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DEVELOPMENT AND EXPERIMENTAL EVALUATION OF RAMMED EARTH INTERLOCKING BLOCKS USING FLY ASH, LIME, CEMENT AND COCONUT COIR AS SUSTAINABLE MATERIALS

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ABSTRACT

Fired clay bricks and cement-based masonry demand large quantities of energy and natural resources and add considerably to carbon dioxide emissions. Unfired, stabilised earth masonry is a lower-impact option, and an interlocking geometry can further cut mortar use and construction time. This study develops and tests rammed earth interlocking blocks made from locally available soil, fly ash, ordinary Portland cement, hydrated lime, coconut coir and water, compacted in a steel interlocking mould. Five mixes were prepared with the same soil (60%), fly ash (30%) and coir (1%) contents, while the combined cement and lime content was fixed at 9% and the cement:lime split was varied from 3:6 to 7:2 (as a percentage of total mix mass). Apparent density and compressive strength were determined for each mix. The measured apparent densities ranged from 931.9 to 1044.9 kg/m³. Compressive strength rose steadily with the cement fraction, from 3.01 MPa (3% cement, 6% lime) to 6.03 MPa (7% cement, 2% lime), which is a doubling of strength. The gain per percentage point of cement became smaller at higher cement contents (about 1.0 MPa per point up to 5% cement, 0.72 MPa between 5% and 6%, and 0.29 MPa between 6% and 7%). Strength showed no consistent relationship with apparent density, which indicates that binder composition governed the response in this series. These results are single-specimen, early-age observations; water absorption, durability, replicate testing and a quantitative brick comparison were not part of the present dataset and are identified as necessary next steps. The study provides a verified experimental baseline for fly ash–lime–cement–coir stabilised interlocking earth blocks and a clear pathway for completing their engineering characterisation.

Keywords: Rammed earth, Interlocking block, Fly ash, Lime, Cement stabilisation, Coconut coir, Compressive strength, Sustainable construction, Affordable housing

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Summary of key values

Item	Value
Compressive strength, Mix A to Mix E	3.01 → 6.03 MPa
Apparent density	931.9 – 1044.9 kg/m³
Combined cement + lime	9 % (ratio 3:6 to 7:2)
Number of mixes	5 mixes (soil 60 %, fly ash 30 %, coir 1 % held constant)

I. INTRODUCTION

The construction sector is among the largest users of natural resources and a major source of environmental pollution. Conventional fired clay bricks need high-temperature kiln firing, which burns large amounts of fuel and releases a significant quantity of carbon dioxide. Cement masonry adds to this burden through the embodied energy of the cement and of the cement mortar used for bonding. Increasing material and transport costs also make affordable housing harder to achieve, particularly in rural and semi-urban regions. These pressures call for building materials that draw on local resources, need little processing and keep embodied carbon low [1]–[5].

Rammed earth is one of the oldest building techniques. A carefully selected soil mixture is compacted inside formwork to give dense, durable and thermally efficient elements, using local soil with minimal processing. Interlocking blocks build on this idea: tongue-and-groove or key-and-lock profiles let the blocks seat accurately against one another, which can lower mortar consumption, speed up wall construction, improve dimensional alignment and, in some systems, allow dismantling and reuse [1], [2]. Because earth alone has limited strength and water resistance, stabilisers such as cement, lime and industrial by-products are commonly added, and natural fibres are used to control cracking [3], [4], [12].

This paper reports the development of rammed earth interlocking blocks stabilised with cement, lime and fly ash and reinforced with coconut coir. Fly ash, an industrial by-product of coal combustion, and coconut coir, an agricultural by-product, are used to lessen the dependence on conventional raw materials. The cement:lime ratio is varied at a fixed total binder content, and the resulting density and compressive strength of five mixes are reported.

