Robotically Carved Adaptive Moulds for Rammed Earth Construction

Adaptability for site-specific design

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Rammed earth has gained renewed architectural interest for its sustainability, thermal performance, and cultural relevance. However, traditional methods remain labour-intensive and limited in geometric and design flexibility (Gomaa et al., 2023, pp. 1–3). To address these constraints, this research explores a block-based approach, customizing each façade to suit local contexts. Two mould-making techniques were investigated to enable design adaptability: 3D-printed moulds and robotic sand carving—a novel, zero-waste method. Both techniques allow for intricate, site-specific geometries with functional and aesthetic benefits. To evaluate the potential of site-specific design, a case study was conducted on optimizing façade geometry for the Middle Eastern climate. Physical prototypes featuring self-shading geometries were developed to delay heat transfer and enhance thermal performance. The study concludes with an optimized wall prototype that integrates both fabrication techniques to produce bespoke blocks. This approach offers a bridge between vernacular practices and advanced fabrication, providing a flexible, sustainable construction method adaptable to diverse design challenges.

Keywords: *Rammed Earth, Robotic Manufacturing, Adaptive Moulds.*

INTRODUCTION

The global climate crisis emphasizes the need to reassess environmental impact. The construction sector accounts for 37% of global CO_2 emissions, with concrete, steel, and aluminum contributing 7% (United Nations Environment Programme, 2024, p. 10). Interest in low-embodied materials like earth-based construction has grown, aiming to standardize manufacturing as an alternative to carbon-intensive materials (Gomaa *et al.*, 2022). Unlike concrete's standardized formula, earth-based construction performance varies with local conditions. This paper focuses on rammed earth, exploring these variations as design opportunities through adaptable fabrication methods tailored to local contexts.

Despite its sustainable advantages, the widespread adoption of rammed earth construction remains limited due to traditional methods being labor-intensive, time-consuming, and restrictive in design flexibility (Alhumayani et al., 2020;Gomaa et al., 2023, pp. 1–3). The technique requires sequential wall construction using rigid wooden frameworks, where excavated soil is layered and compacted. Once filled, the framework is repositioned for the next section (Keable and Keable, 2013 p. 2). To reduce labor in these traditional processes, architect Martin Rauch developed a mechanized system to prefabricate rammed earth walls (Heringer, Howe and Rauch, 2023, p. 80.); however, enhancing design flexibility within this method remains challenging (Gomaa et al., 2023, p. 13).

To improve adaptability and explore non-standard geometries, recent research has investigated ways to manipulate rigid formwork, ranging from low-tech, craft-based methods to advanced digital fabrication tools, each with varying durability and complexity. In India, hand-carved wooden moulds were developed with local carpenters to examine how block shapes influence bonding and wall patterns (Rabie, 2008). To improve flood resilience, fabric-based formwork was used instead of wood, generating unique geometries (Lee, 2022). Architect Yu Zhang has been using 3D-printed moulds for rapid, cost-effective assembly of CEB structures (Zhang et al., 2021). In the Common-action Gardens project, rammed earth blocks were formed using gyroid geometry to function as a vertical planting surface. These blocks were cast in negative moulds made from expanded polystyrene (EPS), robotically cut with a hot wire end effector (Akipek, 2019, pp. 1421–1438). Additionally, the company 'Adapa' developed, developed computationally controlled pin-board moulds for adaptable formwork, though these techniques have yet to be applied to rammed earth (Adapa, no date).

Each mould-making method offers trade-offs in durability, efficiency, and geometric flexibility. For instance, Hand-carved wooden moulds are long-lasting but labor-intensive, while welded steel moulds are relatively faster to produce but restrict design complexity. Despite advancements, existing mould-making techniques cannot be fully reconfigured without generating material waste.

To address these limitations, this research further explores adaptable moulds using 3D-printed negatives and robotic sand-carving. These techniques enable design flexibility while allowing either the mould itself or its material to be reused, making the process more sustainable and efficient. The moulds presented in this paper were digitally fabricated, ensuring a high degree of adaptability for site-specific applications.

