidity, compressive strength tests were conducted on specimens of size 150 × 150 × 150 mm and flexural strength tests on specimens of size 80 × 80 × 300 mm, in accordance with (28,29). Ultrasonic pulse velocity (UPV) and water absorption were evaluated according to (30) and (31), respectively. The wet-to-dry compressive strength ratio was calculated to assess moisture-induced durability. For each mix, results were averaged over three specimens to reduce variability and improve reliability.

Table 1 Details of mix proportions and compaction parameters

Mix ID	Jute (%)	LC^3 (%)	OMC (%)	MDD (kN/m³)
URRE	0	0	18.67	17.32
RREJF.25	0.25	0	18.89	17.12
RREJF.5	0.5	0	19.14	16.86
RREJF.75	0.75	0	19.73	16.48
RREJF1	1	0	20.27	16.01
RREJF1.25	1.25	0	20.86	15.88
SRREJF1LC10	1	10	18.23	17.37

Microstructural characterization elucidated the stabilization mechanisms in jute fiber-reinforced rammed earth blocks (REBs) stabilized with LC^3. Binocular microscopy (7.5×-150×) revealed particle distribution and early densification. X-ray diffraction (XRD) identified crystalline phase evolution from LC^3 hydration and fiber interaction. Field emission scanning electron microscopy coupled with energy-dispersive spectroscopy (FESEM-EDS) using a platinum-coated JEOL JSM-7610F Plus captured high-resolution images of fiber–matrix bonding, pozzolanic products, and microcracks through secondary and backscattered modes. Thermogravimetric analysis (TGA) with a PerkinElmer TGA 4000 monitored thermal decomposition from 50°C to 800°C under nitrogen, highlighting stabilization and compositional shifts. Together, these advanced techniques provided a multi-scale understanding of the microstructural refinement, durability enhancement, and fiber–matrix synergy crucial for sustainable earthen construction.

3.0 RESULTS AND DISCUSSION

3.1 Compaction Test

Standard Proctor compaction tests revealed that the unreinforced rammed earth (URRE) mix achieved a MDD of 17.32 kN/m³ at an OMC of 18.67%. Incorporating jute fibers at 0.25%-1.25% by weight led to a noticeable reduction in MDD, dropping to 15.88 kN/m³ (approximately 8%), accompanied by an increase in OMC to 20.86% (an 11.7% rise). This decline is attributed to the fibers' interference with soil particle arrangement and their inherent water absorption capacity. However, the inclusion of 10% LC^3 in the optimized 1% jute-reinforced mix (SRREJF1LC10) counteracted these effects, raising the MDD to 17.37 kN/m³ and reducing the OMC to 18.23%. This improvement suggests enhanced matrix compactness due to LC^3-induced densification. These observations align with earlier studies by (32–34), and are illustrated in Figures 2 and 3.

