

Microstructural and Mineralogical Characterization of Lime Stabilized Red Soil Blocks Incorporating *Perseamacrantha* Extract

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Abstract

Compressed red soil blocks stabilised with 10% lime and treated with 5% *Perseamacrantha* herbal extract have been shown in earlier studies to perform better in terms of strength and to absorb water much less. Hence, encouraged with such positive results, an attempt is made to explore the associated micro and mineralogical mechanisms behind such enhanced performance in the current study, too. In this context, Scanning Electron Microscopy, Energy Dispersive Scanning, and X-Ray Diffraction analysis have been adopted for the samples of RS+L10+H5%. The SEM micrographs have depicted an enhancement in the extent of entanglement for particles, better bonding, and a higher density of cement matrices, in addition to smaller porosities. The result of the EDX analysis proved the presence of high amounts of calcium and calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) compounds, which are principal agents of strength. The XRD patterns reinforced these observations, providing evidence of new phases generated from the reaction between lime, red soil, and bio-active components of *Perseamacrantha* extracts. The combination of lime and bio-additives in *Perseamacrantha* proved effective in increasing mineral stability and improving the micro-structures of the compacted samples. These research findings scientifically prove and reaffirm the effectiveness of *Perseamacrantha* extracts in mechanical analysis, thereby authenticating *Perseamacrantha* extracts as a promising and eco-friendly bio-additive for soil-based masonry.

Keywords: Lime-Stabilized Red Soil; *Perseamacrantha* Extract; Compressed Earth Blocks; Microstructural Analysis; Mineralogical Characterization; Sustainable Construction Materials.

1. Introduction

In recent years, the worldwide construction industry has demonstrated a growing interest in sustainable and low-impact building materials due to the growing urgency to ameliorate environmental degradation and reduce carbon emissions. Despite their structural durability, conventional building materials like cement-based products and burned clay bricks are linked to high embodied energy and substantial greenhouse gas emissions. As a result, creating economically feasible and ecologically friendly substitutes has emerged as a crucial area of study. Due to their low energy usage, small carbon footprint, and use of locally available soils, which significantly lower transportation-related emissions, compressed mud bricks have become a promising sustainable building material. The sustainability and usefulness of these blocks are further improved by the use of herbal plant extracts as natural binders.

Herbal materials are known to have some beneficial properties such as enhanced binding ability, thermal resistance, and resistance to biological degradation. Hence, their use in eco-friendly construction works. From an environmental perspective, the advantages of mud blocks are evident, being free from the environmental drawbacks of burning bricks and possessing several advantageous properties such as the low emissions of carbon dioxide and energy requirements associated with burning bricks. Furthermore, the use of compressed interlocking mud blocks is convenient and fast for wall construction.

Historical and recent literature has revealed that herbal plant extracts have been widely used in lime and mud mixtures for ancient construction techniques, essentially in traditional architectural structures of places like Kerala, India[1-19]. This study's main goals are to assess the performance of compressed interlocking red soil mud blocks using herbal plant extract as a natural binder and to ascertain how well herbal plant-based binders improve the mechanical and durability properties of compressed red soil mud blocks.

2. Materials and Methodology

Red Soil: The residual soils are developed by deep weathering of crystalline and metamorphic parent rocks under warm and humid climatic conditions. It is distributed extensively in tropical and subtropical areas. The characteristic reddish to brown coloration obtained is due to iron oxides, predominantly hematite and goethite. The intensity of the color of red varies with the iron content, the degree of drainage, and the extent of weathering.

Lime: Locally sourced lime is used as a substituent of the lateritic soil for improvements in mechanical strength of the composite blocks. The use of lime as a stabilizer increases bonding between particles as a result of pozzolanic action between the alumino-silicates and lime, making the composite more resistant to moisture and increasing its strength properties.