II. LITERATURE REVIEW

Interlocking and self-interlocking blocks. A review covering more than 1,100 published studies on interlocking earth blocks found them to be an environmentally friendly alternative to conventional masonry because they need little or no mortar, and it stressed the need for better durability studies and standardised testing before large-scale adoption [1]. Another review, on self-interlocking systems, reported shorter construction time, lower mortar demand and improved sustainability, and also recommended further work on durability and large-scale

implementation [2]. Modular rammed earth blocks stabilised with bio-binders (animal glue, xanthan gum) and produced as prefabricated interlocking units reached compressive strengths of up to about 6.9 MPa, with lower carbon emissions than conventional stabilised earth blocks [11].

Stabilised earth blocks and stabilisers. A systematic review of compressed stabilised earth blocks reported lower environmental impact, energy use and cost than fired bricks; lime and cement improved strength, and the use of local soil reduced transport impacts [3]. Studies on rammed earth stabilised with cement, hydrated lime and natural hydraulic lime, using by-products, showed that suitable dosages markedly improved strength and durability [6]. Lime–ground slag binders improved masonry strength and durability while lowering cement consumption [7], and low-carbon limestone calcined clay cement has been applied successfully to fibre-reinforced rammed earth [10], [14]. Life-cycle work indicates that rammed earth has low embodied carbon, but that excessive cement stabilisation raises emissions, so the stabiliser content should be optimised [5]. Rammed earth containing recycled construction and demolition waste and calcium oxide has been reported to reach about 9 MPa with reduced heat transfer [15].

Natural fibre reinforcement. Reviews of natural fibre-reinforced earth blocks conclude that fibres improve crack resistance, toughness and sustainability, while recommending standardised testing and long-term durability studies [4], [12]. Coir-reinforced stabilised adobe made with construction and demolition waste showed better strength, stiffness and durability at an optimum fibre dosage [8]. Comparable benefits have been shown with other fibres, including recycled carpet fibre, pine fibre and sheep wool [9], [10], [13].

Taken together, these studies repeatedly show that stabiliser type and dosage need to be optimised, that fibres help control cracking only at suitable contents, and that durability and standardisation remain under-studied.

III. RESEARCH GAP, PROBLEM STATEMENT AND OBJECTIVES

3.1 Research gap

Most existing work concerns compressed stabilised earth blocks or rammed earth walls and prisms, and few studies examine interlocking rammed earth units that combine fly ash, lime, cement and coconut coir in a single system. How a fixed total binder content should be divided between cement and lime in such a system is not well documented. The present study addresses this specific question experimentally.

3.2 Problem statement

Conventional burnt clay bricks and cement blocks are energy-intensive, release large quantities of carbon dioxide, deplete natural resources and rely on cement mortar for bonding. Traditional

rammed earth is labour-intensive and is not modular. A low-cost, locally producible interlocking earth block with adequate strength is therefore needed.

3.3 Objectives

1. To develop rammed earth interlocking blocks using locally available sustainable materials.
2. To evaluate the physical and mechanical properties of the developed blocks.
3. To study the effect of material composition on strength, with a view to optimising it.
4. To compare the performance, cost and environmental aspects of the blocks with conventional burnt clay bricks.

The experimental work reported here fully covers objectives 1 and 2 for density and compressive strength, objective 3 for the cement:lime ratio, and objective 4 on a qualitative basis only.

IV. MATERIALS

Soil. Locally available soil served as the main raw material. It was cleared of roots, stones and organic matter before use.

Fly ash. A fine pozzolanic by-product of pulverised coal combustion, used to replace part of the soil in order to improve particle packing and add to long-term strength.

Cement. Ordinary Portland cement was the principal binder; its hydration products bond the soil particles and reduce loss by erosion.

Lime. Hydrated lime was used as a secondary stabiliser. It reacts with clay minerals (cation exchange and flocculation), lowers plasticity and can add long-term pozzolanic strength, particularly in combination with fly ash.