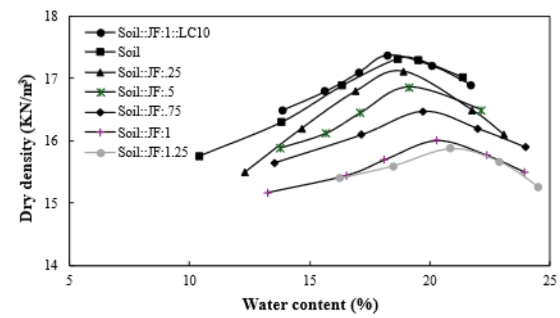


Figure 2 Dry density and moisture relation

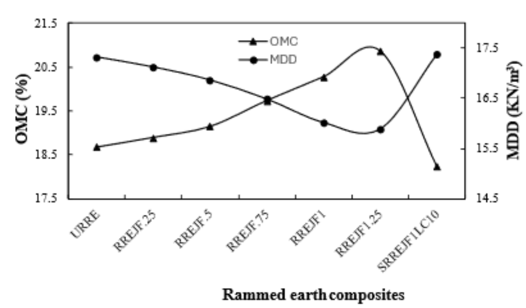


Figure 3 OMC and MDD relation

3.2 Compressive Strength Test

After 28 days of curing, the URRE mix exhibited a dry compressive strength of 1.47 MPa. Incorporating jute fibers (0.25%-1.25%) enhanced strength by up to 49.6%, reaching 2.20 MPa, primarily due to effective crack-bridging and improved stress dispersion. However, higher fiber dosages, beyond 1%, introduced minor porosity and fiber clumping, slightly moderating strength gains, an effect consistent with findings by (35–37). The addition of 10% LC^3 (SRREJF1LC10) further improved strength to 4.32 MPa validated by (38) for UCS with Portland cement, indicating the binder's densification effect and its synergistic interaction with fiber reinforcement. Strength development across mixes is presented in Figure 4.

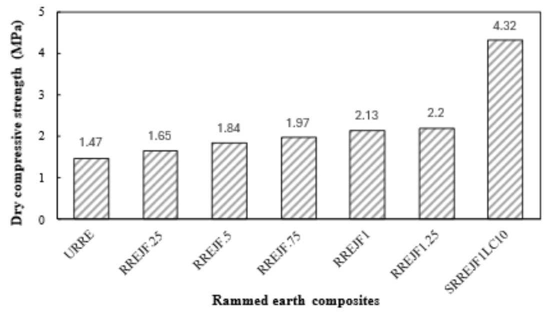


Figure 4 Dry compressive strength

3.3 UPV Test

After 28 days of curing, the unreinforced rammed earth (URRE) mix recorded a UPV of 1107 m/s, indicating moderate density. Incorporating jute fibers progressively reduced UPV, with the highest dosage (1.25%) dropping to 885 m/s, a 20% decrease, due to increased porosity and greater internal heterogeneity in the matrix, as also noted by (39,40). In contrast, stabilization with 10% LC^3 (SRREJF1LC10) increased UPV to 1906 m/s, a 72% improvement over URRE, reflecting enhanced matrix consolidation.

This improvement is attributed to LC^3's ability to refine the pore network, strengthen particle bonding, and fill voids, producing a denser and less porous matrix. The reactive alumina and silica from calcined clay in LC^3 react with calcium to form C-S-H and carboaluminate phases, which precipitate within void spaces, transforming larger capillary pores into smaller gel pores and sealing microvoids. The resulting microstructural refinement aligns with previous observations (26,41,42) and explains the marked UPV increase.

Because UPV is sensitive to matrix continuity and stiffness, reducing pore volume and improving particle contact allows ultrasonic waves to propagate more rapidly with minimal scattering (43). The high UPV in LC^3 stabilized composites is consistent with FESEM micrographs showing compact C-S-H gels and a refined pore structure, confirming improved particle bonding and reduced void connectivity. Figure 5 illustrates the progression of UPV across mixes, highlighting LC^3's role in enhancing overall material integrity.

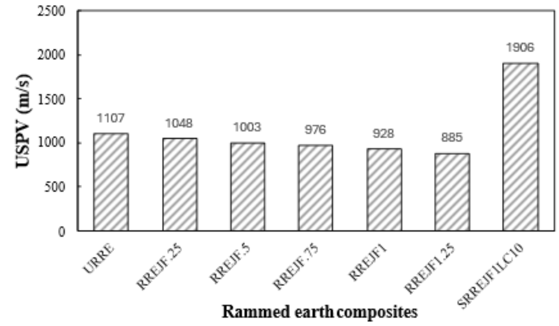


Figure 5 UPV of different composites

3.4 Flexural Strength Test

Flexural performance at 28 days of the URRE mix was limited, with a recorded strength of 0.24 MPa. The inclusion of jute fibers (0.25%-1.25%) led to a significant improvement, peaking at 0.62 MPa for the 1.25% blend (RREJF1.25). This enhancement is attributed to the fibers' ability to bridge cracks and redistribute tensile stresses (44). The addition of 10% LC^3 (SRREJF1LC10) further elevated strength to 1.17 MPa, demonstrating a synergistic effect between fiber reinforcement and matrix stabilization (45). These results align with (46,47), highlighting the role of high-aspect-ratio fibers in improving flexural resistance. Figure 6 presents these trends.

