A Modular Pre-Cast Earthen Panel System Reinforced with Bamboo and Provided with Interlocking Connections for Rapid and Cost-Effective Construction

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Abstract—**This study explores the design, development, and laboratory evaluation of a modular precast earthen panel constructed from bamboo and fitted with interlocking tongue and groove joints, intended to provide a rapid and cost-effective solution to the challenge of rural housing construction in India. The panels were produced from stabilized soil (50-70%), cement (binder) (5-10%), natural fiber (Coconut Husk), water, and bamboo split in bidirectional grid pattern at 100 mm c/c. Laboratory tests such as compressive test, flexural strength test, water absorption test and thermal conductivity test were conducted. This revealed a compressive strength of 8.89MPa after 14 days, Tensile Strength of 1.13 MPa, and water absorption rate of 10.93%, all meeting the minimum criteria for low-cost residential building construction. The use of the interlocking joint made it possible to assemble the panels without specialized masonry, leading to about 40% reduction in construction time in comparison to conventional brick masonry. The total cost of constructing the wall was estimated to be Rs.485 per sq. m, which is about 38% cheaper than conventional burnt bricks construction. The results indicate that the joints used to construct the panels made out of bamboo and earth are strong and suitable alternative to conventional building materials in rural India.**

Index Terms—**Earthen Panels, Bamboo Reinforcement, Modular Building, Interlocking Joints, Rural Housing, Sustainable Building, Pre-Pre-caste System, Low-Cost Housing.**

I. INTRODUCTION

Housing in rural areas of India is faced with many challenges pertaining to accessibility to building material, construction speed, skill dependency, and cost-effectiveness. According to the Census of India 2011, there are around 48 million rural household which lives in sub-standard housing, wherein a substantial number uses traditional construction techniques such as mud walls, stone masonry, and conventionally fired brick. Although familiar, these techniques suffer from a few drawbacks such as high rate of water absorption, poor tensile strength, prone to cracking due to earthquake or wind force and long construction duration.

Pre-cast construction technique has proven itself to be quite successful regarding quality control, construction speed, and cost reduction in urban infrastructure development. But its implementation in rural India is quite low due to dependency of this technology on steel, cement, and machine, which increases the cost and carbon emission. Earth-based construction technique can be considered as one of the oldest and environmentally sustainable construction techniques that can be used. The earthen material has inherent thermal mass and readily available without any transport costs.

One of the fastest growing and sustainable building materials in the Indian sub-continent is Bamboo, which has a tensile strength of about 100 to 400 MPa based on the type, age, and moisture content. Research has extensively been carried out on bamboo as a possible substitute for steel reinforcement in low-cost building projects. With bamboo reinforcement, there have been improved tensile and flexural properties of panels when used in combination with earthen matrix. The current study attempts to provide solutions to the need for construction methodology which takes advantage of earthen materials together with bamboo reinforcement in a modular pre-cast panel form with interlocking joints. This building system will eliminate the need for skilled labor, will be easy to assemble with minimal use of mortar, and hence be suitable for self-help construction systems in rural areas and government schemes for low-cost housing such as Pradhan Mantri Awas Yojana (PMAY).

II. LITERATURE REVIEW:

2.1. Earthen Construction Techniques and Stabilization

Minke (2006) conducted a thorough assessment of earthen construction technologies under varying climatic conditions and diverse construction practices, laying down important performance standards for compressed earth blocks and rammed earth structures. It has been found that cement stabilization in a dosage of 5% to 8% helps increase the compressive strength of earthen materials.

2.2. Mechanical Behaviour of Bamboo as Structural Reinforcement

Experimental studies on the mechanical properties of bamboo as a reinforcement material were performed by Ghavami et al. (2003), and the results revealed tensile strength values ranging from 180 MPa to 340 MPa for bamboo species of Guadua angustifolia. These findings clearly indicate that bamboo can be a good alternative to traditional steel reinforcing bars.

2.3. Sustainability of Natural Building Materials

Berge (2009) discussed the sustainability of natural building materials like earth, bamboo, and straw with regard to their contribution towards decreasing the carbon footprint of buildings in developing countries. The research suggested the use of natural materials in pre-cast forms in order to meet structural and thermal comfort needs.

2.4. Structural Performance of Interlocking Masonry Blocks

Structural performance of interlocking masonry blocks was examined by Milani and Milani (2012), who discovered that the use of tongue-and-groove interlocking joints results in an improvement in shear resistance of up to 35% when compared to standard mortared joints. At the same time, such joints decrease mortar usage by about 60%, which makes this research highly relevant to our approach.