Coconut coir. Natural fibre from coconut husk was cleaned, cut and added at 1% of the batch mass to control shrinkage cracking and improve toughness.

Water. Clean water was added gradually until a uniform, compactable consistency was reached.

Mould. A steel interlocking block mould with projections and recesses gave blocks of consistent geometry. The block volume was 0.003541 m^3 and the loaded area used for the strength calculation was 34,838 mm^2.

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V. EXPERIMENTAL METHODOLOGY

Figure 1 outlines the production and testing sequence: material selection and collection, soil drying and sieving, proportioning, dry mixing of soil, fly ash, cement, lime and coir, gradual water addition and mixing, filling of the interlocking mould, ramming and compaction, demoulding, curing, drying and testing.

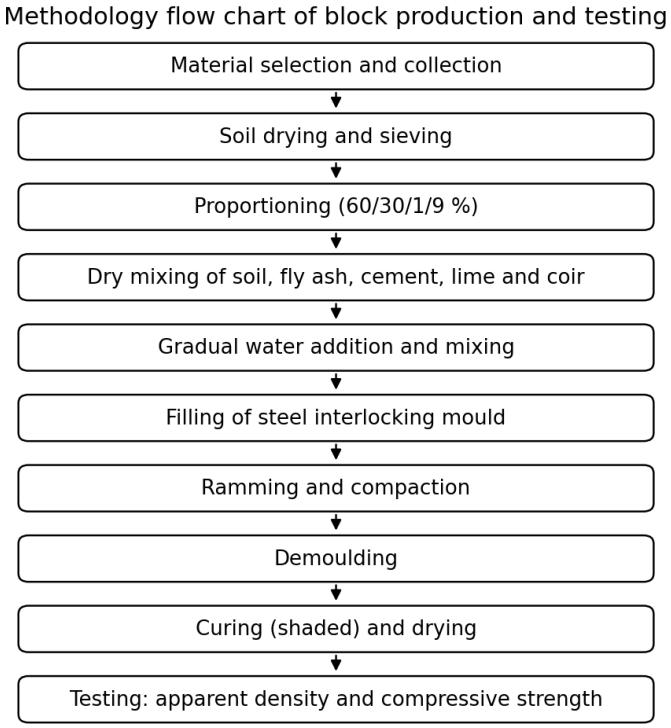


Figure 1. Methodology flow chart: production and testing sequence of the interlocking blocks.

5.1 Mix proportions

Five mixes (A–E) were prepared, each with a total dry batch mass of 3.5 kg. The soil (60%), fly ash (30%) and coir (1%) contents were kept constant. The remaining 9% was shared between cement and lime, with cement rising from 3% to 7% in steps of 1%. The mass of each material was calculated as $W = (P/100) \times T$, where P is the percentage of the material and T is the total batch mass (3.5 kg).

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Table 1. Mix proportions (% by mass of dry batch) and batch quantities (kg).

Mix	Soil (%)	Fly ash (%)	Coir (%)	Cement (%)	Lime (%)	Soil (kg)	Fly ash (kg)	Coir (kg)	Cement (kg)	Lime (kg)
A	60	30	1	3	6	2.100	1.050	0.035	0.105	0.210
B	60	30	1	4	5	2.100	1.050	0.035	0.140	0.175
C	60	30	1	5	4	2.100	1.050	0.035	0.175	0.140
D	60	30	1	6	3	2.100	1.050	0.035	0.210	0.105
E	60	30	1	7	2	2.100	1.050	0.035	0.245	0.070