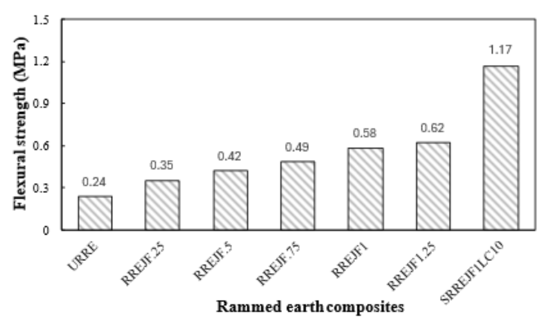


Figure 6 Flexural strength of different composites

3.5 Water Absorption Test

The URRE mix recorded a water absorption of 16.82%. Adding jute fibers (0.25–1.25%) increased absorption, peaking at 22.86% for RREJF1.25, due to the fibers' hydrophilic nature, which promotes moisture uptake and enhances pore connectivity. This moisture sensitivity is consistent with previous findings on cellulosic fibers, which exhibit high water affinity and interconnected pore networks (39,47).

At dosages above 1%, elongated jute fibers disrupt soil particle packing, creating inter-fiber voids not efficiently filled by finer particles. The cellulose matrix also absorbs and retains water, which, upon evaporation, leaves micro-channels that further increase pore connectivity and total porosity. In contrast, incorporating 10% LC^3 (SRREJF1LC10) reduced absorption to 13.18%, indicating enhanced matrix densification and reduced porosity. This reduction reflects LC^3's ability to improve moisture resistance and long-term durability. The observed trend corresponds with the densified microstructure and hydration product deposition seen in FESEM and confirmed by EDS analysis, both of which contribute to enhanced moisture resistance. Water absorption trends are shown in Figure 7.

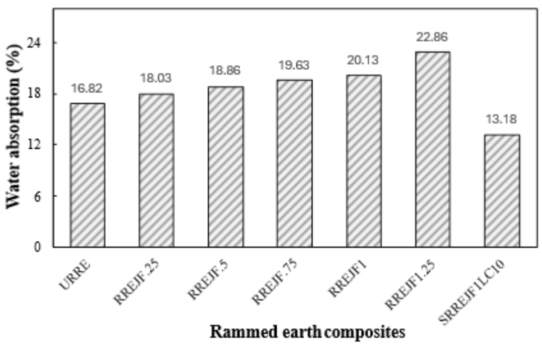


Figure 7 Water absorption of different composites

3.6 Wet/dry Compressive Strength Ratio

LC^3 stabilization emerged as a key factor in enhancing the moisture durability of rammed earth composites after 28 days. Both unreinforced (URRE) and fiber-reinforced (RREJF) variants exhibited significant moisture sensitivity, with up to 33% reduction in wet compressive strength and a 36% rise in water absorption. In contrast, the LC^3-stabilized mix (SRREJF1LC10) achieved a wet strength of 1.77 MPa and reduced absorption to 13.18%, as shown in Figure 8. These improvements underscore LC^3's densifying and pore-refining effects. The results align with prior studies (48–50). Figure 9 further illustrates the inverse correlation between moisture uptake and structural integrity.

