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Bio-stabilized modular rammed earth blocks for sustainable and aesthetic construction

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Abstract

Purpose – This study aims to address critical limitations in rammed earth (RE) construction through a novel modular block system integrating computational design, modular construction and bio-stabilization techniques. The research quantifies environmental benefits and structural performance, establishing empirical foundations for commercial implementation of prefabricated earthen construction technologies.

Design/methodology/approach – The methodology used non-uniform rational B-splines (NURBS)-based parametric design for customized free-form blocks with five distinct types facilitating staggered assembly. Bio-stabilization was evaluated using animal glue and xanthan gum versus unstabilized variants. Life cycle assessment was conducted following ISO 14040 protocols. Full-scale prototyping validated manufacturing through CNC-milled formwork, while experimental validation included 28-day compressive strength testing and environmental impact quantification.

Findings – Full-scale prototyping confirmed technical feasibility of the modular free-form RE block system, achieving consistent production through precision CNC-milled formwork. Staggered assembly methodology enhanced structural stability via embedded reinforcement channels. Animal glue bio-stabilization demonstrated superior performance metrics (6.86 MPa strength, 38.61 kg $CO_{2\text{-eq}}/m^3$ emissions) compared to xanthan gum (5.58 MPa, 60.12 kg $CO_{2\text{-eq}}/m^3$) and unstabilized variants (1.74 MPa, 12.32 kg $CO_{2\text{-eq}}/m^3$).

Originality/value – This research pioneers computational design integration with traditional RE construction, establishing novel methodological frameworks for sustainable building. The synthesis of NURBS parametric geometry, prefabrication protocols and bio-stabilization represents significant advancement in earthen architecture, providing construction professionals with validated methodologies for achieving architectural sophistication while maintaining environmental sustainability.

Keywords Sustainability, Sustainability and green buildings, Open manufacturing/offsite construction, Computer aided design, Life-cycle analysis

Paper type Research paper

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1. Introduction

Rammed earth (RE) construction spans 10,000 years (Jaquin *et al.*, 2008; Xie *et al.*, 2021), historically using simple tools and manual labor (Houben and Guillaud, 1994; Woolley, 2006) while offering low embodied energy and superior thermal mass properties (Allinson and Hall, 2010; Cabeza *et al.*, 2013). Traditional RE buildings faced stability, durability and labor limitations (Gomes *et al.*, 2014; Jaquin *et al.*, 2007; Walker *et al.*, 2005). To address these issues, contemporary RE construction incorporates advanced materials, digital fabrication and sustainable innovations (Arrigoni *et al.*, 2017; Ma *et al.*, 2025, 2024b, 2024a). These advancements extend to bio-stabilization (Blok *et al.*, 2019; Fatehi *et al.*, 2021), prefabrication (Abdelaal *et al.*, 2025; Niroumand *et al.*, 2021) and robotic construction (Gomaa *et al.*, 2023, 2022). While modern RE enables complex geometries and enhanced mechanical performance (Ciancio and Beckett, 2015; Paio, 2013), challenges persist, including labor intensity, height limitations and formwork complexity (Dabaieh, 2014; Maniatidis and Walker, 2008; Preciado and Santos, 2020). To address the above issues, automated systems have been developed aiming to achieve programmable formwork positioning and pneumatic compaction (Willmann *et al.*, 2012).

Earthen construction used diverse stabilization methodologies spanning millennia (Losini *et al.*, 2021). Bitumen was used in Mesopotamian construction from 3000 BCE for waterproofing and structural adhesion (Connan, 1999), concurrent with lime-based stabilization documented from Neolithic sites dating to 5000 BCE (Lu *et al.*, 2023; Xie *et al.*, 2021). Biopolymeric stabilizers, including proteins (casein), polysaccharides (starch) and polyphenols (tannins), also demonstrated effectiveness through both archaeological evidence and contemporary characterization studies (Losini *et al.*, 2022, 2021; Lu *et al.*, 2023). The 19th-century's transition to Portland cement for stabilization – patented by Joseph Aspdin in 1824 and achieving widespread adoption by the 1850s – has revived RE in modern construction (Bennett, 2005; Chen *et al.*, 2025; Gillard, 2018; Scrivener *et al.*, 2018). Natural fiber reinforcement – incorporating straw, animal hair and vegetal materials – enhanced tensile properties while extending durability to more than 20 years (Bui *et al.*, 2009; Gomes *et al.*, 2014). To further enhance tensile and seismic performance for RE, mechanical reinforcement is incorporated in modern RE construction. Bamboo reinforcement is widely used across Asia, Latin America and Africa – demonstrating 139%–167% flexural strength improvements (Tripura *et al.*, 2020; Zhang *et al.*, 2024). Steel reinforcement is adopted in earthquake-prone regions. Meanwhile, hybrid bamboo-steel configurations occur to balance structural performance and sustainability metrics (Beckett *et al.*, 2024; Tripura *et al.*, 2020; Tripura and Singh, 2019). However, the incorporation of reinforcement complicated the construction process and resulted in higher costs and carbon footprints. More importantly, the reliance on cement for stabilization creates notable environmental impacts through CO_2 emissions (Losini *et al.*, 2022; Morel *et al.*, 2007), water consumption and waste (Andrew, 2018; Dams *et al.*, 2021; Galluccio *et al.*, 2019; Madlool *et al.*, 2011; Zhang *et al.*, 2012), necessitating contemporary reassessment of bio-based alternatives within sustainability frameworks. Bio-binders from agricultural and animal by-products offer sustainable alternatives (Abdelaal *et al.*, 2025; Fatehi *et al.*, 2021; Losini *et al.*, 2021) requiring further large-scale research. Earth processing demands only 1% of energy compared to fired bricks or concrete (Minke, 2006) due to minimal processing and local sourcing (Dams *et al.*, 2021). Bio-stabilizers such as xanthan gum and animal glue maintain performance, while reducing impacts through lower processing temperatures (60°C–65°C) versus conventional stabilizers (Abdelaal *et al.*, 2025; Idris *et al.*, 2010). These align with circular economy principles through waste reuse (Xie *et al.*, 2024), reducing embodied energy and emissions (Scrivener *et al.*, 2018; Worrell *et al.*, 2008).

