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An assembly-oriented novel low-carbon masonry building method with unfired 3D printed earthen blocks

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Abstract

Conventional earthen building methods such as cob and adobe are relevant for developing countries but labour-intensive, expensive and slow for developed countries. Automation in construction has been increasingly favourable in developed countries, especially buildings constructed with 3D printed cementitious materials. 3D printed earthen materials demonstrate a better environmental performance compared to 3D printed cementitious materials due to the energy intensive manufacturing of cement. Moreover, conventional earthen methods, such as cob, create earthen buildings with solid sections while 3D printing allows a hollow section and various infill designs using less material. Despite the benefits, the research on the mechanical strength of 3D-printed earthen structures is still limited. The lack of data on the mechanical performance of 3D printed earthen structures, is one of the obstacles preventing the mainstream construction industry from approaching this novel building method. Our research investigates an assembly-oriented novel low-carbon masonry building method with unfired 3D-printed earthen blocks and explores its adaptability to the mainstream construction industry with a critical comparison based on mechanical properties.

Keywords: 3D printing, construction techniques, digital modelling and fabrication, earthen architecture, low carbon construction, automation

1. Introduction

Manufacturing of industrial construction materials contributes up to one-third of all carbon dioxide emitted by the construction industry[1]. Conventional materials like steel and concrete are high embodied energy materials because of the energy required to provide high temperatures necessary for their production [2]. In contrast, unfired earth requires no industrial processing and is generally available at the excavation site or locally. Moreover, earthen buildings can balance humidity and regulate indoor temperatures, eliminating the need for mechanical heating and cooling systems, further reducing the carbon footprint of the building [3].

Nearly a third of the world's population lives in earthen dwellings [4]. Nonetheless, earth is still not considered a conventional building material. Earth is generally perceived as a primitive material only used for dwellings in rural areas or developing countries. Yet, there are numerous contemporary earthen buildings for various architectural purposes built for various economic classes and urban environments in developed and developing countries. Moreover, earth is an excellent material for constructing with the principles of the circular economy [5]. For example, Brussels Cooperation in Belgium creates earthen building elements from 36 million tonnes of earth excavated from the Belgian construction sites, which would otherwise be waste [6]. This approach is promising to create innovative and sustainable future urban habitats within a circular economy.

2. 21st century Mud

2.1. Why 3D printing with earth?

During a lecture at the Pratt Institute in 1973, Louis Kahn had his famous conversation with a brick, asking the brick what it wants to be, later added that the same conversation could happen with concrete or marble, emphasising the importance of understanding the nature of each material or "honoring the material" [7]. Today architects and designers take this discourse even further with computational design and digital fabrication. Gramazio and Kohler [8] observe that the advanced design and fabrication techniques blur the boundaries between data and material along with programming and construction, creating a "digital materiality" which "enriches material by information". Additive manufacturing methods such as 3D printing are revolutionising architecture and design by enabling the manufacture of data-driven complex forms created by computational design, which would be hard and expensive for conventional craft and making to realise. By placing the material exactly where its needed, structural stability could be gained with less material. Developed countries are increasingly investing in automation in construction and labour intensive nature of the conventional earthen building methods prevents its uptake by the mainstream construction industry. Population growth combined with the high cost of housing makes access to affordable housing one of the most critical concerns of the 21st century. On-site robotic 3D printing with concrete is a novel construction strategy suggested as a fast and affordable solution for housing. For example, a house in Nantes(France) is the first habitable 3D printed concrete building constructed in 54 printing hours and claimed to be 20% cheaper than conventional concrete construction [9]. This construction system eliminates material waste caused by the use of formwork. However, 3D printed concrete is more carbon intensive than conventional concrete due to plasticiser added to the mix to be able to 3D print. 3D printed earthen buildings are a low-carbon alternative to 3D printed concrete [10], while adapting to the construction industry in developed countries and automating the building process. Without adding chemical stabilisers, the earth from the site or locality could be re-printed until the desired result is achieved. First housing prototypes built with on-site robotic 3D printing with earth, such as Casa Covida [11] by Rael&San Fratello in the USA, Tecla [12] by World`s Advance Saving Project (WASP) and Mario Cucinella Architects in Italy, and Tova [13] by Institute for Advance Architecture of Catalonia (IAAC) in Spain present a natural and low-carbon alternative to 3D printed concrete houses. Since the uptake of steel and concrete after World War II, earth has been neglected as a rural and weak material. The juxtaposition of this humble material with cutting-edge technology also removes this bias and creates a contemporary "21st Century Mud".