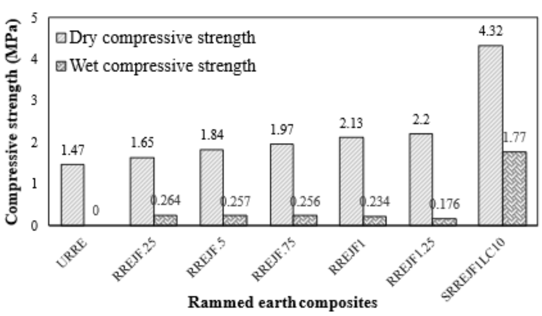


Figure 8 Wet and dry compressive strength

Comprehensive analysis of compaction behavior, compressive strength, and ultrasonic pulse velocity (UPV) identified 1% jute fiber as the optimal reinforcement level. At this dosage, the reduction in MDD remained within acceptable limits, while further increases in fiber content yielded diminishing returns in strength. Notably, fiber additions beyond 1% resulted in substantial UPV reduction and elevated water absorption, reflecting increased internal porosity and compromised matrix integrity. These trends suggest a threshold beyond which fiber benefits are offset by adverse effects on compactness. Consequently, the 1% jute composite was selected as the baseline for subsequent enhancement through 10% LC^3 stabilization.

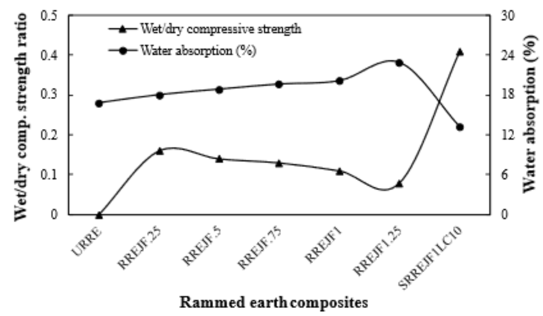


Figure 9 Wet and dry compressive strength ratio and water absorption

3.7 Compressive Fractography

Figure 10a depicts a localized and abrupt failure pattern in jute-reinforced but unstabilized composites, characterized by wide, well-defined cracks that propagate rapidly under loading. Although the presence of jute fibers offers limited crack-bridging, the absence of a cementitious phase results in weak interparticle bonding and poor energy dissipation. In contrast, Figure 10b shows a more gradual and distributed failure mode in the LC^3-stabilized, jute-reinforced specimens. The incorporation of LC^3 improves matrix cohesion and crack resistance, while its interaction with the jute fibers enhances stress redistribution, reduces crack width and penetration, and increases overall toughness and post-peak load-bearing performance.

3.8 Flexural Fractography

Figure 11 (a-d) illustrates the sequential crack development in jute-reinforced, LC^3-stabilized rammed earth (SRREJF1LC10) under flexural loading, from the initiation of fine hairline cracks (a), followed by surface crack formation (b), progressive propagation (c), and ultimately the formation of a continuous but stable crack path (d). Despite visible cracking, the specimen retained its structural integrity throughout the loading process. This controlled and gradual failure pattern underscores the effectiveness of jute fibers in bridging micro-cracks and dissipating energy, while LC^3 enhances matrix cohesion (10). Together, they produce a tougher failure mode, unlike the abrupt cracking.