Extract from *Perseamacrantha* Bark: Adopting bio-based and alternative materials is essential to the advancement of sustainable building techniques. The tropical tree species *Perseamacrantha*, sometimes called big-leaf avocado or bay laurel, has great potential as a natural binder for compacted earth bricks. Adhesive, antibacterial, and insect-resistant chemicals are found naturally in *Perseamacrantha* bark extracts. These characteristics promote resistance to biological degradation and interparticle cohesiveness when used in the manufacturing of compressed blocks.



Fig 1. Extract from *Perseamacrantha* Bark

2.1. Methodology

The amount of red soil, lime, and *Perseamacrantha* bark extract used in producing blocks is determined by the mix design used in the experiment. All the ingredient quantities are weighed using the precision weighing balance. The amount at which the lime replaces the red soil in the blocks is set at 0%, 5%, 10%, and 15%. The amount of *Perseamacrantha* bark extract used in the mixture is set at 5%, 7.5%, and 10% for every 100 L solution. First, the red soil and lime are well mixed together under dry conditions to facilitate the even distribution of the binder. This is followed by the wet mixing stage, whereby the herbal extract solution is added into the dry mixture. The addition is carried out using a drum mixer to provide a homogenous mixture.

This prepared wet mixture is next compressed into a block from using a hydraulic compression machine. A standard mold of the dimensions 300 × 200 × 150 mm is used for forming the block. A hydraulic press exerts the desired force on the mixture to compress it into interlocking compressed blocks. This is repeated until the desired number of test pieces are produced. The blocks are then demolded, marked, and placed in a shaded area to cure. The air-cured blocks are assessed for compression strength and water absorption. Depending on the results of mechanical performance, blocks with the best proportion of mix ingredients are chosen for further analysis using scanning electron

microscopy (SEM), energy-dispersive X-ray analysis (EDX), and X-ray diffraction analysis (XRD). The analysis processes help in understanding the microstructural characteristics and mineral composition of the mix ingredients.