Figure 1-2-3. Traditional earthen building methods such as cob and adobe are labour intensive and slow.

Figure 4. Tecla [12], Photo credit: Iago Corrazza

Figure 5.Tova [13], Photo credit:Gregori Civeru

Figure 6-7-8. On-site 3D printing of Tecla[12] photo credit:WASP, Casa Covida[11], photo credit: Emergent Objects and Tova[13], photo credit: Gregori Civeru.

2.2 On site vs off-site (prefabricated) 3D printing with earth

On-site additive manufacturing with earth has several environmental and financial benefits. Earth has an advantage for regions where wood and concrete are expensive and require long-distance transport. This process does not need scaffolding and is largely waste-free. However, the construction site must be protected as earthen walls are prone to erosion by rain and strong winds. Strong directional sunlight also creates irregularities in geometry and cracking, if one side of the wall dries much faster than the other side so shading is essential. On the other hand, off-site construction is not weather dependent, making all year fabrication possible in a climate-controlled environment.

Although on-site additive manufacturing offers continuity of the construction, there is only a certain height that can be printed in session, then it is necessary to wait for the walls to dry and gain strength before continuing with the printing. Off-site prefabrication of earthen blocks allows continuous fabrication where blocks can be stacked for drying. The control over the production with expert staff also avoids mistakes caused by craftsmanship on site, ensuring a result without discrepancies, making it more favourable to the mainstream construction industry. Also, prefabrication enables better precision and tolerances for earthen blocks that shrink in volume and weight while drying. The prefabricated rammed earth walls of Ricola Herb Centre by Martin Rauch is a recent example of how a prefabrication approach was welcomed for a contemporary building while using the local earth from the construction area. Experimental research projects such as Terraperforma [14] and Digital Adobe [15] investigates a similar approach with robotic fabrication. Despite several advantages, off-site production also presents challenges, such as transporting and assembling heavy earthen blocks. Building construction hubs close to the site to fabricate earthen blocks combined with fast robotic assembly on site could solve these challenges.

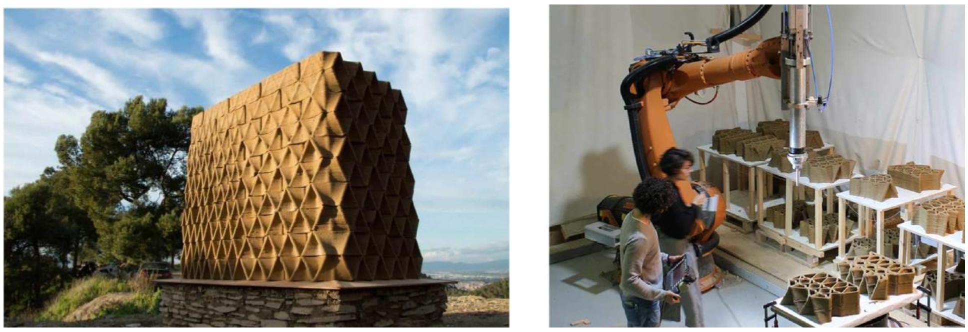

Figure 9-10 : IAAC Terraperforma [27] Image credit: Gabriel Frederick

3. Prefabricated 3D printed earthen blocks

3.1 Fabrication process

As demonstrated in detail in our research paper for IASS 2022 [15], we have designed and 3D printed eight earthen blocks with KUKA KR 60 high-accuracy robot and a custom-designed extruder at the Welsh School of Architecture, using local clay-rich soil from Cardiff. The goal was to print robust earthen blocks with minimum material using block geometry and infill strategies.

Figure 11,12,13. KUKA KR60 six axis high accuracy industrial robot, the dual extruder [16] and the custom fabricated steel end effector connecting 3D printed nozzle to the pressure hoses.

Blocks were designed with Rhinoceros® Grasshopper® with a parametric design approach, introducing parameters based on wall thickness, number of wall layers, layer height, number of undulations, and width, length control which allowed us to produce and test multiple iterations without the need to design each block from scratch.