Modular construction presents an opportunity to address traditional RE implementation challenges while maintaining RE's sustainability benefits. This methodology represents a shift from traditional on-site to off-site manufacturing (Bertram *et al.*, 2019). Analysis demonstrated that modular implementation could reduce total construction duration by 33% (18–24 to 13–16 months) and on-site construction time by 83% (2–12 months), while achieving 10%–25% savings in on-site labor costs (Bertram *et al.*, 2019). This evolution, driven by advanced material technologies, digital integration and increased emphasis on sustainability (Ferdous *et al.*, 2019), faces challenges in RE implementation including material optimization, modular design strategies and complex integration of design, manufacturing and assembly processes (Subramanya *et al.*, 2020).

Modern RE production methods include prefabrication in controlled environments – improving quality control and material properties (Giuffrida *et al.*, 2019; Pan, 2012). However, prefabrication for RE construction faces several challenges. These include logistical complexities, transportation constraints due to module dimensions and weight, susceptibility to edge damage during transport (Lee *et al.*, 2022) and interoperability between construction phases (Giuffrida *et al.*, 2019). These considerations necessitate the development of optimized block sizes that balance structural performance with manufacturing efficiency, requiring careful attention to load-bearing capacity, stability and inter-module connections (Hendry, 1998; Niroumand *et al.*, 2021). To address these challenges, this research proposed a novel modular RE block system combining advanced computational design, modular integrated construction and sustainable bio-binder stabilization. The system featured free-form blocks with smooth geometry transitions, staggered block arrangement and interconnection, validated through full-scale prototyping and a wall construction.

2. Methodology

2.1 Modular design principles

The design used a two-step geometric approach. First, an inner boundary was created through uniform offset, with distance determined by continuity requirements for smooth module transitions and desired curvature profiles. Second, shared symmetric boundaries defined surface continuity conditions, with tangency guides and height parameters controlling variation.

Identical edge geometry enabled four rotational positions per block. This flexibility, multiplied by assembly blocks, created design possibilities while preserving structural integrity and continuity. Prototype dimensions (50 cm × 50 cm × 25 cm) balanced structural requirements with practical handling.

The block geometry was defined by a parametric non-uniform rational B-splines (NURBS) surface with boundary conditions and tangency constraints, where u-v directional isocurves form a curvilinear mesh network. Within this variable domain, non-uniform geometric deformation maintained geometric continuity while allowing for design variation. This continuity was validated through zebra striping visualization analysis, which demonstrated surface coherence across adjacent blocks, with vertical red contours revealing the topographic characteristics of the surface geometry (see Figure 1).

The system enabled designers to manipulate UV curves through control points, generating diverse surface geometries while maintaining inter-module continuity. The underlying geometry (see Figure 2) was defined by a parametric NURBS surface with boundary conditions and tangency constraints, where u-v directional isocurves form a curvilinear mesh network. Within this variable domain, non-uniform geometric deformation maintained geometric continuity, characterized by its control mesh and spline-based interpolation.

(a)

(b)

Figure 1. Block geometry: (a) rendered image of modular rammed earth block with free-form surfaces and (b) zebra striping visualization demonstrating surface continuity with vertical red contours revealing topographic characteristics
Source: Author's own work

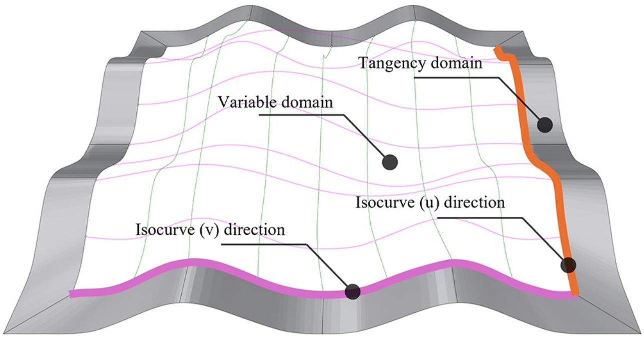


Figure 2. NURBS surface geometry illustrating the variable domain, tangency domain and isocurve directions (*u* and *v*) that define the parametric block geometry with controlled deformation parameters
Source: Author's own work

The modular assembly configuration (see Figure 3) used parametrically defined surface components with symmetrical edges. NURBS-based geometry-maintained curvature continuity across blocks while allowing for controlled deformation within variable domains. UV isocurves formed the curvilinear mesh network for defining topology, enabling customisation while preserving continuity across the system geometry.