3. Results and Discussion

3.1. Comparison of Compressive Strength of 28days Cured Compressed Red Soil Blocks

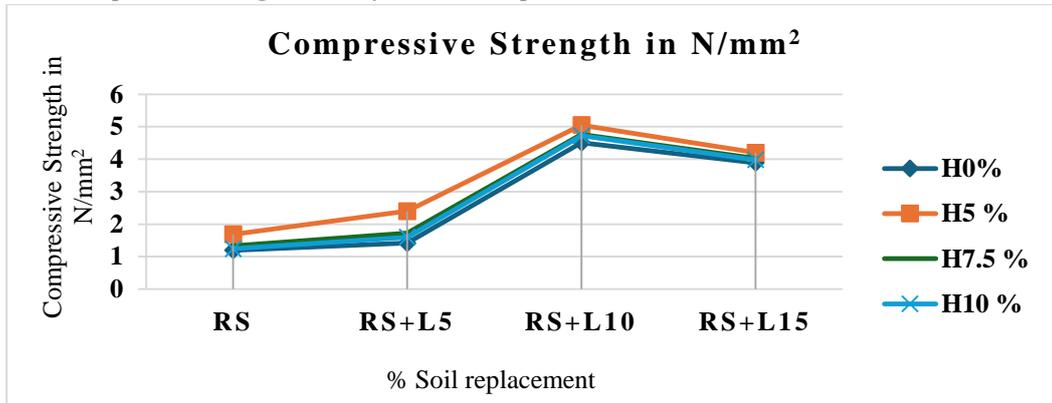


Fig 2. Comparison of Compressive Strength of 28days Cured Red Soil Blocks

3.2. Comparison of water absorption of 28days cured compressed red soil blocks

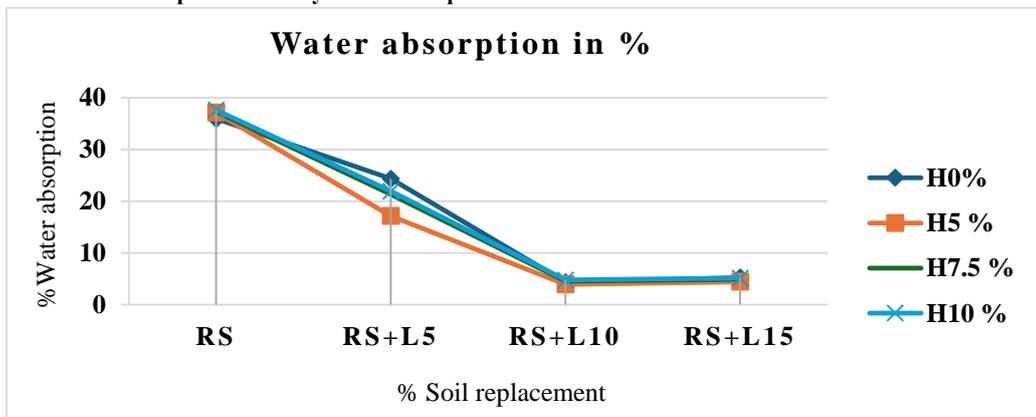


Fig 3. Comparison of Water Absorption of 28days Cured Red Soil Blocks

3.3. Composition of Red Soil (EDX) and SEM:

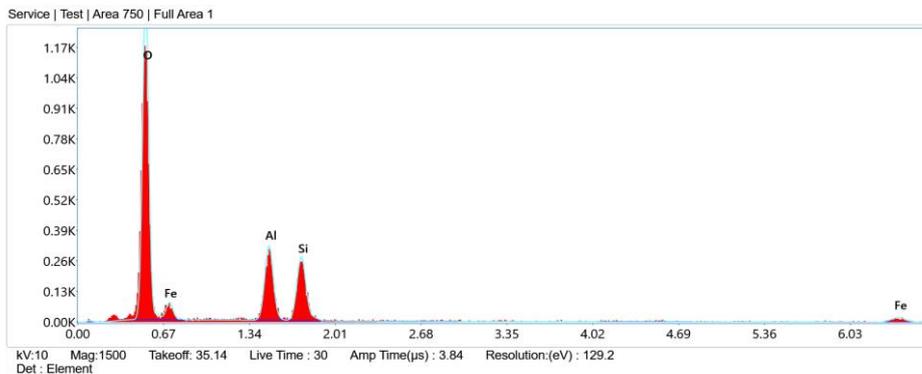


Fig 4. Elemental composition of Red Soil (EDX)

Table 1. Elemental Composition Red Soil

Element	Weight %	Atomic %	Error %
OK	57.4	72	7.3
Al K	17.3	12.9	6.5
Si K	17.1	12.2	6.6
Fe L	8.2	2.9	16.8

The Energy Dispersive Spectroscopy (EDS) spectrum of the red soil composition is dominated by the following elements: oxygen (O), silicon (Si), aluminum (Al), and iron (Fe). The high concentration of oxygen corresponds to high oxide levels in the soil mineral components. The high peaks of silicon and aluminum atoms are an indication that the soil is composed of aluminosilicate minerals common in laterite soil. Iron is a major element that makes up iron oxide components which are common in soil that is reddish in color. The elemental analysis shows that the soil is dominantly made up of minerals containing silica and alumina, which are binding agents such as iron oxide. This is responsible for the natural binding and binding capability of the resulting compacted mass. The presence of Si, Al, and Fe indicates a good pozzolanic reaction in the presence of calcium, which is a binding mechanism of increased strength. Taking everything into account, the EDS data has confirmed that the red soil has been found to have the required mineral makeup for the manufacture of compressed earth blocks for construction purposes using natural binders like lime.