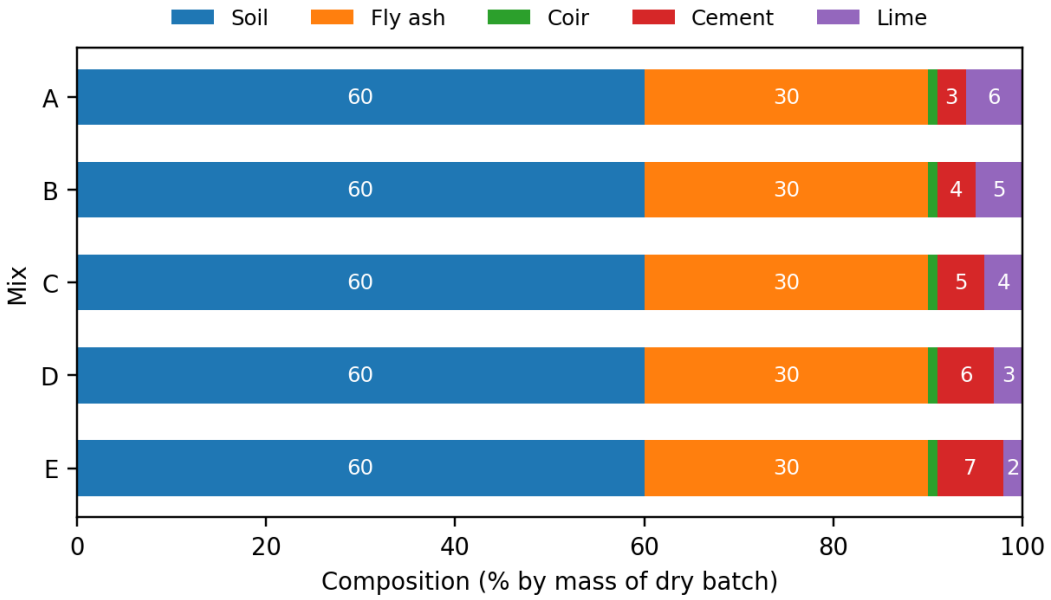


Figure 2. Composition of Mixes A–E (% by mass of dry batch). Only the cement:lime split varies; the combined binder stays at 9%.

5.2 Block manufacture and curing

The dry constituents were mixed thoroughly by hand in a tray until uniform, water was added gradually, and the mixture was filled into the interlocking mould and compacted. The blocks were demoulded with care and cured under shaded conditions before testing.

5.3 Apparent density

Apparent density was obtained as the mass of the block divided by the block volume, $\rho = m / V$, with $V = 0.003541$ m³.

5.4 Compressive strength

Each block was placed centrally between the platens of a compression testing machine (CTM) and loaded continuously until failure. Compressive strength was calculated as $f = P / A$, where P

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is the maximum load (N) and *A* is the loaded area (34,838 mm²). One block per mix was tested in the present series.

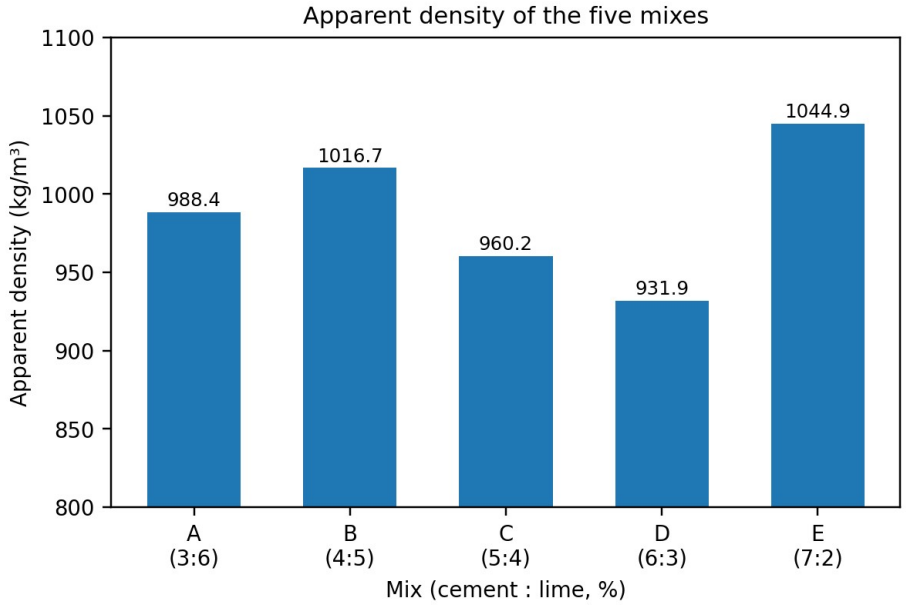
VI. RESULTS

6.1 Apparent density

Table 2. Apparent density of the blocks.