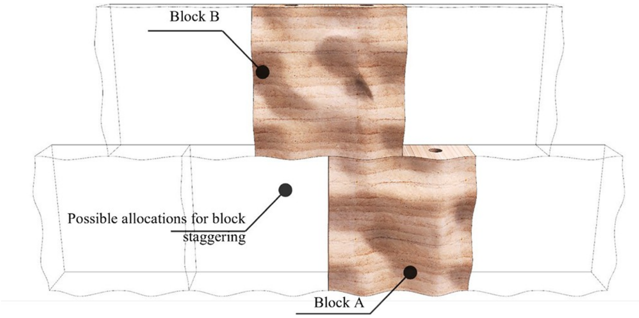


Figure 3. Modular assembly configuration showing block staggering possibilities with block A and block B, demonstrating how the symmetric boundary design facilitates geometry continuity and structural integrity
Source: Author's own work

The system used five block types (see Figure 4) designed for different structural roles to build an architectural four-wall enclosure. Primary blocks (A–B) functioned as main load-bearing elements, while secondary blocks (C–E) served as connection components and space-forming elements. Each block type included variations with strategically positioned reinforcement channels that enhanced structural performance without requiring additional manufacturing time or materials. The standardized dimensions facilitated field measurements, manual handling and planning efficiency (Kamali and Hewage, 2016). This modular system allowed flexible configurations (Huang *et al.*, 2023), while the earth-based composition delivered reduced embodied energy and environmental benefits (Greer and Horvath, 2023; Wu *et al.*, 2024).

2.2 RE block fabrication

CNC-milled bases defined surface geometry, while removable side panels established boundaries, and positioned holes provided reinforcement channels (Figure 5). Production proceeded through formwork setting, soil filling, then layered compaction (Figure 6). This approach enabled consistent production with geometric precision across block types. The modular system facilitated efficient assembly/disassembly, reducing time while ensuring quality control. Released blocks maintained geometric properties fulfilling structural and architectural requirements (Figure 7).

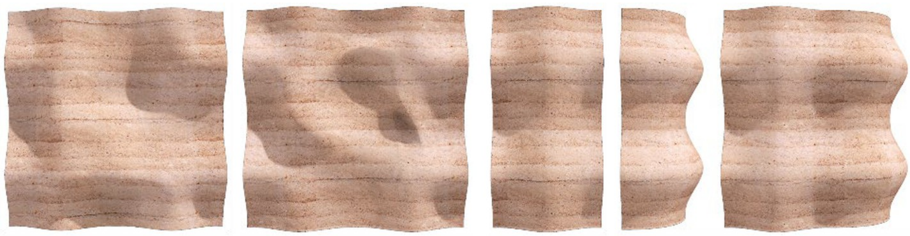


Figure 4. Five modular rammed earth block types: Block A and B serve as primary structural blocks, while blocks C, D and E function as secondary connection elements
Source: Author's own work

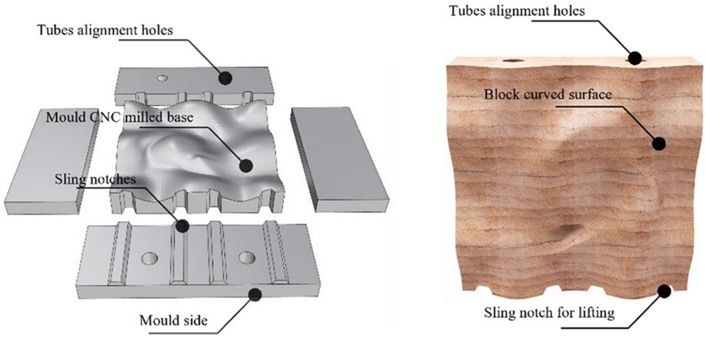


Figure 5. Formwork system components showing: CNC-milled base with tube alignment holes on the left, and the resulting block with curved surface geometry and integrated sling notches on the right after formwork removal

Source: Author's own work

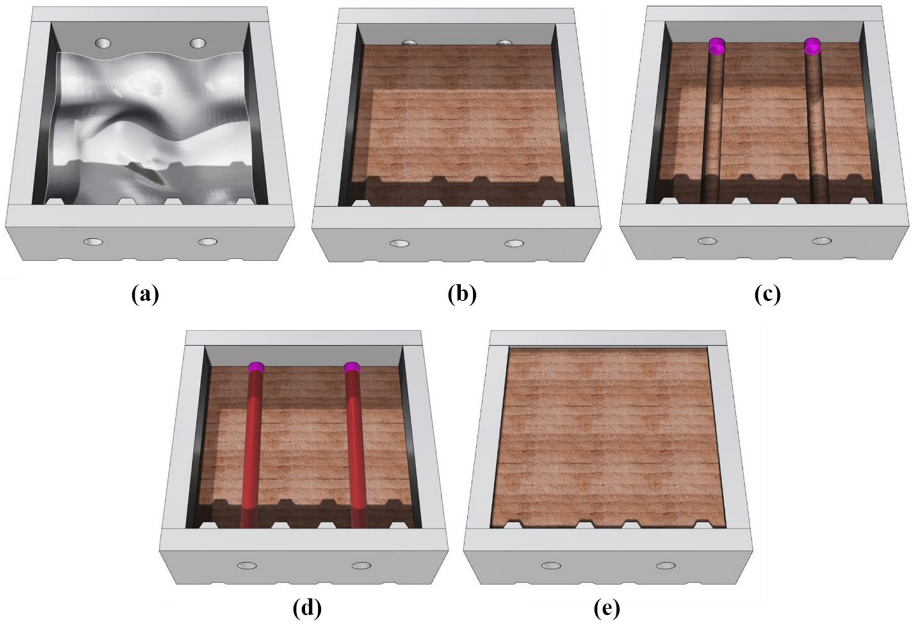


Figure 6. Block production: (a) the formwork assembled, (b) filling soil and ramming the initial layers, (c) concentring the ramming force to create a gap for the PVC tubes and assembly of the clamps, (d) assembly the tubes in position and (e) filling soil and ramming remaining layers and completing the final ramming sequence