During the prototyping process, several blocks were tested while an optimum robot speed at 0.09 m/s, 0.1 m/s extruder speed and soil mix viscosity was defined. The outcomes of the prototyping process confirmed successful data for block parameters such as layer height, number of layers and undulations to finalise the block and infill geometries. Simultaneously, the final earth mix recipe was confirmed as 61% soil, 0.3%straw, 22% sand and %17 water. This recipe was fluid enough to ensure a continuous material flow from the extruder through the pipe and to the nozzle while solid enough to print the blocks without buckling.

Once the prototyping process was finalised, we printed eight blocks that transformed in size, form and infills to create the tapering and slightly rotating wall once assembled. Printing each block took less than 5 minutes, at a rate that demonstrating the potential for fast production.

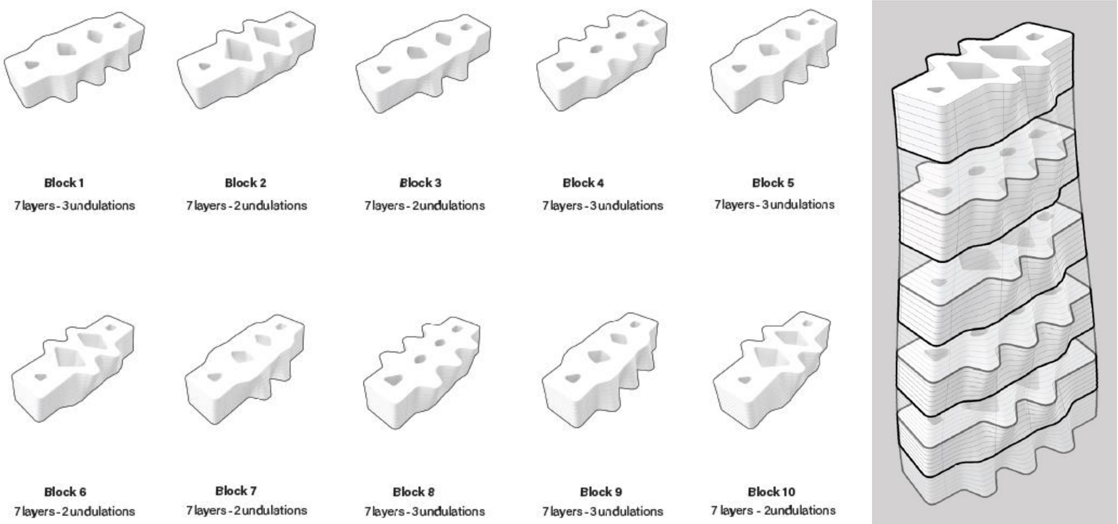

Figure 14: Final design optimisation and blocks to be printed with undulations and infills blending into the wall form. Images courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

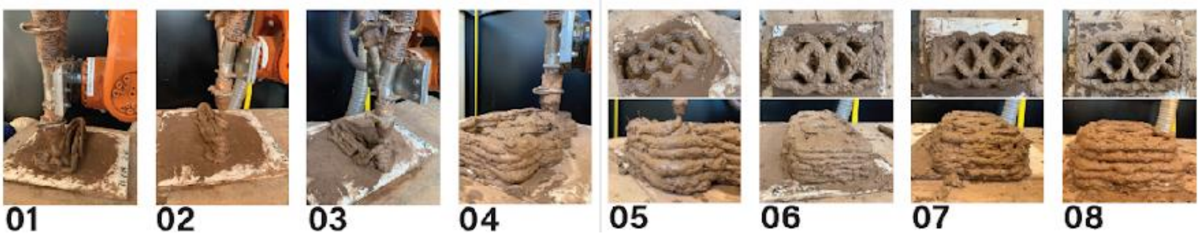

Figure 15. Trials with various robot speeds and layer heights while keeping the extrusion speed at 0.1 m/s and printing with the 25 mm nozzle.