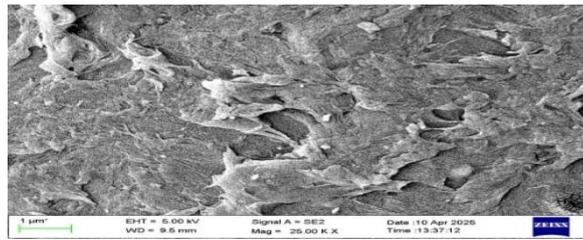


Fig 5. SEM Image Red Soil (RS)

The SEM micrograph reveals that the red soil has the appropriate mineral composition and morphology for stabilization. The porosity and irregular surfaces in the red soil particles can be good conditions for lime reactions and natural binder adsorption, thus aiding in particle interlocking, densification, and strength development in the production of compressed earth blocks.

3.4. Red Soil +Lime 10 % without Perseamacrantha Bark Extract: EDX and SEM Image (RS+L10+H0):

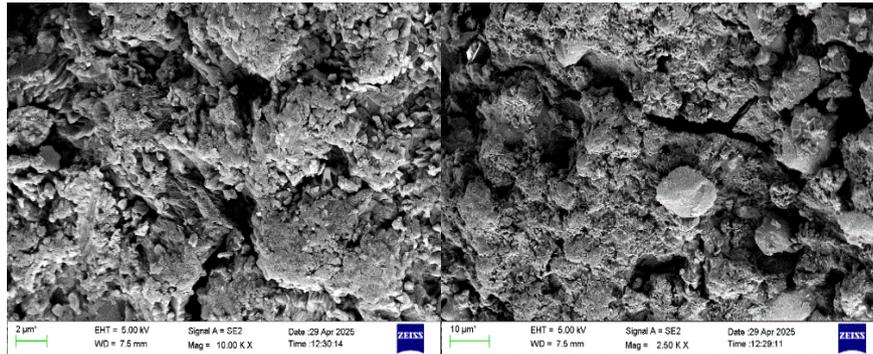


Fig 6. SEM RS+L10+H0

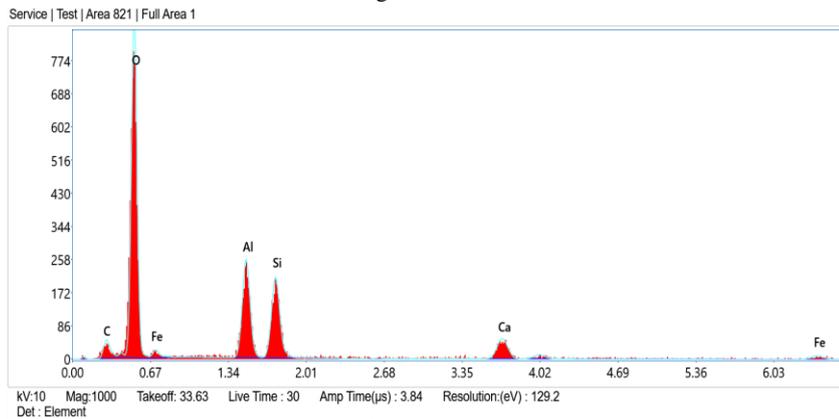


Fig 7. EDX RS+L10+H0

The SEM micrograph of red soil stabilized with 10% lime without herbal extract (RS + L10 + H0) reveals a heterogeneous and loosely packed microstructure characterized by angular soil particles, plate-like crystals, and visible interparticle voids.

Table 2. Elemental Composition RS+L10+H0

Element	Weight %	Atomic %	Error %
C K	4.3	7.1	22
O K	53.3	66.2	9.3
Al K	13.7	10.1	6.7
Si K	12.8	9	7

The presence of partially reacted lime particles and flaky mineral fragments indicates limited pozzolanic interaction between lime and the soil matrix. The distinct particle boundaries and micro-cracks suggest incomplete cementation, resulting in weaker particle bonding and a comparatively porous structure.