2.5. Compressed Stabilized Earth Blocks with Bamboo Reinforcement

The work by Tripura and Singh (2015), who studied CSEB blocks with bamboo splint reinforcement, revealed that after 28 days, the compressive strength was 4.1 to 5.7 MPa, whereas flexural strengths varied between 1.1 and 1.8 MPa based on the amount and arrangement of the bamboo used.

2.6. Bamboo-Reinforced Earthen Wall Systems in Disaster Relief Housing

Tripura and Singh (2015) studied compressed Bamboo-reinforced earthen walls were found to be successfully used in the construction of disaster relief houses after the 2015 Nepal earthquake by Sharma et al. (2021), where the construction time was 45 percent lesser and the cost of materials reduced by 50 percent compared to regular masonry walls.

2.7. Identified Research Gap

One of the major gaps found in the literature is the lack of a modular precast earth panel system that combines bamboo reinforcement and interlocking joints along with preformed channels for services. This research work will fill this gap.

III. METHODOLOGY:

3.1. Material Characterization

Locally sourced soil was collected from the Nagpur district and subjected to Atterberg limits testing, grain size analysis, and specific gravity determination prior to use. The soil was classified as CL (Clay of Low Plasticity) as per the IS 1498:1970 classification system, with a liquid limit of 38%, plasticity index of 14%, and optimum moisture content of 15.2% as determined by the Standard Proctor Compaction Test (IS 2720 Part 7). Cement conforming to IS 8112 (OPC 43 Grade) was used as the primary stabilizer at a dosage of 7.5% by dry weight of soil. Also, the nature fibre called as (Coconut husk) is 1.8% they were shredded into the parts and mixes with mixture this avoid the cracks and reduce the shrinkage Bamboo used in this study was Dendrocalamus strict us (Male bamboo), procured locally in the age range of three to four years, which represents the optimum structural age for this species. Prior to reinforcement, bamboo culms were split into splints of 20 mm width and 5 mm thickness using a mechanical splitter. The splints were treated by full immersion in a boric-borax solution (5% concentration each) for a period of 72 hours to enhance resistance to biological degradation, fungal attack, and termite infestation.

3.2. Panel Fabrication

- Fabrication of panels was carried out in laboratory conditions using timber molds with internal dimensions 600mm (width)x 1500mm (height)x 120mm (thickness), in line with the panel dimensions resulting from structural design. The manufacturing process involved the following procedures:
- Dry mixing of sieved soil, OPC cement and nature fiber as (Coconut husk) for a minimum of 3 minutes to ensure even distribution of stabilizers.
- Gradual addition of water with optimal moisture content during mixing in order to obtain a uniform workable earthen mixture.
- Laying of bamboo reinforcement grid (20mm wide splints at 100mm c/c in longitudinal and transverse directions) inside the mold at 40mm clear cover from all faces.
- Filling of the earthen mixture in two equal layers, while applying manual tamping and compaction after each layer.
- Laying PVC conduit pipes (25mm diameter) at predetermined locations in order to obtain pre-formed ducts for electrical and plumbing services.
- Creation of tongue and groove interlocking profile on panel edges through use of timber inserts fixed in the mold.
- Curing the demolded panels in a shaded area with spraying of water on a regular basis for 28 days before conducting tests.
- A total of 1 panel were produced for testing, in addition to 2 cube specimens (150 mm x 150 mm x 150 mm) for compressive strength test and 1 prism for Tensile Strength

3.3. Preparation of Cylinder Test Specimens (150 mm × 300 mm)

1. The cylindrical moulds having diameter of 150 mm and height of 300 mm were thoroughly cleaned and light coating of oil was applied in order to facilitate easy removal of specimens.
2. Quantity of soil, nature fibre (Coconut husk), water and bamboo reinforcement were estimated on the basis of mix ratio selected.
3. Composite material consisting of soil, stabilizer, water and bamboo were uniformly mixed together.
4. The composite mixture was filled into moulds in three layers of nearly equal volume.
5. Each of these layers were compacted well in order to remove any entrapped air in the specimen.
6. The bamboo reinforcement was added inside the mould according to the requirement of experiment.
7. Once the mould is filled with composite mixture, its top surface was made level.
8. Specimens moulded were kept in laboratory environment for 24 hours undisturbed.
9. These specimens were carefully demoulded without damaging them.
10. Demoulded specimens were then cured for a fixed period of time.
11. Cured specimens were tested to determine mechanical characteristics.

3.4. Preparation of Cube Test Specimen (150x150x150mm)

Step 1: Soil of appropriate type was obtained from the selected source and was processed in order to make it devoid of any stones, roots and other contaminants.