As a site-specific case study, this project samples climate data from the Middle East (Leick, 1998). With global temperatures rising, the region is projected to warm by 3°C by 2050, potentially reaching 50°C by 2100 (Lelieveld et al., 2016, p. 245). Given its proven ability to regulate indoor temperatures passively, rammed earth remains a viable building method (Heringer, Howe and Rauch, 2023, pp. 50-54). To further enhance thermal performance, additional design strategies may be required, such as increasing thermal mass through thicker walls or modifying facade geometry. This paper examines the latter, investigating how adaptive geometries can slow heat transfer through both digital models and physical prototypes (figure 1).

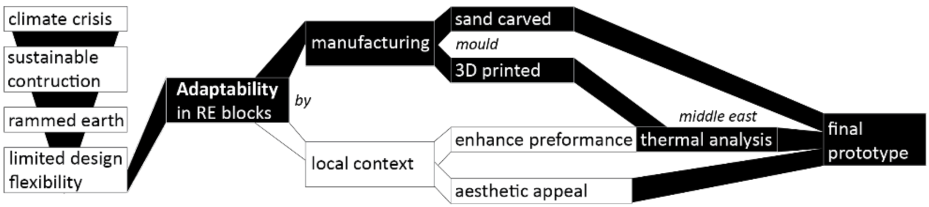


Figure 1
Research workflow

Scope

This research aims to develop rammed earth structures adapted to local conditions, recognizing the importance of site-specific design in vernacular construction. Environmental factors and cultural aesthetics drive geometrical adaptability, allowing designs to respond to their surroundings.

To achieve adaptability, the study investigates flexible moulding techniques for earth construction, focusing on 3D-printed moulds and robotic sand-carving moulds. Inspired by the concept that rammed earth can naturally return to the ground without a lasting footprint, this project introduces a sustainable, reusable mould using sand and clay blocks carved by a robot into negative geometries. As proof of concept, a final wall section was constructed, integrating both fabrication methods into an optimized façade. The façade's geometry was designed to enhance thermal performance under site-specific conditions, demonstrating the potential of these techniques in sustainable construction.

MATERIAL RESEARCH

Rammed earth construction relies on a soil mixture of clay, silt, sand, and gravel. Clay acts as a binder when damp, and solidifies the structure as it dries. An optimal mix typically consists of 5-15% clay, 15-30% silt, and 50-70% sand and fine gravel (Keable and Keable, 2013, p. 18).

Although this project was designed for a specific locality, material testing, prototyping, and machining were conducted off-site at the B-made workshop at University College London. The required materials, red earthen powdered clay, building sand, and 10mm shingle gravel, were transported to the site and mixed accordingly.

To further understand the material's behavior, its compressive strength was tested. The New Zealand standard specifics a compressive strength of a minimum of 1.3 MPa for compressed unstabilized earth blocks (New Zealand, 1988, p. 24) . In the test, four blocks (20 × 14 × 8 cm) were produced using the same soil composition, compacted with a hydraulic press, with variations in soil layering and compaction weight (figure 1).

Blocks 1 and 3 were formed from a single batch of soil, with compaction weights of 4 and 5 tons, respectively. Blocks 2 and 4 were constructed in two layers- an initial 4 cm layer, followed by a second layer compacted to a total height of 8 cm. Block 2 was compacted at 4 tons, and Block 4 was compacted at 5 tons. The results indicate that increasing compaction weight and layering the material enhance compressive strength. Blocks 2 and 4, which incorporated layered compaction, achieved strengths of 1.06 MPa and 1.14 MPa—approaching the 1.3 MPa target. However, further testing is required to fully meet the standard (Table 1).

Table 1
Material testing

Blocks	B1	B2	B3	B4
				
Compaction [ton]	4	5	4	5
Layers	1	2	1	2
Strength [MPa]	0.6	1.06	0.86	1.14

ADAPTABLE MOULD RESEARCH

Two methods of generating adaptable negative moulds were examined: 3D-printed moulds and sand-carved moulds. Desktop 3D printing was selected as the most accessible solution for mould-making; However, it raises sustainability concerns due to plastic use. In contrast, sand carving enables a more sustainable yet technologically demanding approach. The mould was built using a wooden framework, into which the adaptable negatives were placed.