3.5. Red Soil +Lime 10 %With 5% Perseamacrantha Bark Extract SEM Image and EDX(RS+L10+H5):

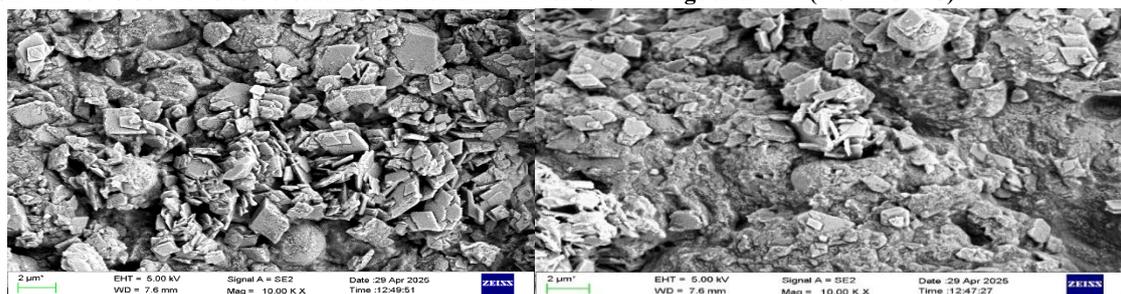


Fig 8. SEM RS+L10+H5

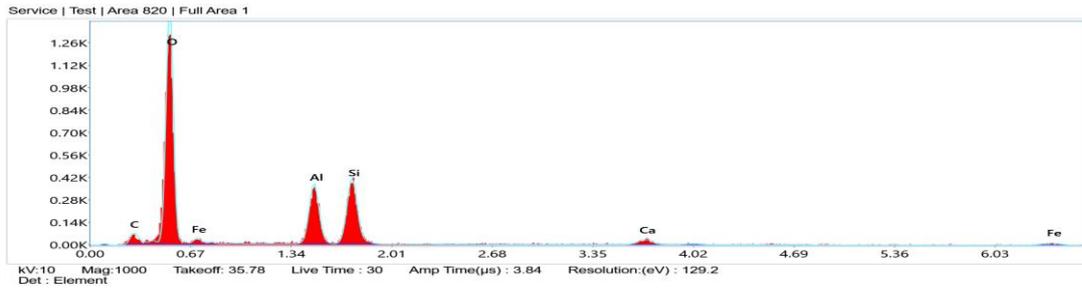


Fig 9. EDX RS+L10+H5

Table 3. Elemental Composition RS+L10+H5

Element	Weight %	Atomic %	Error %
C K	4.7	7.6	21.2
O K	54.2	65.8	8.2
Al K	14.3	10.3	6.2
Si K	17.8	12.3	5.9
Ca K	6	2.9	18.4
Fe L	3	1	16.8

The SEM image of red soil stabilized with 10% lime and 5% herbal extract (RS + L10 + H5) exhibits a denser and more compact microstructure with reduced pore spaces and improved particle agglomeration. The soil particles appear well embedded within a continuous gel-like matrix, indicating enhanced formation of cementitious products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). The smoother texture and diminished visibility of discrete particles confirm improved interparticle bonding and effective pore filling. This microstructural densification demonstrates that the herbal extract acts as a bio-activator, accelerating pozzolanic reactions and significantly improving the stabilization efficiency of lime-treated red soil.

3.6. Red Soil +Lime 10 % with 0% Perseamacrantha Bark Extract XRD Analysis (RS+L10+H0):

The X-ray diffraction pattern of red soil stabilized with 10% lime, without the addition of any herbal extract, reveals quartz as the predominant crystalline phase, indicated by intense reflections in the 2θ range of approximately 20° – 30° , with a prominent peak near 26.6° . Minor diffraction peaks associated with alumino-silicate clay minerals such as kaolinite and illite are also observed at lower intensities. The persistence of quartz confirms its inert nature during lime treatment, while the reduced sharpness and intensity of clay mineral peaks suggest partial structural modification due to chemical interaction with lime.