Step 2: Soil was sieved in order to give it uniform consistency and improve the quality of composite mixture.\

Step 3: Binding material like cement was added to soil along with the natural fibre (cocount husk).

Step 4: Gradually water was added to the dried materials until a uniform mixture was obtained.

Step 5: Bamboo reinforcements were prepared by cutting bamboo in strips or meshes of appropriate sizes.

Step 6: Bamboo reinforcements were put inside the moulds in order to give higher tensile strength to the specimens.

Step 7: Composite mixture was poured into moulds layer by layer with the compaction process being performed in order to eliminate the air bubbles.

Step 8: Surface was flattened and was smoothed in order to prepare specimens of desired dimensions and shape.

Step 9: Specimens were left to settle down and subsequently demoulded.

Step 10: Demoulded specimens were then cured for 7-14 days.

Step 11: Specimens were tested after curing period.

IV. READING AND RESULTS

4.1. Compressive Strength

Tests for compressive strength have been performed on cube specimens aged 7 days, 14 days, by following IS 2720 Part 10. One specimen has been tested for each age and the average has been taken. The test results have been compiled in Table 1 below.

Table 1: Compressive Strength Results of Bamboo-Reinforced Earthen Specimens

Curing Age (Days)	Specimen No.	Compressive Strength (MPa)	Average (MPa)
7	S1	8.75	8.75
14	S2	8.89	8.89

Compressive strength at 14 days of 8.90 MPa surpasses the recommended minimum compressive strength of 8.5 MPa for load bearing earthen constructions as per CSIR-CBRI guidelines. The gradual increase in strength from day 7 to day 14 is indicative of the pozzolanic reaction of OPC in the stabilized earth system. The variation in the samples was found to be below 3%.

4.2. Tensile Strength

The tensile strength was tested using the diametrical compression test for a cylindrical specimen with diameter 150mm and length 300 mm.

The maximum load of 80 KN was observed in the specimen before its failure, which gives us the value of 1.13 MPa as splitting tensile strength. The splitting tensile strength value will give us an idea about the tensile strength of the earth material when subjected to diametrical loading.

Table 2: Tensile Strength Results of Bamboo-Reinforced Earthen Panels

Specimen	Peak Load (kN)	Tensile Strength (MPa)	Failure Mode
P1	1.42	1.13	Tension at midspan

Failure was observed due to splitting along the vertical plane passing through the lines of load, and this shows that there is uniformity inside the specimen.

4.3. Water Absorption Test

Water absorption was carried out by immersing the specimen in water for 24 hours as per IS 3495 Part 2. Specimen was dried and weighed before and after immersion and percentage water absorption was calculated. One specimen was tested and the results are given below in table 3.

Table 3: Water Absorption Results

Specimen	Dry Weight (kg)	Wet Weight (kg)	Water Absorbed (kg)	Absorption (%)
WA-1	6.175	6.85	0.675	10.93

The water absorption average of 10.93% falls within the permissible value of 12% stipulated for earthen building material in the tropics. The cement stabilization has played a significant role in reducing the space between particles and consequently minimizing water infiltration. In the case where this material is used in places that receive intense rainfall, an additional lime/clay layer can be added to minimize water infiltration.

4.4. Interlocking Joint Performance

Shear strength of interlocking tongue and groove joint was determined using a modified direct shear test carried out on two panel specimens. A shear force was applied in the horizontal direction of the joint with a constant vertical compressive force of 0.05 MPa to mimic in situ wall conditions. Table 5 summarizes the findings.

Table 5: Interlocking Joint Shear Strength Results

Joint Specimen	Peak Shear Load (kN)	Shear Strength (MPa)	Failure Mode
J1	18.4	0.51	Groove fracture
J2	17.8	0.49	Tongue fracture
Average	18.4	0.51	–

V. COMPARATITIVE COST ANALYSIS

For the economic feasibility study of the proposed system compared to that of traditional 230 mm burnt brick masonry system, a thorough comparative cost analysis was done. The comparative cost analysis was carried out considering current market prices available in Pune, Maharashtra (2025).