Method 1- 3D printed mould negatives

During production, the limitations of printed mould geometry and durability under compaction were explored. Two mould geometries were printed using PLA on a desktop 3D printer (Ultimaker 2+) with a standard 15% infill. The first mould had a curved shape, while the second featured sharp edges (figure 2).

The moulds were placed within a wooden framework, filled with a rammed earth mixture (40% sand, 30% gravel, 15% clay, 5% water), and compacted using a hydraulic press.

Both moulds failed after several compaction attempts due to distortion. In the sharp-edged mould, the tip fractured immediately, and in both moulds, the infill crushed.

To improve durability, geometric modifications and increased infill were tested. In the sharp-edged geometry, filleting edges and chamfering the tip helped reduce stress points. An increase of infill to 30% was also tested, and this adjustment proved sufficient durability.

At 30% infill, the moulds remained relatively lightweight. As noted by Yu Zhang, this is a significant advantage, allowing off-site printing and on-site shipping, making the moulds accessible in areas without 3D printing technology (Zhang et al., 2021, p. 345). However, from a sustainability perspective, the use of plastic materials and the environmental impact of transporting moulds to remote communities, particularly in terms of CO_2 emissions and logistical costs, raise important concerns that warrant further evaluation.

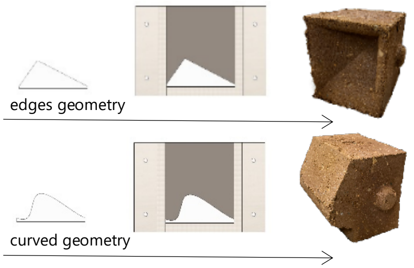


Figure 2
Fabrication process from top to bottom. Left, sharp geometry. Right, curved geometry.

Method 2- Robotic carving mould negatives

The second method explores a novel approach using sand-based moulds carved by robots. It tests a material mixture designed to withstand both compaction and carving, while addressing geometric limitations imposed by tool capabilities and material properties. Additionally, it examines methods to refine the surface finish.

This approach follows stereotomic principles to generate the mould. First, compressed sand-based blocks were created, which were then carved to achieve the final mould design. The block must be soft enough for carving but durable enough to withstand compaction. Three blocks with varying clay content 0%, 20%, and 35% were tested. Each block was carved into the same geometry and placed in a wooden framework for compaction. During testing, the pure sand mould collapsed, the 20% clay mould cracked under compaction, and the 35% clay mould exhibited sufficient durability.

Several parameters influence the final mould geometry:

- Dry State of the Sand-Clay Blocks: After compaction, the blocks must be air-dried evenly for 5-7 days. Damp sections can break off in chunks, preventing smooth carving.
- Mould Geometry: Similar to 3D-printed moulds, sand-clay moulds perform better with smooth, rounded geometries over sharp edges to prevent sanding and flattening during compaction.
- Carving Tool Limitations: A custom 3D-printed silicon end effector was designed for this task and attached to a Universal Robot (UR-10). The end effector connects to a steel tube at the front and a vacuum (hoover) at the back (figure 3). As the robot follows a computed toolpath, the steel tube gently scrapes the surface, while the vacuum collects excess sand, which can later be reused for future block moulds. The tool's radius and

- angle influence the carving details. In this case, a 16 mm diameter tube with a 30-degree angle was used.
- Toolpath Programming: The robot's movement was directed along controlled XZ or YZ carving sequences (figure 4). The toolpath must avoid overlaps or excessive stationary movement, which could distort the geometry (figure 5). Even when the tube is not in direct contact with the block, it can affect the surrounding soil.


Figure 3
Sand carving end effector

To further refine the surface finish, two additional techniques were employed: First, a nylon film was placed between the mould and the rammed earth soil to prevent adhesion, and second, a layering compaction strategy was used. A fine sand-clay mix (4:1 ratio) was applied before the standard soil to prevent gravel from imprinting on the surface and damaging the mould's texture.