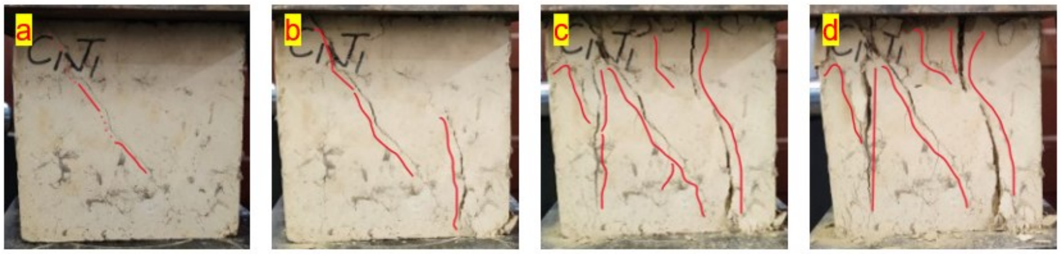


Figure 10 (a) Failure progression with jute fiber

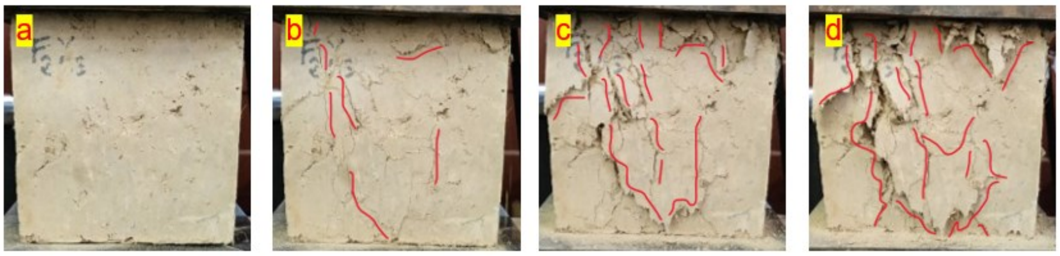


Figure 10 (b) Failure progression with jute fiber and LC^3

Figure 11 Flexure failure crack progression

3.9 Binocular Microscopy

Binocular microscope observations (Figure 12a & b) offer an initial visual assessment of the soil-jute-LC^3 composite. Pre-curing (Figure 12a), the matrix appears loose and porous, with unevenly distributed fibers. In contrast, the post-curing image (Figure 12b) displays a noticeably denser and more cohesive microstructure, reflecting enhanced compaction and fiber–matrix adhesion after 28 days. These visual cues affirm the development of internal bonding and structural integrity, serving as a precursor to more detailed microstructural analysis via FESEM-EDS.

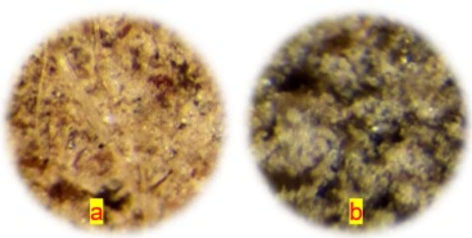


Figure 12 Binocular microscope images: (a) pre-curing, (b) post-curing at 28 days.

3.10 XRD

The XRD patterns for URRE and SRREJF1LC10 composites are presented in Figure 13. The unreinforced sample (URRE) exhibits characteristic peaks primarily associated with quartz, kaolinite and feldspar, indicative of the dominance of siliceous minerals in the native soil.

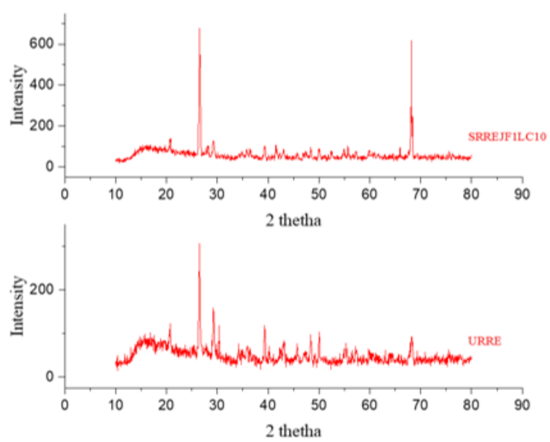


Figure 13 XRD diffraction pattern

In contrast, the SRREJF1LC10 sample reveals notable changes in peak intensities and broadening of certain diffraction bands. The SRREJF1LC10 pattern shows intensified and new peaks, indicating the formation of C-S-H (51,52) and carboaluminates from LC^3 hydration, leading to matrix densification. These changes confirm pozzolanic activity and improved crystallinity, aligning with (10), who linked higher crystallinity to better mineral stability and mechanical performance in soils. This supports the enhanced strength and moisture resistance of LC^3-stabilized composites.