3.2 Drying and assembly of blocks

Printed blocks were left to dry in a heated room for a month. Avoiding the temperature and humidity fluctuations allowed the blocks to dry without significant deformations in form. During the drying period, blocks lost 15% in weight as the water evaporated. Once fully dry, blocks were stacked on each other after being sanded and wetted with the same soil mix used as mortar. The same mortar recipe with adding more water and eliminating the straw can be robotically sprayed on the 3D printed samples to smooth the surface of the blocks, if needed. The assembly process has shown discrepancies between the block design, 3D printed blocks and dried specimens due to the unpredictable nature of the printing and drying process, which presents a challenge for the adaptation to the mainstream construction industry, where predictability and precision are essential. Nonetheless, prefabrication in a controlled environment presents the opportunity to improve the precision of the process by multiple calibrations exempt from weather conditions and accurate prediction of the final geometry after the drying period. This optimisation process to fabricate the blocks is essential to develop various assembly methods and block connections.

Figure 16, 17. Assembled wall and the assembly process

4. Mechanical properties of 3D printed blocks

4.1 Introduction

As mentioned in the previous sections, 3D printing with earth can enable building robust structures using less material as material scarcity becomes increasingly critical. Cob is a technique of mixing clayey earth and fibres such as straw and then applying them by hand with pushing them to create a monolithic wall. The plastic nature of cob also makes it ideal to use it for 3D printing, with increasing the amount of water to make the mix printable, as previously mentioned. It can be argued that conventional cob is an additive manufacturing method where the mix is gradually added by hand to create walls, while 3D printing cob, automates and accelerates this process. Moreover, conventional earthen methods, such as cob, create earthen buildings with solid sections while 3D printing allows a hollow section and various infill designs using less material. 3D printing also enables the designer to use the gaps in the infill for insulation or ventilation. Despite the benefits of this new approach, the research on the mechanical strength of 3D-printed blocks is still limited. To our knowledge, only three research papers are published on the subject [18] [19] [20]. The lack of data on the mechanical performance of 3D printed earthen structures prevents engineers and contractors from approaching this novel building method. More data and research on the mechanical properties of 3D printed earthen blocks is essential to accelerate the mainstream industry's uptake of this novel building method.

Compressive strength is the main mechanical property when defining the integrity of earthen structures as it shows the loadbearing capacity [21]. Gomaa et al. [18], looked into sixteen research papers, including conventional cob's compressive strength, and found that values fall between 0.4-1.35 MPa. Previous research on the compressive strength of 3D printed earthen specimens is documented as between 1.2 and 1.8 MPa for a cob-like mix using alginate seaweed polymer instead of straw [19], 0.87 MPa for 3D printed cob cylinders [18], and 2.32 Mpa for a 3D printed load-bearing element by WASP [20]. Our compression tests aimed to find out where our specimens fall in this range and compare the compressive strength of each specimen to see if the geometry and the thickness of the block infill affect the compression strength.

4.2 Test Specimens

Figure 18,19,20. Test Specimens, Block A, Block B, Block C. Photo Credit: Lina Ahmad

Three 3D printed blocks, fabricated with the process and material mix explained in section 3 were selected as test specimens. The infill geometry, number of undulations and thickness of the blocks are slightly different for each specimen. The width of specimens are 15 cm at the narrowest and 20 cm at the widest. The heights of the specimens are 7-8 cm and the length of the specimens is 35-36 cm.

4.3 Test preparation, equipment and method

Before the testing, quick-setting dental plaster was applied to the top of the blocks to have a flat surface to ensure uniform load distribution and avoid stress concentrations that could lower the compressive strength values. In addition, prior to dental plaster application, the holes on the blocks were filled temporarily to avoid plaster penetrating inside the block.

Figure 21,22,23. Dental plaster application to flatten the block surface prior to testing.

1MN Servo-hydraulic fatigue testing machine was used for testing to accommodate the size of specimens. First, compression platens were installed and the height of the platens were adjusted according to the block heights. Subsequently, each specimen was subjected to a uniform axial load. Initially, the load was applied at a conservative 0.001418 mm/s to Specimen A and the test took about

50 min. Then, the speed was increased approximately five times to 0.008255 mm/s for specimens B and C, and the test took about 25-30 min for each specimen.