Mix	Cement : lime (%)	Mass (kg)	Volume (m³)	Apparent density (kg/m³)
A	3 : 6	3.5	0.003541	988.4
B	4 : 5	3.6	0.003541	1016.7
C	5 : 4	3.4	0.003541	960.2
D	6 : 3	3.3	0.003541	931.9
E	7 : 2	3.7	0.003541	1044.9

Apparent density ranged from 931.9 kg/m³ (Mix D) to 1044.9 kg/m³ (Mix E), a spread of about 12%. Density did not change systematically with cement content: Mixes B and E were denser than their neighbours, whereas Mixes C and D were lighter.



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Figure 3. Apparent density of the five mixes.

6.2 Compressive strength

Table 3. Compressive strength of the blocks.

Mix	Cement : lime (%)	Loaded area (mm²)	Maximum load (kN)	Compressive strength (MPa)
A	3 : 6	34,838	105	3.01
B	4 : 5	34,838	140	4.02
C	5 : 4	34,838	175	5.02
D	6 : 3	34,838	200	5.74
E	7 : 2	34,838	210	6.03

Compressive strength increased with every rise in cement content, from 3.01 MPa for Mix A to 6.03 MPa for Mix E, a 100% increase across the series. The increments between successive mixes were +1.01, +1.00, +0.72 and +0.29 MPa, so the benefit of each extra percentage point of cement, offset by one point less lime, dropped sharply beyond 5–6% cement.

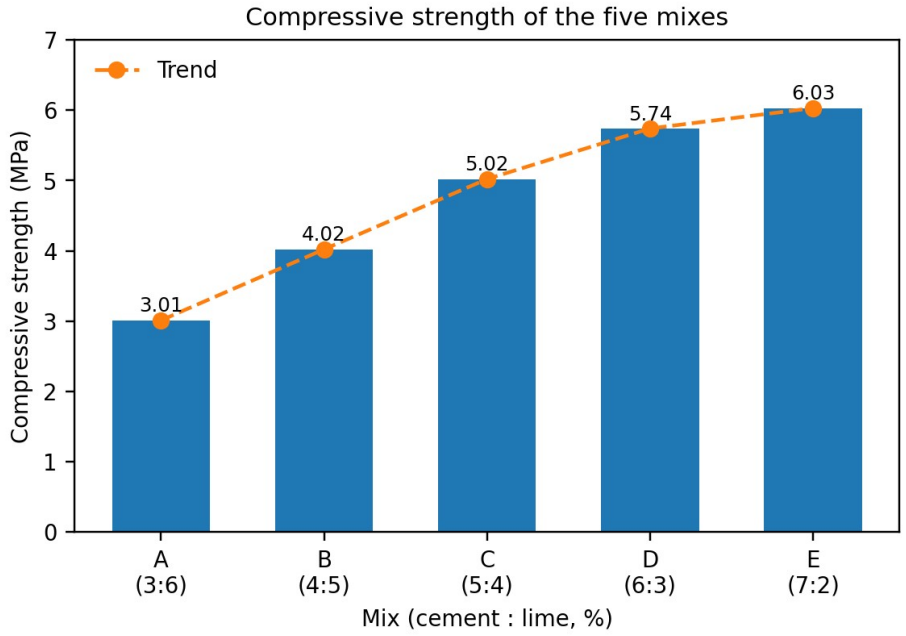


Figure 4. Compressive strength of the five mixes.