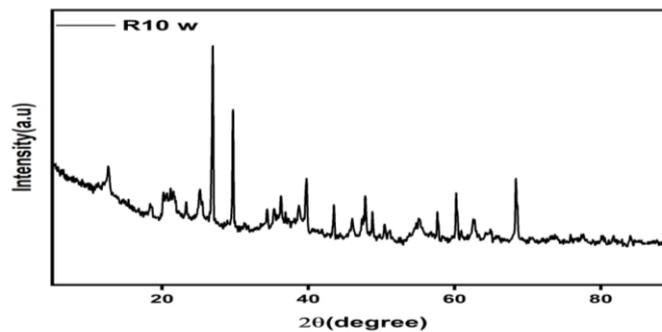


Fig 10. XRD Analysis RS+L10+H0

Lime stabilization induces significant microstructural changes through pozzolanic reactions between calcium ions and the silica and alumina present in the soil matrix. The emergence of calcium-related phases and peak broadening in the mid-range of the diffractogram indicate the formation of poorly crystalline cementitious compounds, such as calcium silicate hydrate and calcium aluminate hydrate. These amorphous reaction products contribute to improved particle bonding and matrix densification, which are consistent with the previously reported enhancement in compressive strength of the stabilized red soil. The absence of herbal extract ensures that the observed mineralogical transformations are solely attributed to lime soil interactions.

3.7. Red Soil +Lime 10 % With 5% Perseamacrantha Bark Extract XRD Analysis (RS+L10+H5):

The X-ray diffraction pattern of red soil treated with 10% lime and 5% herbal extract indicates quartz as the dominant crystalline phase, with a strong diffraction peak observed near 26.6° (2θ), which is characteristic of siliceous minerals commonly present in red soils. Additional low-intensity peaks corresponding to clay minerals such as kaolinite and illite are identified within the lower 2θ range. Compared to lime-only stabilization, the overall reduction in peak intensity and increased peak broadening suggest a modification of the soil's mineral structure due to enhanced chemical interaction promoted by the herbal extract. The incorporation of the herbal extract alongside lime appears to accelerate pozzolanic reactions, as evidenced by the diminished crystallinity and the development of diffuse diffraction features. These changes indicate the formation of amorphous cementitious compounds, primarily calcium silicate hydrate and calcium aluminate hydrate, resulting from the reaction between lime, soil minerals, and organic constituents of the extract. The herbal additive likely improves ion mobility and reaction kinetics, leading to better particle aggregation and matrix densification. This synergistic effect between lime and the

herbal extract contributes to improved microstructural stability and supports the observed enhancement in mechanical performance of the stabilized red soil.