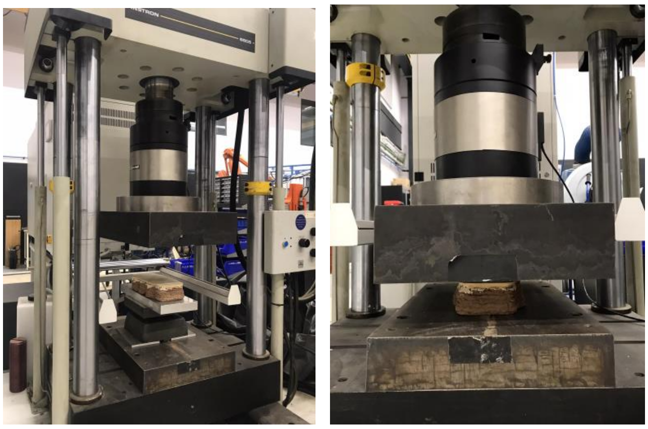

Figure 20. 1MN Servo-hydraulic fatigue testing machine used for the compression tests

Figure 21. Typical failure at the corners and along the perimeter was observed for all specimens

4.4 Test Results

The testing machine has generated data for force (kN) vs displacement (mm). The stress was calculated based on σ = P/A formula, where P is the applied force and A is the cross-section area of the block. The axial strain was calculated based on the εaxial =Δ/L formula, where Δ is the displacement and L is the length of the blocks.

Figure 22. Specimens before and after testing (broken pieces are disposed of).

The irregular infill geometry makes it harder to get an accurate cross-section area with manual dimensioning. Therefore, we extracted each block's accurate cross-section areas from the scanned models of the blocks using Rhinoceros®.

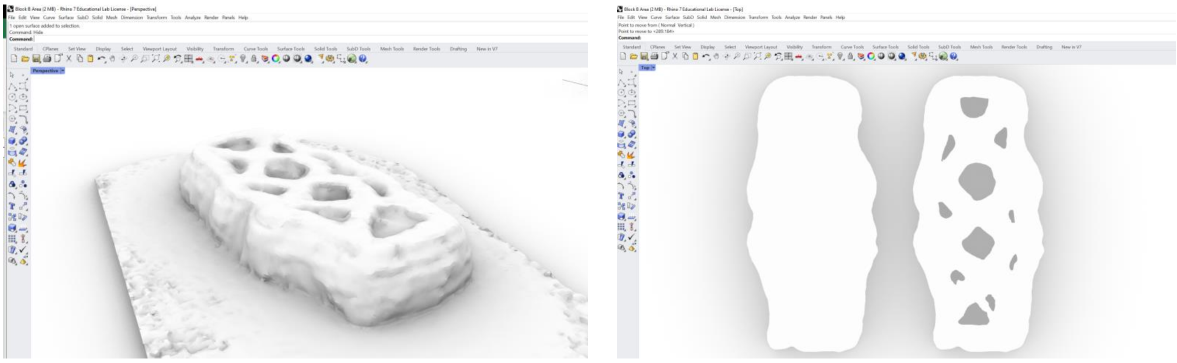

Figure 23.3D scanned specimen B in Rhinoceros® and cross-section area with and without the gaps in the block.

Cross Section Areas (mm^2)	**Specimen A**	**Specimen B**	**Specimen C**
Infill gaps included	54000	48500	56500
Infill gaps excluded	41261	42744	50087
Block Solidity	76.4%	88.1%	88.6%

Table 1. Area and solidity comparison of test specimens

Based on blocks cross-section areas (gaps excluded) shown above, the compressive strength of Specimen A is 1.7 MPa, Specimen B is 4.4 MPa and Specimen C is 3.1 MPa. When the compressive strength is calculated based on cross-section areas with gaps included, then the compressive strength of Specimen A is 1.3 MPa, Specimen B is 3.8 MPa and Specimen C is 2.8 MPa. All blocks performed well considering the average conventional cob compression strength and previously recorded compression strength of the 3D-printed cob. The stress-strain diagram for each block is shown below.

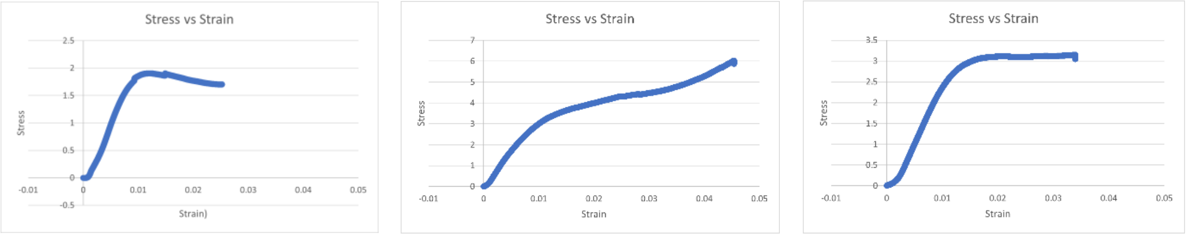

Figure 24. Stress-Strain Diagrams for Specimen A, B and C.