Source: Author's own work

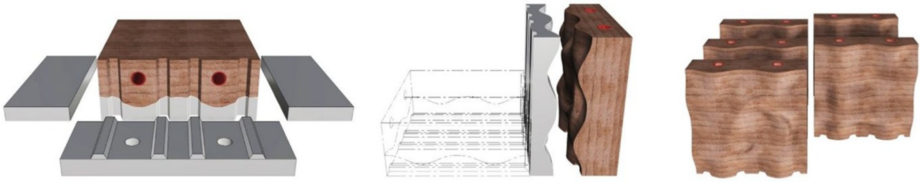


Figure 7. Formwork system and resulting blocks: (a) initial block setting after 24-h with side panels removed showing the CNC-milled base with sling notches, (b) flipped block setting after 48-h initial curing period with the base removed and (c) finished rammed earth blocks arranged for the remaining three-week moisture stabilization

Source: Author's own work

2.3 Assembly process

Following 28-day curing, blocks were assembled on-site. Positioning used bottom-surface slings (Figure 8), avoiding top lifting. Assembly followed predetermined sequences: foundation placement, then vertical stacking considering load distribution. Reinforcement bars inserted through embedded channels ensured alignment while enhancing structural integrity. The staggered configuration, with half-length overlap, eliminated continuous vertical joints and enhanced stability through geometrical interlocking.

Upon completion of the primary assembly, post-processing was conducted to fill the lifting notches with soil and smooth the surface through sanding. This final step ensured geometric continuity throughout the structure while preserved the aesthetic qualities inherent in the natural textures of RE material.

2.4 Environmental impact assessment

This study examined the environmental benefits of using bio-binders (Abdelaal *et al.*, 2025), with a functional unit of one cubic meter. The life cycle assessment followed ISO 14040 guidelines, focusing on the material preparation phase, while excluding transport emissions and the fabrication processes described in Section 3.2 due to their prototype-scale variability. The base mixture comprised three equal portions of soil with varying grain sizes 0–2.36 mm, 2.36–13.2 mm and 13.2–20 mm, totaling 2,862 g for each sample, combined with 10% water 286.2 g and 1% binder 28.62 g. All soil materials were sieved to obtain the required particle size distribution prior to mixing. Three configurations were evaluated using different binding agents: un-stabilized rammed earth (URE), stabilized with animal glue (AG) and stabilized with xanthan gum (XG). Emissions calculations were based on material embodied carbon values and process energy requirements for preparing the mixtures. Mechanical performance was assessed through 28-day compressive strength tests conducted on 100 mm cube specimens for all three mixture types (URE, AG and XG). The production process for the AG mixture involved an energy-intensive boiling step requiring 2.2 kWh/m^3(Abdelaal *et al.*, 2025), contributing 1.5026 kg $CO_{2\text{-eq}}/m^3$, while all mixtures underwent a mixing process consuming 1.2 kWh/m^3 (based on product manufacturing details), adding 0.8196 kg $CO_{2\text{-eq}}/m^3$. The energy-related emissions were calculated based on Australian electricity mix using an electricity carbon intensity factor of 0.683 kg CO_2/kWh (Stuart, 2017), while material embodied carbon values were obtained from multiple sources: 0.004 kg $CO_{2\text{-eq}}$/kg for soil (Avila *et al.*, 2021), 0.866 kg $CO_{2\text{-eq}}$/kg for animal glue (technical data from Gelita Australia), 1.67 kg $CO_{2\text{-eq}}$/kg for xanthan gum (Kumar *et al.*, 2023) and 0.0002 kg $CO_{2\text{-eq}}$/kg for water (Shobeiri *et al.*, 2023). In terms of performance as shown in (see Figure 9), plain URE demonstrated the lowest CO_2 emissions at