3.11 FESEM

The FESEM images (Figure 14, a-d) depict the microstructural evolution of rammed earth composites from raw soil to LC^3-stabilized and jute-reinforced systems. Image (a) shows the untreated matrix with loosely packed particles and high porosity, indicating weak bonding. LC^3 addition (b) results in a denser structure with visible plate-like hydration products. At higher magnification (c), compact C-S-H gels and layered formations confirm active pozzolanic reactions and improved densification. Image (d) depicts strong bonding between jute fibers and the LC^3 matrix, where hydration products adhere to the fiber surface, enabling efficient stress transfer and effective crack-bridging (53,54). The observed refinement supports the enhanced strength and durability of the jute-LC^3 composite system. The microstructural observations align with the findings of (55,56) confirming that accurate elemental mapping is crucial to understanding phase formation and material performance. These microstructural improvements correlate directly with mechanical performance gains, as denser matrices and stronger fiber-matrix bonding reduce crack initiation and propagation under load.

3.12 EDS

The EDS analysis (Figure 15) of the LC^3-stabilized jute-reinforced soil highlights hydration and pozzolanic product formation. Spectrum 11 shows high O, Si, Ca, and Al, indicating C-S-H/C-A-S-H gels. Spectrum 12 reveals elevated C, Mg, Fe, and K, possibly from carbonates or fiber remnants. Spectrum 13 also confirms strong silicate phases supportive of cementitious gel formation. Consistent Al, Fe, and Mg suggest active calcined clay reactions. Together, these affirm effective chemical bonding and matrix densification, supporting SEM-based microstructural enhancement.

3.13 TGA

The TGA curve (Figure 16) compares the thermal behavior of URRE and SRREJF1LC10. The URRE sample exhibits gradual mass loss up to ~700 °C, primarily due to the evaporation of free and bound water and decomposition of organic matter. In contrast, SRREJF1LC10 shows higher total mass loss (~6.3%) over the same range, with a more pronounced drop between 400–600 °C. This sharp loss indicates dehydration of calcium silicate hydrate (C-S-H) and decarbonation of carboaluminates, products of LC^3 hydration.