A similar behavior was observed for specimen A and C on these diagrams, where a linear rise ended with the peak and reached a plateu after a small reduction in slope. On the other hand, Block B has shown an irregular behaviour where the linear rise has started again after reaching a plateau. This irregularity might be caused by the dental plaster holding the pieces together and delaying the brittle response. Hence, the first peak before reaching the plateau has been considered for specimen B while calculating maximum compressive strength and the second peak is ignored.

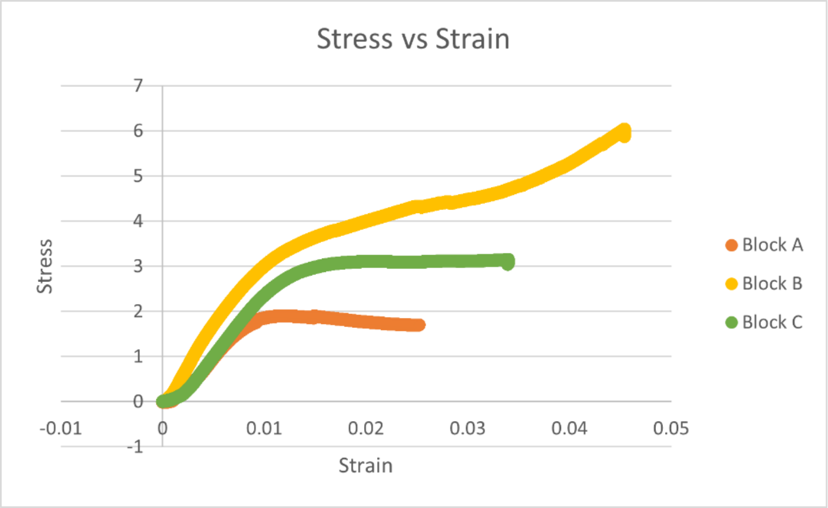

Figure 24. Stress-Strain Diagram, comparison between Block (Specimen) A,B and C

As mentioned in the previous section, during the prototyping process, the block form was updated with more significant undulations to gain better structural stability and avoid buckling, while 3D printing and interlocking waves were added to the infill geometry to work as buttresses. However, the compression test has shown that while the buttress strategy increases the structural strength of the block, the undulations of blocks on the perimeter have no effect. Additionally, although specimens A and C have similar geometry, specimen C performed much better under axial load due to thicker infill layers. Specimen C also had a stronger buttress connection than Specimen A, which supported its strength too. While dental plaster helped attain a uniform load distribution, it might have held the blocks together longer than usual, preventing an expected brittle behaviour after blocks reached their maximum strength and demonstrating an unusually long plateau in stress-strain diagrams.

5. Conclusion

3D printing enables short supply chains and localised fabrication while providing an opportunity to use less material and ensuring structural stability with geometric optimisation. Prefabrication of the 3D printed earthen blocks has the potential to mitigate the uncertainties about the earthen block fabrication and provide precision in a controlled environment while enabling rapid fabrication for a greater demand. Precision and rapid fabrication can accelerate the adoption of earthen construction by the mainstream construction industry in the developed world. However, the lack of data about the properties of 3D-printed earthen construction creates doubt for construction professionals. Our research explored the mechanical properties and compression strength, in particular, of 3D-printed earthen blocks. As mentioned above, our research has demonstrated that geometry, infill strategies and the infill's thickness affect the compression strength of the 3D printed blocks. Moreover, our specimens performed well compared to the average conventional cob compression strength and previously recorded compression strength of the 3D-printed earthen elements. However, further tests are required to investigate the role of infill geometry on compression strength. In addition, different fibres could be used to explore it`s effect on the strain response of the blocks. This design and fabrication method is promising to allow bespoke block and infill geometries to be created and fabricated using local earth. The increase in the availability and affordability of 3D printing equipment, combined with the increase in the data about the performance of 3D printed earthen structures, will spread it`s use as a novel low-carbon building method in the mainstream construction industry.

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