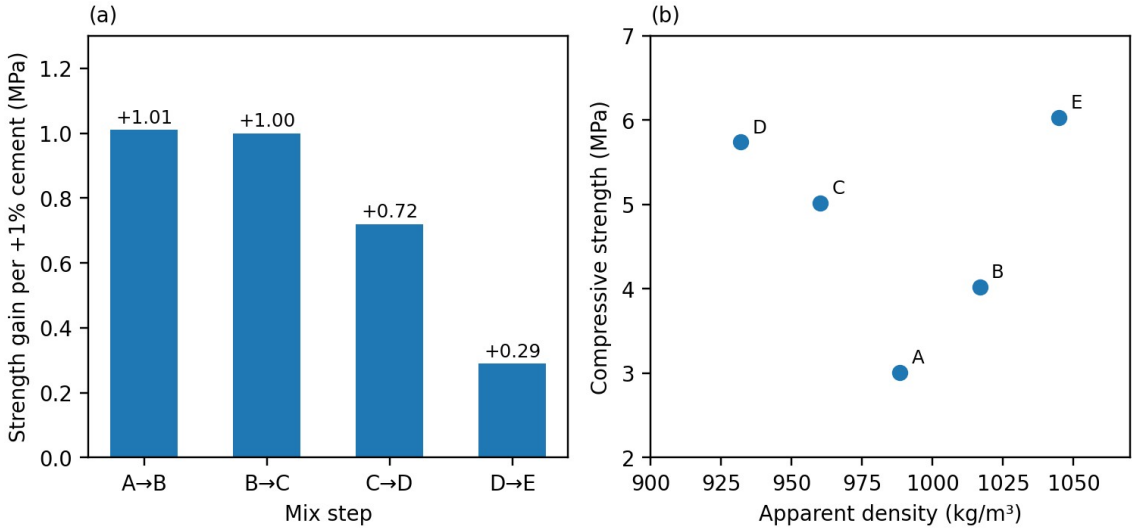


Figure 5. (a) Strength gain for each additional 1% of cement between successive mixes; (b) compressive strength against apparent density, showing no consistent relationship.

6.3 Qualitative comparison with burnt clay bricks

Table 4. Qualitative comparison of rammed earth interlocking blocks and conventional clay bricks.

Aspect	Rammed earth interlocking blocks	Conventional clay bricks
Constituents	Soil, fly ash, cement, lime, coir, water	Clay, water, sometimes additives
Process	Mixing, moulding, compaction, curing	Preparation, moulding, drying, kiln firing
Energy use	Generally lower when unfired	Higher due to kiln firing
Emissions	Avoids firing; depends on cement and lime content	Kiln firing causes greenhouse gas and air pollution
Shape	Interlocking	Usually rectangular
Mortar	May be reduced by interlocking	Generally laid with mortar
Construction speed	Can be faster due to interlocking	More time for mortar and alignment
Performance	Depends on soil, stabiliser, compaction and curing	Depends on clay, firing temperature and quality

This comparison is descriptive only. No clay bricks were tested in this study, so no quantitative claim of superiority is made.

VII. DISCUSSION

Effect of the cement:lime ratio. Within the fixed 9% total binder, replacing lime with cement raised the strength at every step. This agrees with the literature, which treats cement as the

faster-acting strength contributor and lime as a slower stabiliser whose effect depends on the soil [3], [6]. Lime reactions with clay and fly ash develop over longer periods, so the low strength of the lime-rich mixes may partly reflect the early age of testing and not a permanent deficiency; this can only be settled by 28-day and later tests.