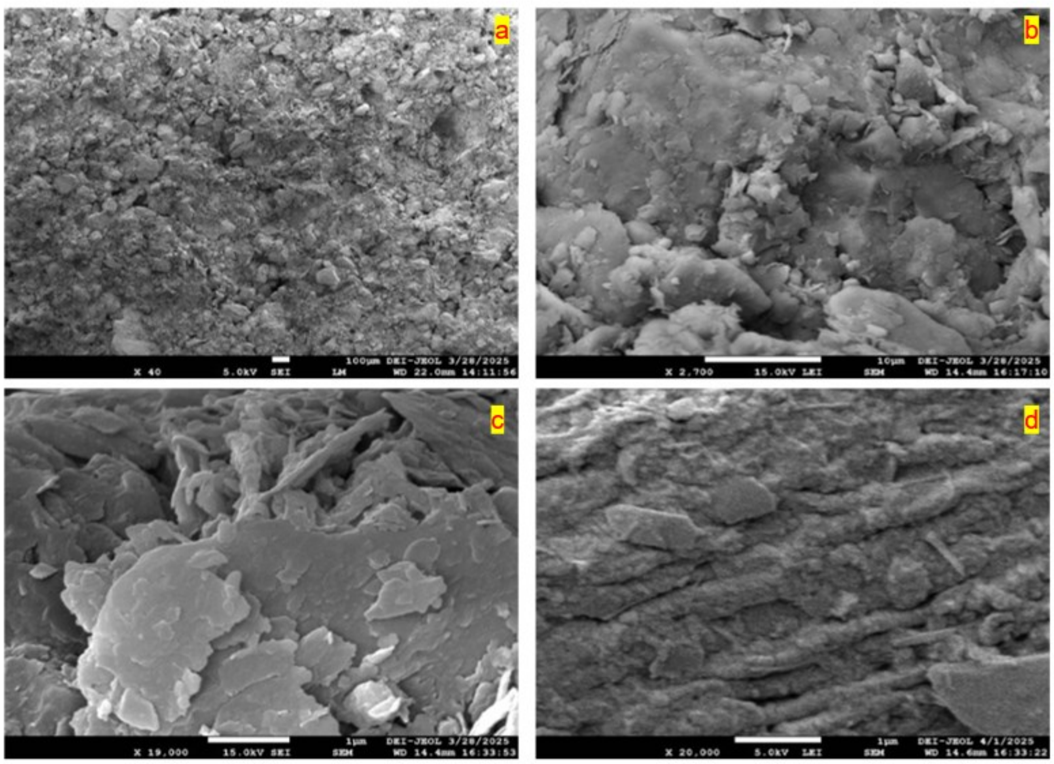


Figure 14 FESEM images

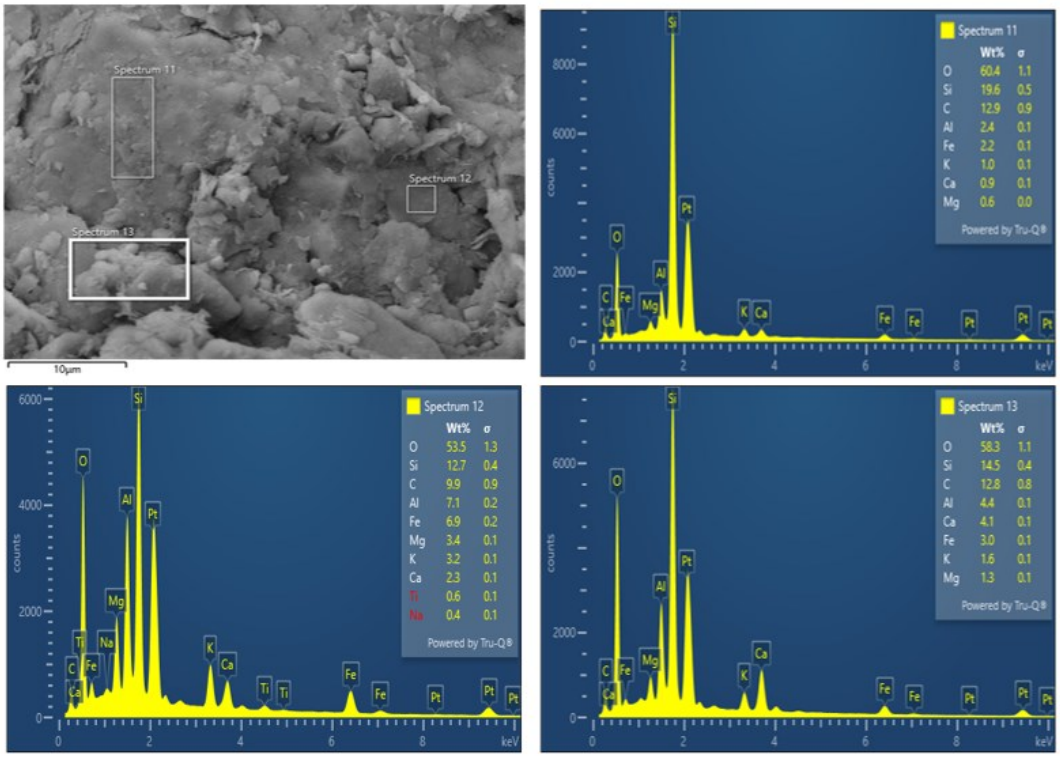


Figure 15 EDS analysis

The broader degradation profile of SRREJF1LC10 confirms the presence of chemically bound water in hydration products, absent in untreated soil. These findings validate the formation of pozzolanic reaction phases (57,58) and enhanced matrix densification, consistent with XRD and FESEM–EDS results. The presence of thermally stable hydration products detected in SRREJF1LC10 corresponds with the enhanced wet strength and reduced water absorption, demonstrating their role in improving long-term durability.