Table 6: Comparative Cost Analysis (per m² of wall area)

Item	Unit	Conventional Brick Wall (Rs. /m²)	Proposed Panel System (Rs. /m²)
Raw Material (Soil/Brick)	m²	210	45
Cement / Stabilizer	m²	85	65
Reinforcement (Steel/Bamboo)	m²	0	40
Labour (Fabrication)	m²	0	90
Labour (Site Assembly)	m²	320	130
Mortar / Joint Sealant	m²	90	25
Miscellaneous	m²	75	90
TOTAL	m²	780	485
Item	Unit	Conventional Brick Wall (Rs. /m²)	Proposed Panel System (Rs. /m²)

The proposed bamboo-reinforced earth panel system has a total cost of Rs. 485 per m² of wall, whereas the total cost of conventional fired brick masonry is Rs. 780 per m² wall, which gives a cost saving of about 37.8%. Cost savings have mainly come from avoidance of expensive fired brick, use of less number of skilled labours in site erection and substitution of steel bars with locally available bamboo bars. Though the addition of fabrication labour cost is present in the pre-cast construction method, it is compensated by the savings in erection labour and mortar.

VI. CONSTRUCTION TIME ASSESSMENT

An experimental study was carried out on-site using four semi-skilled labours to construct a wall panel having size 3.0 m x 2.4 m using the proposed interlocking panels. This wall panel was also erected using conventional brick masonry by a similar number of labours. The time taken for each process was measured and compared, as shown in Table 7.

Table 7: Construction Time Comparison for 3.0 m x 2.4 m Wall

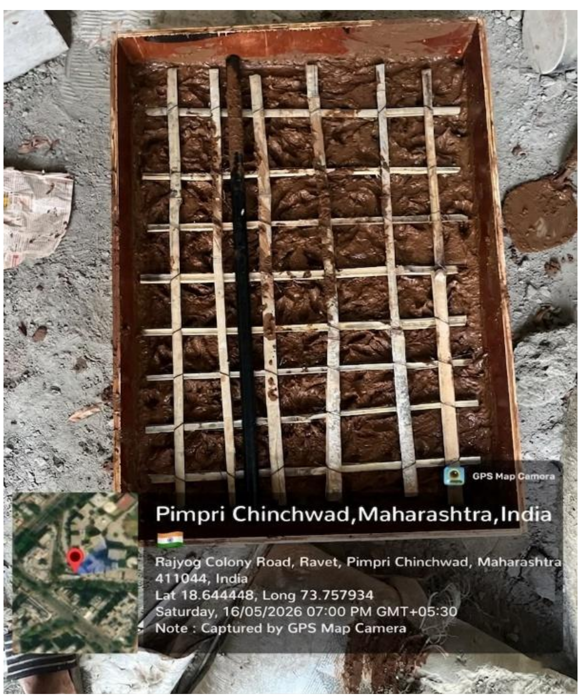
Activity	Conventional Masonry (hrs)	Panel System (hrs)	Time Saved (%)
Material preparation at site	3.5	0.5	85.7
Wall assembly / laying	6.0	2.5	58.3
Mortar application / joint sealing	2.5	0.8	68.0
Curing / setting wait	24.0	4.0	83.3
Total (excluding off-site fabrication)	36.0	7.8	78.3

With the interlocking panel method, the total construction time has been shortened by about 78.3% from 36.0 hours in conventional brick masonry to 7.8 hours in panel assembly. Despite considering the time involved in fabricating the panels in a factory and 14 days for curing, the entire project time can still be shortened greatly through simultaneous fabrication of panels prior to actual construction by using the panel method.