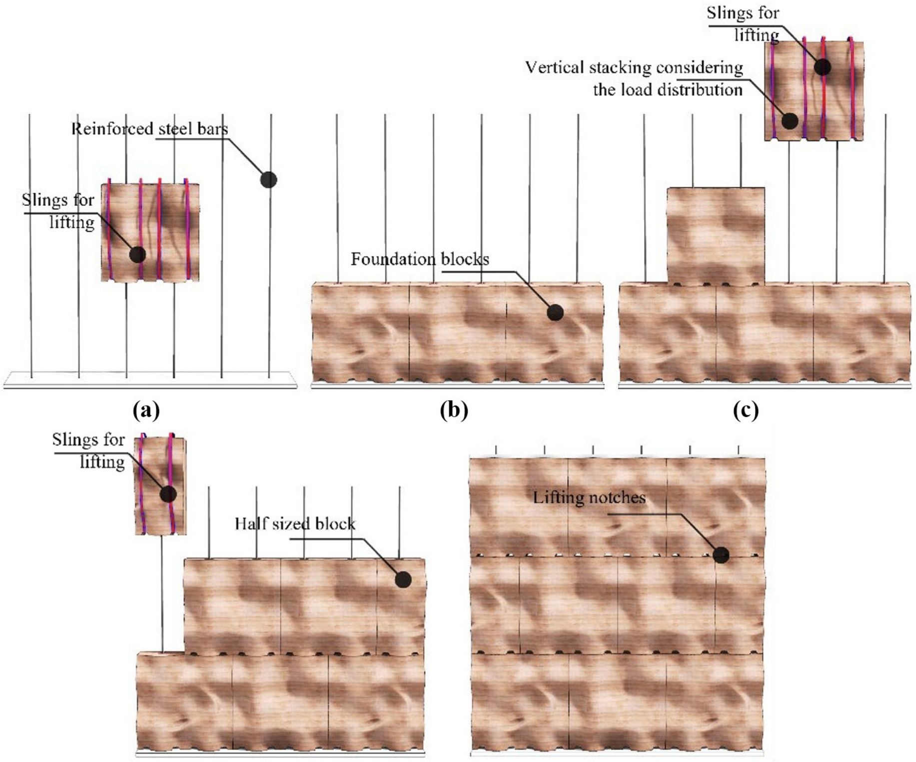


Figure 8. Assembly procedure for the rammed earth blocks showing: (a) reinforced steel bars and slings for lifting, (b) foundation block placement, (c) vertical stacking considering load distribution, (d) half-sized block integration with the assembly and (e) the final assembled wall
Source: Author's own work

12.32 kg $CO_{2\text{-eq}}/m^3$ but achieved only 1.74 MPa strength, indicating limited structural capacity. The AG-stabilized mixture produced moderate emissions at 38.61 kg $CO_{2\text{-eq}}/m^3$ while achieving the highest strength of 6.86 MPa, resulting in the most efficient kg $CO_{2\text{-eq}}/m^3\cdot$MPa ratio of 5.63. In contrast, the XG mixture generated the highest emissions at 60.12 kg $CO_{2\text{-eq}}/m^3$ with 5.58 MPa strength, yielding the least favorable kg $CO_{2\text{-eq}}/m^3\cdot$MPa ratio of 10.77. The analysis concluded that the AG-stabilized mixture represents the optimal balance between environmental impact and structural performance, while XG, despite its good strength, proves least sustainable due to its high environmental impact. These findings underscored the importance of considering both environmental and structural factors in sustainable construction material selection, with AG emerged as a promising binder for RE applications.

3. Prototyping

3.1 Mixture, preparation and production

The modular RE blocks incorporated a soil mixture of 50% 5 mm minus cream crusher dust and 50% 10 mm minus cream crushed rocks from Hastings region quarries in Victoria,

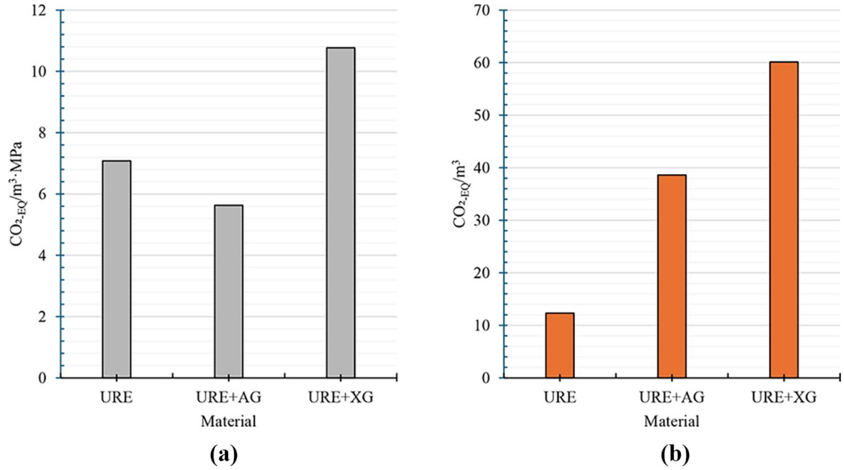


Figure 9. Environmental impact assessment comparing three rammed earth mixtures: (a) efficiency ratios and (b) emissions
Source: Author's own work

Australia, with edible bovine gelatine 200 bloom grade serving as a sustainable bio-binder at 1% by soil weight and 10% water content. Compaction was performed in seven successive layers using two different rammers. The initial two layers were compacted with a Trax KPT-1L Kawasaki sand rammer operating at 1,800 blows per minute with 18 mm butt diameter. For the remaining five layers, an Ingersoll Rand 241A1M floor sand rammer was used, operating at 1,590 blows per minute with 102 mm stroke length and 33 mm bore. Each layer underwent 30–40 s of compaction to minimize voids and optimize compression. Following compaction, specimens underwent curing in a semi-controlled outdoor environment representative of Melbourne ambient conditions.

3.2 Off-site fabrication process

The modular RE block fabrication used precision manufacturing techniques to create the complex geometries required for the block system. The formwork system consisted of a CNC-milled obomodulan® 710 terra polyurethane base (700 kg/m³ density, 25–30 MPa compressive strength) to achieve precise free-form geometries (see Figure 10). The process involved assembling removable plywood formwork sides with sufficient rigidity (see Figure 11). The formwork walls were constructed with a 36 mm thickness to ensure adequate stiffness and minimize deformation during the high-pressure ramming process. This formwork system accommodated the positioning of PVC tubes, creating channels for reinforcement bars that facilitate structural connectivity between blocks during final assembly (see Figure 12).