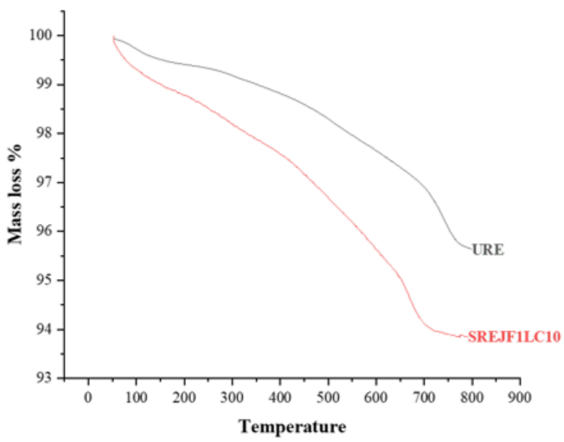


Figure 16 Thermo gravimetric performance

3.14 Practical Applications and Implementation Potential

The optimized composite with 1% jute fiber and 10% LC^3 demonstrates a strong potential for use in low-cost, sustainable housing, particularly in rural and resource-constrained regions. Its improved moisture resistance and mechanical strength make it suitable for use in load-bearing and non-load-bearing walls in tropical and subtropical climates, where high humidity and seasonal rainfall pose challenges to unstabilized earth materials. In arid and semi-arid regions, the reduced water absorption can enhance resistance to erosion and weathering. Given its performance and sustainability profile, this composite could serve as a viable alternative to conventional fired clay bricks or cement blocks, reducing embodied energy and carbon emissions while supporting local material sourcing and labor.

3.15 Limitations

While the laboratory-based results demonstrate significant improvements in mechanical, durability, and microstructural properties, certain limitations should be noted. The curing period in this study was limited to 28 days, which may not capture long-term performance changes. Field trials under real weather exposure, including wet-dry were not conducted and may influence durability outcomes. Additionally, while fiber dispersion was carefully controlled, potential clumping effects, known to impact matrix uniformity, were not directly quantified. Addressing these aspects in future studies would provide a more comprehensive evaluation of the material's real-world performance.

4.0 CONCLUSION

This study evaluated the mechanical, durability, and microstructural performance of rammed earth composites reinforced with jute fiber and stabilized with LC^3. Incorporating 0.25-1.25% jute fiber reduced MDD and increased OMC due to interference with particle packing and greater water retention.

However, mechanical performance improved, with compressive strength reaching 2.20 MPa, a 49.6% increase, and flexural strength increasing to 0.62 MPa. At higher fiber contents, UPV decreased and water absorption increased, reaching 22.86% at 1.25% jute. Considering strength, density, and moisture response, 1% jute was identified as the optimum fiber content, balancing strength gain, minimal density loss, and acceptable moisture resistance. Performance declined beyond this threshold.

The incorporation of 10% LC^3 into the 1% jute-reinforced mix significantly improved overall performance. Compressive strength increased to 4.32 MPa, flexural strength reached 1.17 MPa, and UPV increased to 1906 m/s. Water absorption decreased to 13.18%, while wet compressive strength improved to 1.77 MPa. The stabilized composites also exhibited finer and more distributed cracking, indicating improved stress distribution and matrix cohesion. Microscopy and FESEM-EDS showed improved fiber-matrix bonding and deposition of hydration products on fiber surfaces, while XRD and TGA indicated the formation of hydration-related phases associated with matrix refinement.

The optimized jute-LC^3 composite therefore shows potential for low-cost and climate-resilient rammed earth construction, particularly in rural and resource-constrained regions. The use of LC^3 can reduce clinker demand and associated CO_2 emissions, while renewable jute fibers further improve the sustainability of the composite. Future studies should focus on extended curing periods, field weathering, wet-dry durability, fiber dispersion and treatment, different LC^3 proportions, and life-cycle environmental assessment to establish its long-term field performance.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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