This research explores robotic sand carving as a flexible, sustainable alternative to rigid moulds. The removed sand retains its strength and can be reused for new moulds, reducing material waste. By integrating computational design with digital fabrication, this approach enhances adaptability, enabling custom construction.


Figure 4
direction of carving

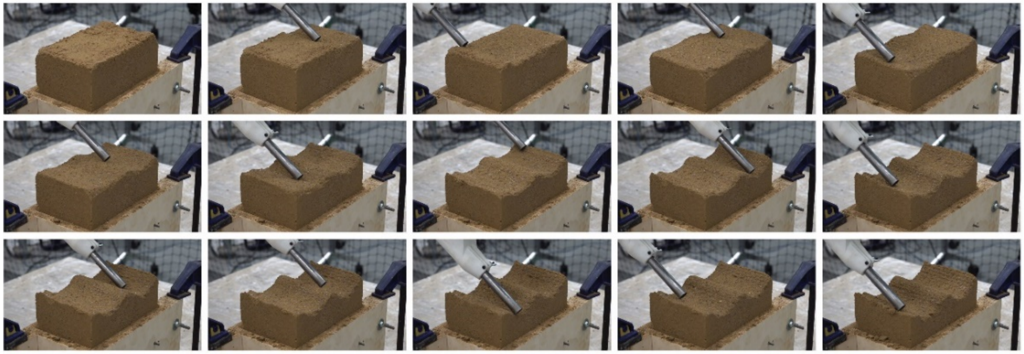


Figure 5
Sand carving end effector

TAILORING A DESIGN TO LOCALITY-CASE STUDY

This study examines adapting a design to the Middle East climate, slowing the process of heat transfer to prolong interior thermal comfort time.

The formula used to measure the rate of heat transfer through a material by Fourier law is (Yener and Kakac, 2008, pp 14-18):

$$\frac{k \times A \times (T1\text{-}T2)}{L} = Q \qquad (1)$$

- Q = Heat transfer rate (W or J/s)
- K = Thermal conductivity of the material (W/m·K)
- A = Cross-sectional area (m^2)
- T1,T2 = Temperatures on exterior and interior (K or °C)
- L = Thickness of the material (m)

From this formula, reducing the speed of heat transfer may be achieved by lowering the temperature difference between the wall's exterior and interior surfaces (T1 - T2). One effective strategy is to lower the exterior surface temperature by reducing the wall's exposure to direct sunlight. This approach led to the development of blocks with self-shading geometries. Due to limited research on self-shading in rammed earth construction, a physical proof-of-concept experiment was conducted. This test aimed to illustrate the design workflow and explore key parameters influencing thermal performance in different wall geometries, rather than produce definitive data on performance.

Prototype Setup

Three wall sections with the same thermal mass were tested: flat wall (control sample), vertical shading wall, and grid shaded wall (vertical and horizontal shading). The two self-shaded walls were manufactured using 3D printed mould negatives, curved geometry for vertical shading, and sharp-edged geometry for grid shading. All three wall sections were placed inside an insulated box to simulate a closed room environment.

In accordance with methodologies used in previous experiments on thermal behavior in rammed earth structures in Spain, thermometers were installed at various points along the wall to monitor temperature variations (Serrano et al., 2017, pp. 281–288). In this experiment, four critical temperature points were recorded: Exterior environment, inside the insulated box, on the wall interior surface, and the exterior surface- monitored using a thermal camera (figure 6)

Temperature data was recorded every 10 minutes. To simulate the conditions of a west-facing facade in the Middle East, a 1000-watt stage lamp was positioned at a 275° azimuth and 75° latitude to mimic sunlight exposure during the summer afternoon, 14:00–17:00 (figure 7).

Figure 6
Experiment setup showing placement of thermometers. Left, inside the insulated box. Right, outside the box.