The fabrication process followed a systematic procedure for integrating reinforcement channels in the RE blocks. Initially, the formwork base and boundaries were assembled without the reinforcement tubes, as illustrated in Figure 13. The soil mixture was then compacted in sequential layers following the methodology detailed in Section 2.3. Upon reaching the designated height for tube placement (approximately mid-height of the block), the ramming process was temporarily halted. At this stage, PVC tubes were precisely

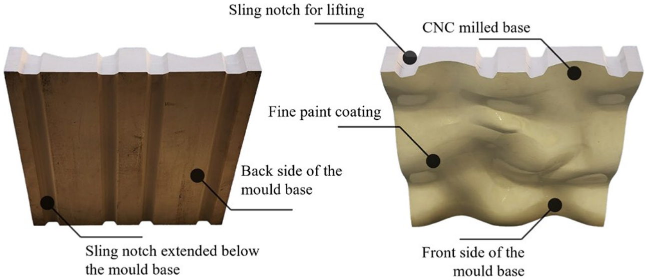


Figure 10. Formwork base components: front and back views of the CNC-milled timber base, showing integrated sling notches for lifting
Source: Author's own work

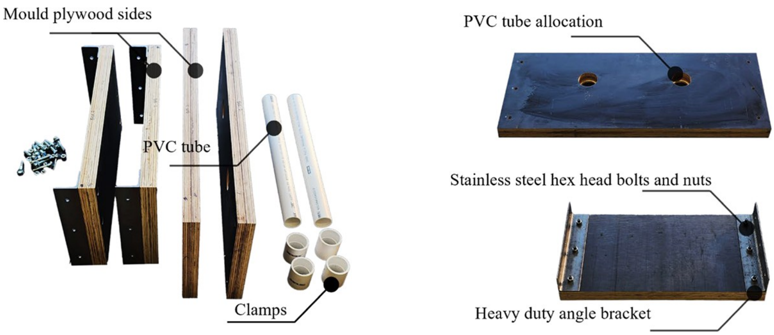


Figure 11. Formwork component assembly showing the main structural elements and tube positioning system
Source: Author's own work

positioned according to the predetermined layout (see Figure 14), creating channels that will later accommodate steel reinforcement bars. After securing the tubes in position, the ramming process continued until the block reaches its final thickness of 25 cm. This integrated channel system provided critical structural benefits: it ensured precise alignment during wall assembly, enhanced load distribution across the wall system and significantly increased the composite structure's resistance to lateral forces. The strategic positioning of these channels – following the block's geometry contours – maintained the structural integrity while facilitating the reinforcement connectivity that is essential for creating a cohesive wall assembly.

The completed RE blocks required precise dimensional control to ensure both aesthetic quality and proper assembly fit. The bottom surface featured consistent lifting notches specifically designed to accommodate slings for handling. Following compaction, the RE blocks followed a systematic desiccation procedure: 24 h within the formwork, followed by side panel removal. Then, a 48-h initial curing period was implemented to ensure the structural integrity of the blocks during flipping and handling. Following this phase, blocks were transferred to the designated curing location for the remaining three-week moisture stabilization period (see Figures 15 and 16).

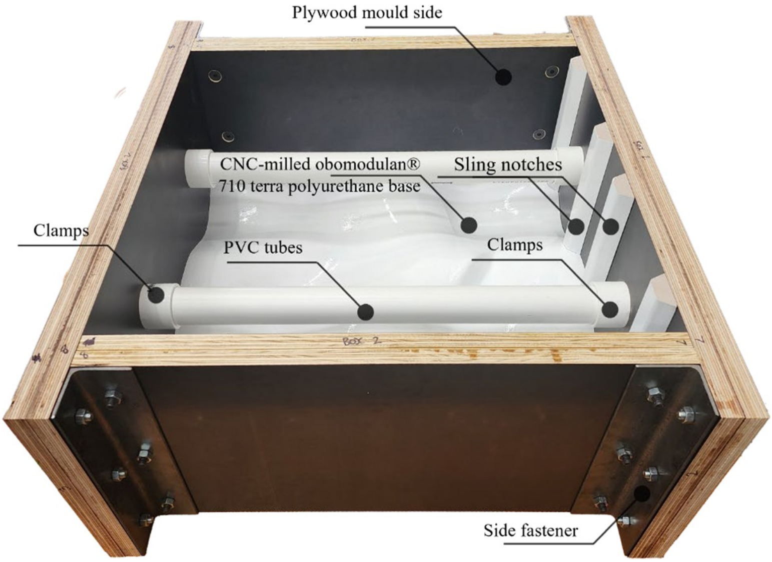


Figure 12. Complete formwork assembly showing all setting and the tubes that will be placed after ramming to its level, including plywood formwork side, sling notches, PVC tubes, CNC-milled obomodulan® 710 terra polyurethane base and side fastener

Source: Author's own work

4. Results and discussion

4.1 Assembly of prefabricated rammed earth wall

Upon completion of a 28-day curing period, the RE blocks attained sufficient compressive strength for transportation to the construction site. The assembly protocol (see Figure 17) used sling mechanisms for block placement and implemented a staggered configuration for optimal structural stability. The assembly proceeded in two sequential steps: first, establishing a triangular wall configuration using the full-sized primary blocks; second, completing the wall formation by installing the remaining blocks. Due to laboratory constraints during the prototype testing phase, timber spacers were temporarily used in place of the half-sized blocks.

The wall assembly was constructed using eight blocks in a staggered configuration, yielding overall dimensions of 1.5 × 1.5 m [Figure 18(a)]. The experimental protocol excluded notch filling and surface finishing procedures to examine raw interface characteristics. This approach revealed interface discontinuities, particularly at notch locations. Surface damage from transport was identified in areas requiring refinement: notch design modifications and edge reinforcement. Block curing and assembly were carried out during Melbourne's winter period (July 2024, rainfall: 96.8 mm, 67% above average). Despite variable environmental exposure, the RE blocks achieved adequate strength for assembly, enabling completion of the 1.5 × 1.5 m prototyping.

The anticipated low-rise structure, upon completion, was expected to resemble the visualization [as shown in Figure 18(b)–(c)]. These rendered images illustrated the potential integration of the modular RE wall system in a single-story residential application.