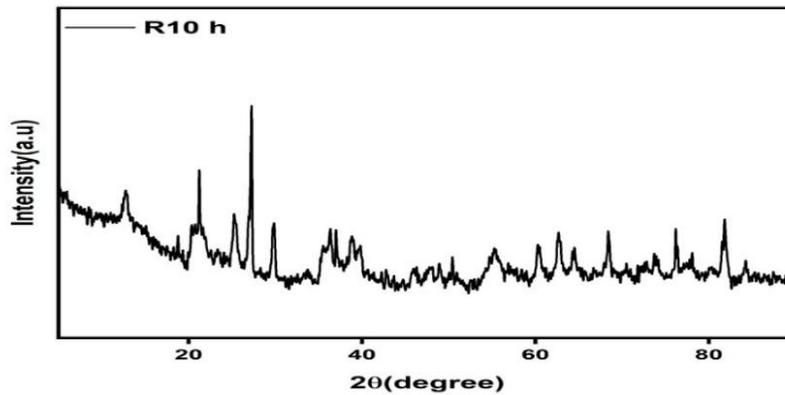


Fig 11(a). XRD RS+L10+H5

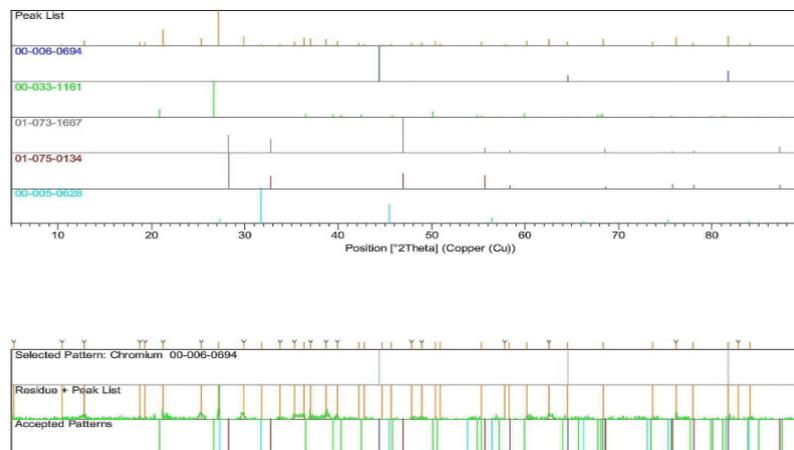


Fig 11(b). XRD Analysis RS+L10+H5

The XRD peak list and reference pattern matching confirm the presence of multiple crystalline phases in the stabilized red soil system. The dominant diffraction peaks show strong correspondence with **quartz (SiO₂)**, which remains the primary mineral constituent, as evidenced by the high-intensity reflections around 26–27° (2θ). Additional matched peaks indicate the presence of **clay-derived aluminosilicate phases**, such as kaolinite or illite, which are typically found in lateritic and red soils. The persistence of these phases suggests that while lime and herbal additives modify the soil structure, the fundamental siliceous framework remains largely intact.

The accepted pattern overlays and residue plot indicate partial suppression of crystalline clay peaks and the emergence of diffuse background intensity. This behavior is indicative of **pozzolanic reactions**, where lime reacts with reactive silica and alumina to form poorly crystalline hydration products. The presence of minor calcium-bearing phases suggests the formation of secondary compounds such as calcium hydroxide or carbonate due to lime hydration and carbonation. The increased amorphous content, reflected by peak broadening and reduced peak intensity, supports the development of cementitious gels that enhance inter-particle bonding. These mineralogical transformations corroborate the observed improvement in mechanical properties and confirm the effectiveness of lime–herbal extract stabilization in modifying the microstructure of red soil.

4. Conclusions

1. The experimental results show that the addition of 10% lime to red soil with 5% *Persea macrantha* herbal extract significantly enhanced the performance of interlocking compressed earth blocks. The said mix was found to exhibit the highest compressive strength of 5.0 N/mm², thereby showing an increased bonding and load-carrying capability over the reference mix. However, on the other side, the same composition had exhibited a minimum value of water absorption of 4%, which reflected improved densification and also developed resistance against moisture ingress. Thus, the findings confirmed that the incorporation of a small dose of *Persea macrantha* herbal extract acts as an effective natural binder, promoting improved strength and durability characteristics. In general, the bio-stabilized system provided a sustainable and efficient alternative towards enhancing the structural quality of compressed earth blocks. The obtained compressive strength and water absorption values satisfy the requirements specified in IS 1725 and IS 3495 (Part 2), confirming the suitability of the developed blocks for sustainable masonry applications.
2. It is evident from the comparative SEM results that the addition of herbal extract to lime-stabilized red soil improves microstructure quality and leads to reduced porosity. This positive effect on microstructure is the key reason for the improved mechanical properties and supports the efficacy of using herbal extract as an admixture in lime-modified red soil.
3. The result from the XRD test further affirms that the addition of lime stabilization without the herbal extract additive (RS+L10+H0) results in low mineral transformation, and there is less formation of the secondarily cementitious phases. On the other hand, the addition of the herbal extract additive (RS+L10+H5) has substantially contributed to overall pozzolanic activity, and there is reduced peak intensity and more amorphous phases. The herbal extract additive has promoted the better dissolution of silica and alumina, accelerating the formation of CSH and CAH gel bindings that improve interparticle forces. This result proves the effectiveness and efficiency of the herbal additive in improving the stabilization process using lime for red soil.

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