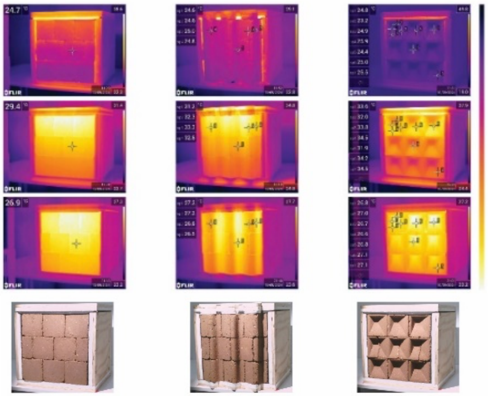


Figure 7
Wall saturation over a three-hour experiment. Left to right: flat wall, vertical shading, and grid shading. Top to bottom: progression from the start to the end of the experiment.

Results and observations

The hypothesis of this test was that self-shaded walls would maintain a cooler exterior surface, reducing overall heat transfer. Measurements began when all three walls had the same interior and exterior temperature. The graph below tracks their interior temperatures, starting at 22.9°C. After three hours, the temperature increased by 3.2°C for the flat wall, 2.9°C for the vertical shading wall, and 3.4°C for the grid wall. The vertical shading wall consistently maintained a lower interior temperature, reducing heat transfer by 9.6%–10.6% (Figure 8). In addition, the vertical shading wall's curved geometry proved more durable, while the grid wall's sharp edges were prone to breakage and difficult to handle.

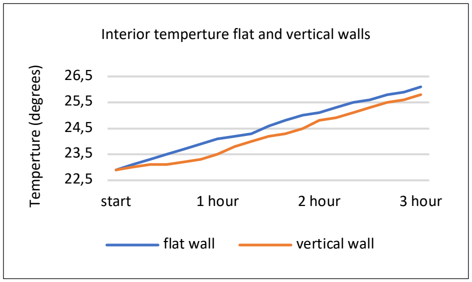
Initially, this improved performance was attributed to a higher shading-to-surface area ratio, but analysis revealed that the grid wall had 7% more shaded surface. Despite this, the vertical wall performed better, suggesting other factors influenced its thermal efficiency. Further research is needed to understand these results.

FINAL PROTOTYPE FOR THE BESPOKE SELF-SHADED WALL

Incorporating research insights, the final geometry responded to mould manufacturing constraints, local environmental conditions, and block fabrication methods.

The final blocks were produced using both sand-carved and 3D-printed moulds. To accommodate the constraints of both methods, sharp corners were avoided to improve mould durability (Figure 9). Each block used three negative moulds: two 3D-printed moulds on opposite faces simplified assembly, enabling horizontal alignments and vertical overlaps. Flipping the mould allowed a 22.5° assembly angle, enabling non-linear walls.

Digital environmental tools, such as Ladybug and Galapagos, adapted the design to Middle Eastern climate conditions. Building on previous heat transfer studies, the vertical shading wall was digitally optimized to minimize surface area and maximize shading. Adjustable parameters like wave radius and angle enabled design flexibility, ranging from a simple extrusion using four custom blocks to intricate, bespoke geometries. This adaptability supports variation based on resources and aesthetic preference (Figure 10). While other parametric patterns like grid- or horizontal-based shading could be tested, typical techniques like staggered brick stacking are less suited for rammed earth, as exposed edges increase vulnerability to erosion.



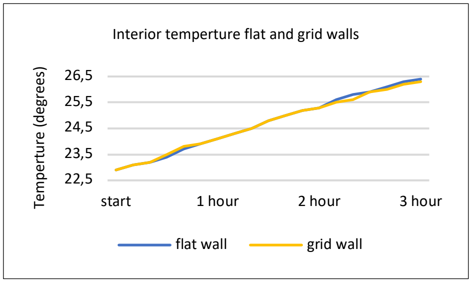


Figure 8
Graphs showing results

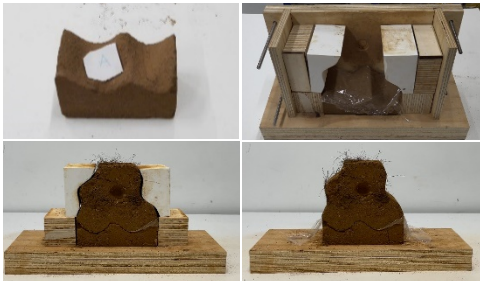


Figure 9
Fabrication process from left to right

The final design combined the use of two 3D-printed moulds for alignment and eight bespoke sand-clay carved moulds for the exterior façade. Each mould type was selected for its advantages: 3D-printed moulds, designed to withstand repetitive compaction, were reused 24 times per block, while sand-clay moulds were used only three times under compaction (figure 11). Since the exterior facade requires multiple unique moulds that are not intended for extensive repeated use, the reusability of sand-clay provided a sustainable solution.