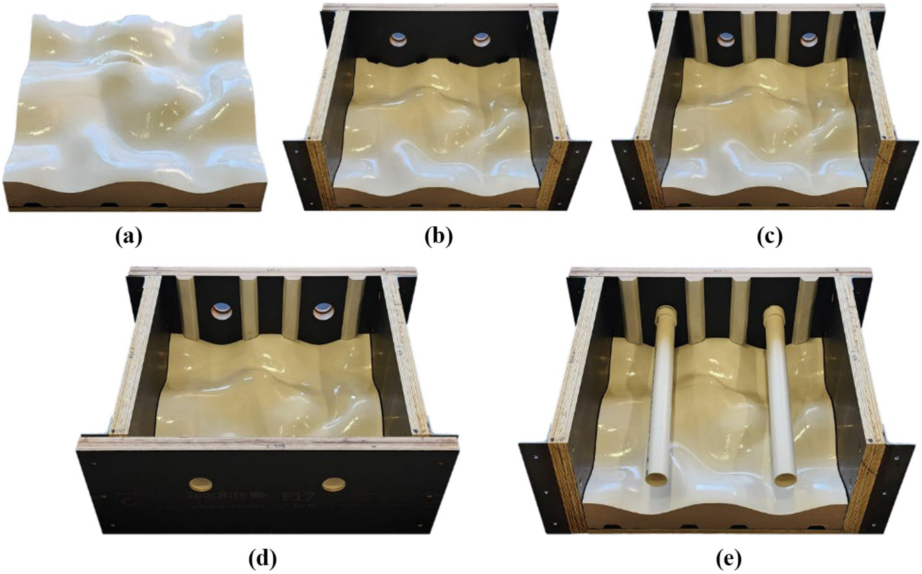


Figure 13. Formwork assembly sequence: (a) CNC-milled lower base of the formwork with surface curvature positioned on the flat layer with channels for sling placement, (b) side panels attached to the base, (c) slings positioning guides installed, (d) completed formwork assembly before soil compaction and (e) PVC tubes installed in position for creating reinforcement channels
Source: Author's own work

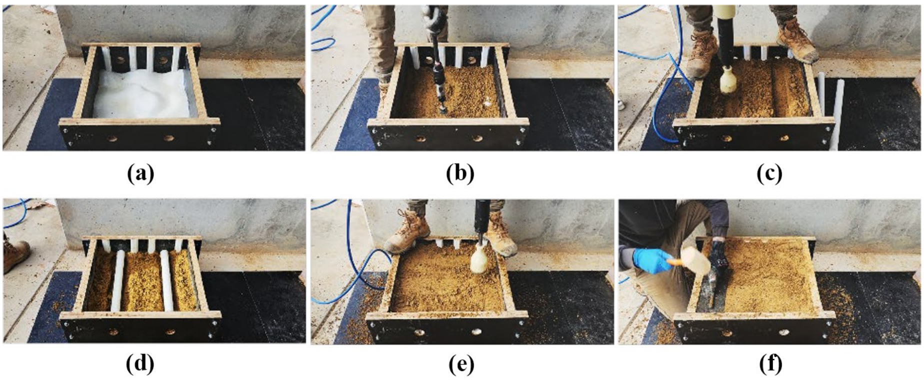


Figure 14. Block production: (a) the formwork assembled, (b) ramming the initial two layers, (c) concentring the ramming force to create a gap for the tubes, (d) the tubes assembled in place, (e) ramming last layers and (f) flattening the last layer manually
Source: Author's own work