Diminishing returns and sustainability. The strength gain per point of cement fell from about 1.0 MPa to 0.29 MPa at the top of the range, while cement is the most carbon-intensive ingredient in the mix. Reviews caution that excessive cement stabilisation weakens the carbon advantage of earth construction [5]. The data therefore suggest that an intermediate mix such as D (6% cement, 3% lime, 5.74 MPa) may give a better balance of strength and sustainability than E (6.03 MPa), whose extra 1% of cement bought only about 5% more strength. This is an indication and not a conclusion, since every result comes from a single specimen.

Density and strength. Strength increased while density varied irregularly. Mix C was less dense than Mix B yet stronger, and Mix D was the lightest yet reached 5.74 MPa. In this series, binder composition rather than apparent density seems to control strength. The recorded densities are low compared with values commonly reported for compacted stabilised earth. This is plausible for a mixture rich in fly ash and coir, but it also depends on the moisture state at weighing and on the compaction effort, which should be reported alongside the data.

Role of coir and fly ash. Coir and fly ash were held constant, so their individual effects cannot be separated here. The literature suggests that coir mainly improves crack control and post-peak toughness rather than peak strength, and that too much fibre reduces compaction [4], [8], [12].

Suitability for construction. For context, a strength of about 3.5 MPa is commonly cited as the lowest class of common burnt clay building brick in Indian practice (IS 1077). On that basis Mixes B–E exceed this value and Mix A falls marginally below it at early age. Such a comparison is valid only for equivalent specimen conditions (age, wet or dry testing, specimen geometry), which have not yet been established here, and these blocks should not be used for load-bearing applications without further testing, wall-level assessment and engineering approval.

7.1 Limitations

- Only one block was tested per mix, so the mean, variability and statistical significance cannot be reported.
- Only the cement:lime ratio was varied, at a fixed total binder; the results do not cover water content, fly ash content, coir content or coir length.
- Curing age at testing was early, and no strength-development series (for example 7 and 28 days) is available.
- Water absorption, durability (wetting–drying, erosion), dimensional accuracy, thermal behaviour, cost analysis and tests on clay brick controls were not performed.

- The qualitative sustainability claims rest on the literature and not on a life-cycle or cost calculation in this study.

VIII. FUTURE SCOPE

1. Replicate testing (at least three blocks per mix) at 7, 14 and 28 days, with the curing method stated.
2. Systematic variation of fly ash, coir content and length, and water content, using statistical design of experiments.
3. Water absorption, wetting–drying and erosion tests, and dimensional checks of the interlocking profile.
4. Prototype wall and prism tests to establish masonry-level strength and interlocking efficiency, including mortar-free assembly.
5. Cost analysis and life-cycle assessment against burnt clay bricks with equivalent functional performance.
6. Investigation of lower-carbon binders (for example rice husk ash, ground granulated blast-furnace slag, lime–slag systems) to reduce cement dependence [7], [10].
7. Thermal and acoustic performance, and standardised quality-control procedures for small-scale producers.

IX. CONCLUSIONS

Rammed earth interlocking blocks were produced from soil, fly ash, cement, lime, coconut coir and water, with soil (60%), fly ash (30%) and coir (1%) held constant and the cement:lime split varied from 3:6 to 7:2 at a combined 9%. On the basis of the experimental evidence of this study:

1. Compressive strength increased with cement content from 3.01 MPa (Mix A) to 6.03 MPa (Mix E).
2. Strength gains diminished at higher cement contents (+0.72 MPa from 5% to 6% and +0.29 MPa from 6% to 7%), indicating that a mix near 6% cement and 3% lime is the more balanced choice among those tested, subject to confirmation with replicated tests.
3. Apparent density (931.9–1044.9 kg/m^3) did not follow strength, indicating that binder composition governed strength in this series.
4. Because the results come from single, early-age specimens and no absorption, durability, cost or brick-control data were collected, the study does not claim an optimised mix, proven durability or superiority over clay bricks.

The work provides an experimental baseline for fly ash–lime–cement–coir interlocking earth blocks and sets out the replicated, durability and wall-level studies required to qualify them for affordable and sustainable construction.

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