The block fabrication process followed a soil layering strategy, improving the block's strength and appearance. First, the mould was filled up to one-third of its height with a fine sand-clay mixture to capture intricate surface details when compacted (figure 12). Next, a second layer of rammed earth mix was added and compacted. Each block was then labelled to simplify assembly.

The block's bounding box measured 20 × 15 × 15 cm—suitable for manual 1:1 assembly. Scaling to a full façade with custom moulds requires further research on stronger soil mixtures or limiting unique blocks to select fragments. In contrast, 3D-printed moulds are better suited for repetitive elements (Figure 13).

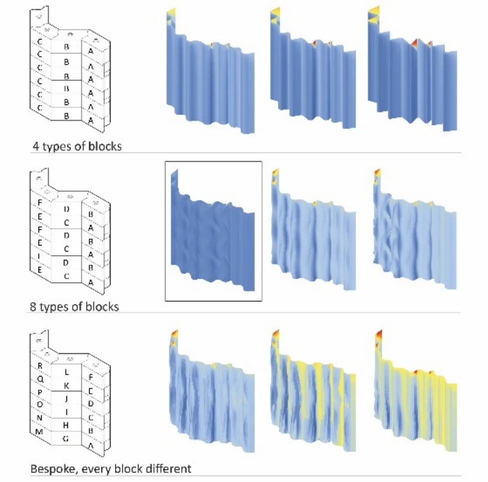


Figure 10
Surface Optimization: Minimizing Surface Area and Maximum Shading.
The adjustment of parameters impacts the complexity of wall manufacturing, varying from 4 bespoke blocks to 8 and 24 blocks

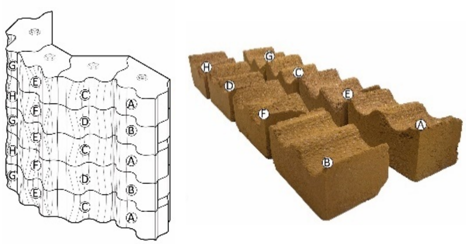


Figure 11
Left, Proposed wall design with corresponding labelled moulds. Right, Fabricated sand carving mould with labels.

Figure 12
Block assembly shows two layers of soil: the exterior surface features a fine-grain layer, while the rest of the block consists of a rammed earth mixture with gravel.

Figure 13
Final prototype design

CONCLUSION AND FURTHER RESEARCH

This project explores adaptable mould-making methods for rammed earth blocks, recognizing that the best-suited technique depends on local knowledge and available resources. While robotic sand carving demands more time and expertise than 3D-printed moulds, it provides a fully reusable and sustainable alternative. However, unlike transportable 3D-printed moulds, sand-carved moulds must be produced on-site, and the limited global accessibility of robotic tools presents a challenge. As this method requires an on-site robot, future research could investigate using the same robotic system for block assembly by adapting the blocks' weight and geometry to enable a pick-and-place strategy. Beyond rammed earth, this method holds potential for other fabrication techniques, such as sand casting, thereby expanding new design opportunities.

This study demonstrates how adaptable moulds enable precise geometric refinements, enhancing both the thermal performance and aesthetic quality of rammed-earth facades. Given the limited research on self-shaded rammed earth blocks, the next phase of this project will involve on-site thermal performance testing to validate the effectiveness of these designs under real-world conditions. Additionally, future research may investigate how these adaptable mould-making methodologies can be used in different climatic conditions. While the current study focuses on improving thermal performance in the Middle Eastern climate, other regions, such as parts of Africa, may face challenges like erosion, necessitating alternative geometric solutions.

By increasing design flexibility and functionality, these methods can help challenge and encourage a wider adoption of rammed earth as a sustainable building technique.

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