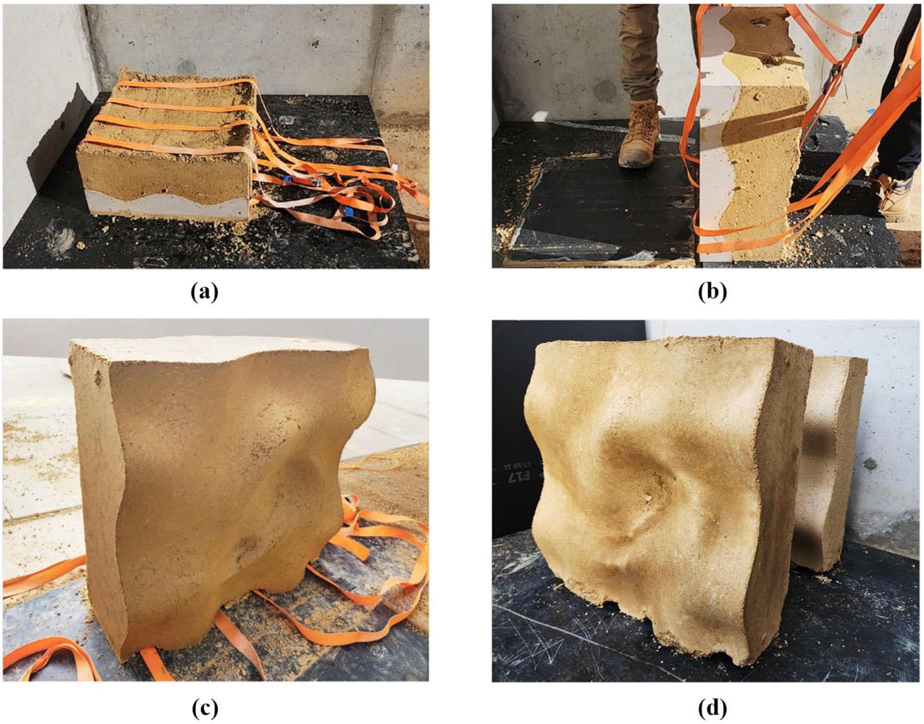
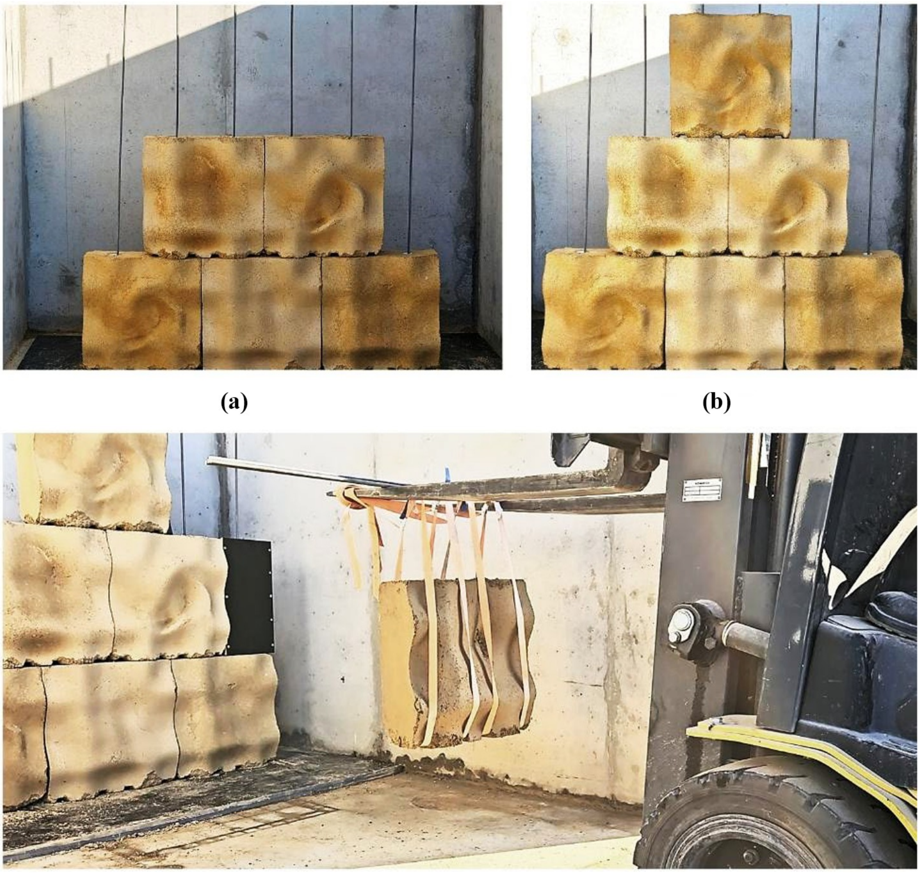


Figure 15. Block handling and stockage preparation: (a) sliding slings into grooves at the bottom of the CNC milled base, (b) fastening slings, (c) flipping the block onto slings, (d) removing the CNC milled base, (e) sling slot detail allowing removal and (f) stacking blocks for the drying period
Source: Author’s own work

Figure 16. Finished rammed earth block showing curved surface geometry after being released from the CNC milled base for drying, with visible notches at the bottom surface for handling
Source: Author’s own work



(a) (b) (c)

Figure 17. RE wall assembly process using mechanical lifting equipment: (a) first stage assembly showing bottom rows of blocks arranged in a triangular formation, (b) continued assembly with additional top block and (c) second stage assembly showing slings for safe handling
Source: Author's own work

4.2 Limitation and future work

This research explores the feasibility of freeform modular RE blocks integrating advanced parametric design with bio-stabilization techniques. While the current study focuses on the geometry modeling and construction workflow, systematic assessments on the mechanical and durability performance of the proposed system will be critical for the next steps. These include axial compression and tensile tests, as well as flexural, seismic, hygrothermal and fire resistance evaluations. Durability testing through wet–dry cycling and freeze-thaw protocols will further validate the practical applicability. Development of automated modular construction systems will also be necessary to improve efficiency while ensuring consistent quality.

(a)

(b)

(c)

Figure 18. Modular rammed earth implementation and conceptualized applications: (a) physical prototype showing completed wall with free-form surface blocks, (b) and (c) computer-generated visualizations of potential applications with (b) a free-standing wall structure using modular blocks and (c) conceptual rendering of a complete building incorporating the rammed earth block system
Source: Author’s own work

5. Conclusion

This study proposed a novel modular RE block system that integrates computational design, modular construction and bio-stabilization techniques. The system introduced customized free-form blocks with smooth geometry transitions and a systematic assembly method that enables staggered block arrangements with integrated steel reinforcement for enhanced structural stability. Comparative analysis of stabilization methods demonstrated that animal glue bio-binder provided an optimal balance between mechanical performance and environmental impact (6.86 MPa compressive strength with 38.61 kg $CO_{2\text{-eq}}/m^3$ emissions) when compared to both unstabilized RE (1.74 MPa, 12.32 kg $CO_{2\text{-eq}}/m^3$) and xanthan gum-stabilized RE (5.58 MPa, 60.12 kg $CO_{2\text{-eq}}/m^3$). The precision manufacturing process, using CNC-milled formwork and strategically embedded reinforcement channels, facilitated consistent production and reliable assembly. Full-scale prototyping confirmed the technical feasibility of the system and demonstrated its potential for architectural implementation. The research contributed to advancing sustainable construction methods that addressed traditional design and building limitations while maintaining the inherent environmental advantages of earth-based building materials.

Data availability

Data will be made available on request.

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