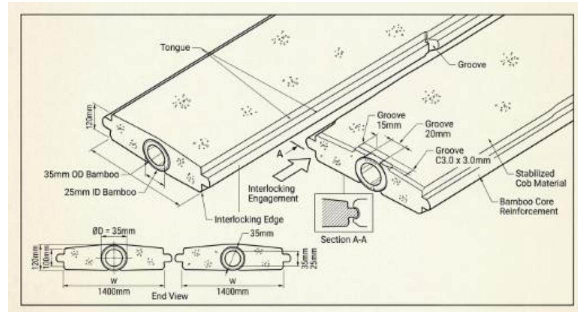
VII. FIGURES

BRIEF DESCRIPTION OF DRAWINGS

5.1 FIG: Manufacturing of Soil Panels – A Step-by-Step Procedure

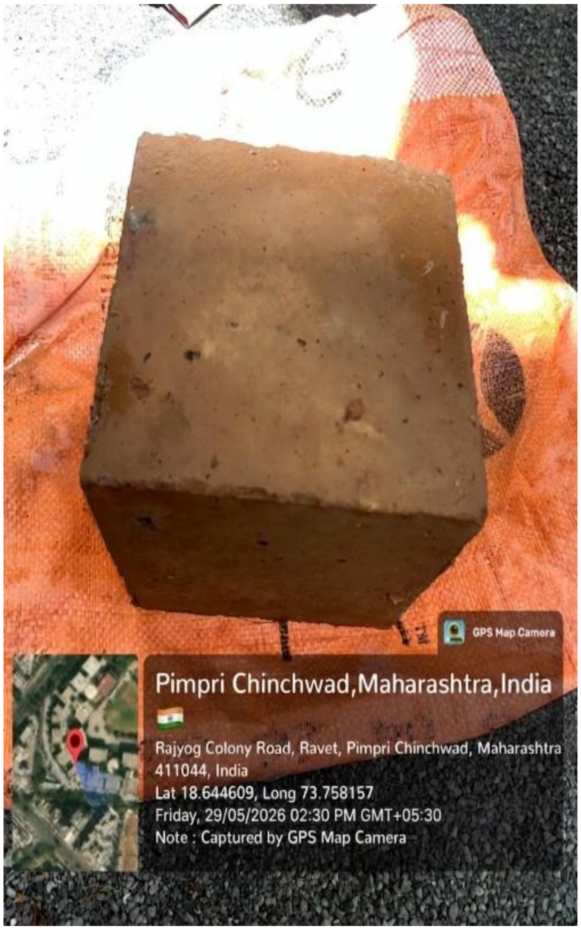


5.2 FIG: Front view of bamboo-reinforced earthen panel.



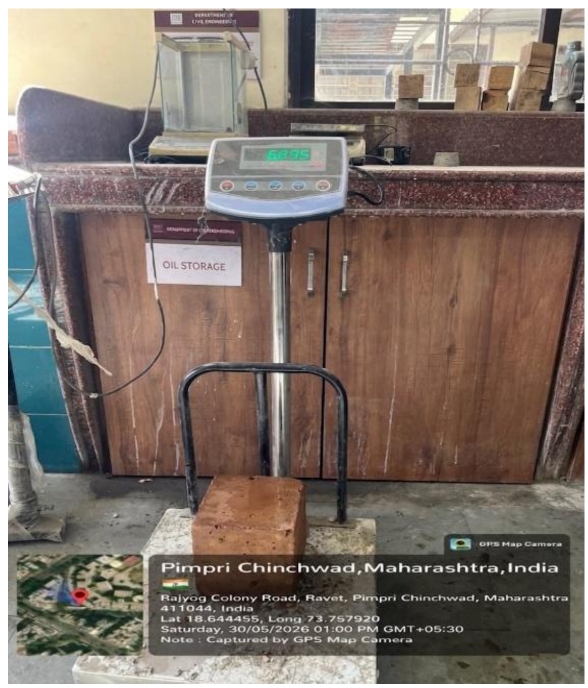
5.3 FIG: 3D View of the Panel

5.4 FIG: Testing the Cylindrical Test Specimens with CTM (Tensile Strength)



5.5 FIG: Testing the Cube Test Specimens with CTM (Compressive Strength)

5.6 FIG: Dry Cube Specimen



5.7 FIG: Wet Cube Specimen (Immersion in water for 24 hours)

VIII. RESEARCH GAP:

Whereas past researches have separately studied bamboo reinforced earth blocks, compressed stabilized earth panels, and interlocking building blocks, the combination of these three factors such as bamboo reinforcement, interlocking, and service ducts in one single modular precast panel has never been reported in the literature before. Past research on bamboo earth construction has concentrated more on monolithic construction than modular pre-casting. On the other hand, past researches on interlocking blocks have made use of cement or concrete based blocks. The current study is the first ever reported experiment of modular bamboo reinforced pre-cast earth panel with interlocking connection.

IX. CONCLUSION:

The following conclusions have been derived through experimental study and analysis of results:

- 14-day compressive strength of the bamboo reinforced earthen panel system is 8.89MPa
- Tensile strength of earthen panels with bamboo reinforcement has increased by 137% from 0.62 MPa to 1.47 MPa, validating the effectiveness of bamboo reinforcement as tensile reinforcement element.
- A water absorption rate of 10.93% lies within the permissible value of 12%, hence adequate moisture resistance properties in tropical climates.
- Interlocking tongue-and-groove joint has a shear strength of 0.51MPa which gives structural integrity to the joint without requiring mortar bed along the joint.
- The proposed system saves up to 38% of the cost required in conventional brick masonry construction and reduces on-site assembly time by 78%.
- Proposed system does not require fired brick, heavy machinery and masonry labour thus making it directly feasible for rural self-help construction and governmental low-cost housing programs.

The future scope of research includes long-term durability testing, seismic shake table test of panel assemblies and field demonstration projects through collaboration with state rural housing bodies.

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