Design of a Low-cost Extruder for Large Scale Additive Manufacturing with Earth-based Pastes

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Abstract. This research explores the potential of earth construction as a low-carbon solution for large-scale additive manufacturing in the global south. Existing expensive printing technologies for earth-based structures limit their application in economically challenged regions. To address this, the study proposes and tests a low-cost extruder design using a paint/mortar mixer powertool, a metal hopper, and a 3D printed nozzle. The extruder is mounted on a CNC manipulator for precise control. Printing tests demonstrate the reliability of the design. The findings show that the low-cost extruder is a viable and sustainable option for large-scale printing, significantly reducing construction costs. By promoting the use of earth-based pastes, the research contributes to more environmentally friendly construction practices, aiding in mitigating the construction industry's environmental impact in the long run.

Keywords: Additive Manufacturing, Robotic, Earth Construction, Large-scale Additive Manufacturing, Sustainable Design.

1 Introduction

The vast environmental impact of construction requires research for low-carbon materials solutions. In this context, earth construction presents a promising outlook and large-scale additive manufacturing through soil-based paste extrusion is an active field of study. Promising advances include the research by Mario Cucinella, the IAAC Team (Instituto de Arquitectura Avanzada de Catalunia) and Rael San Fratello, among others. However, the printing technologies used in those research projects is expensive, and a low-cost solution is missing, considering that most applications of earth-based printed buildings are expected to be applied in the global south, where economy is essential.

To address this gap, this research proposes, tests and shares a low-cost design for an extruder for earth-based pastes for large-scale printing. The extruder design underwent several iterations, and printing tests were conducted to ensure its reliability and feasibility. The final extruder design was documented to allow for its replication and use by other researchers.

The low-cost extruder design proposed in this research consists of an affordable paint/mortar mixer powertool, a metal hopper, and a 3D printed nozzle. The powertool, which can be purchased off-the shelf for a relatively low cost, serves as the motor that drives the extruder. The metal hopper is used to hold and stir the earth-based paste. The 3D printed nozzle is used to extrude the paste in a controlled manner. Additionally, the extruder is housed in a casing and mounted onto a CNC manipulator, allowing for precise and automated control of the extrusion process. This design enables researchers to create large-scale structures using earth-based pastes, at a fraction of the cost of existing technologies. Several printing tests were conducted, demonstrating the reliability of the extruder and its key performance indicators such as the flow rate and the admissible viscosity of the paste.

The research findings suggest that the low-cost extruder design for earth-based pastes is a viable solution for large-scale printing in the global south. The design can be produced at a much lower cost than existing printing technologies, enabling more sustainable construction practices in these regions. In the longer term, the contribution of this research is significant in the promotion of sustainable construction. The use of low-carbon materials such as earth in construction is an essential step in mitigating the environmental impact of the construction industry, and the low-cost extruder presented in this research will increase the accessibility of these sustainable practices in regions where construction costs are a significant barrier.

2 State of the Art

This investigation involves four main areas of study: Environmental benefits and technical challenges of soil construction, Large-scale Soil 3D printing systems, and examples of 3D printed units.

2.1 Environmental benefits and technical challenges of soil construction.

Construction with soil presents several environmental benefits. Although is not a renewal resource, it is typically sourced locally with minimum transportation and processing related emissions (Pacheco-Torgal and Jalali, 2012). In addition, the construction and demolition waste in soil construction is readily recyclable by reintroducing waste as construction material without processing. Morton (2010) estimates that for example, soil construction can reduce construction waste by 24 million tons in the UK. In addition, soil construction improves indoor air quality, with fewer Volatile Organic Compounds (VOCs) and better moisture control (Minke, 2000).

Despite the well-documented benefits of soil construction, there are several barriers that prevent its deployment. Lack of specialized labor and cultural preferences are existing obstacles that can be overcome with the introduction of digital technologies for soil construction, a rapidly evolving field (Gomaa et al 2022) (Paparella and Percoro, 2023). From these advanced technologies, additive manufacturing of soil buildings has seen significant academic and commercial development, but none focuses on the development of low-cost solutions appropriate for developing economies.

2.2 Current Large-scale Soil 3D Printing Systems

Large-scale printing systems for or compatible with soil-based pastes exist in the industry. The four most prevalent systems, and their estimated price are presented below and showed in Figure 1. No low-cost solution is available in the market or the literature.

Be More 3D is a Spanish company specialized in concrete additive manufacturing. It developed printing systems of different sizes using a CNC gantry. Build volumes range from 4x4x2.5 meters to 12x5x3.6 meters.

CyBe, a Dutch company, also developed several concrete 3D printing systems, with building range up to 6x6x3.25 meters of build size, providing both robotic arms and gantry positioners depending on the build size. A 3x5x2.5 meter printer starts at 200.000 EUR.

ICON is an American company that provide 3D concrete printed houses and printing services using their Vulcan 3D printer system and proprietary concrete mix. Their system provide the largest build volume, with 30x11x3.5 meters. **WASP** is a an Italian company, which developed printing systems for a variety of pastes. They have been successful in advancing 3D printing with earth-based materials and developed collaborations with designers and academic institutions. According to their website, their basic printing system 3x3x2 meters start at 125.000 EUR.

Figure 1. Examples of commercial large-scale 3d printing equipment. Top left: Be More. Top right: CyBE, Bottom left: ICON, Bottom right: WASP. Source: https://bemore3d.com/, https://cybe.eu/, https://www.iconbuild.com/ and https://www.3dwasp.com/.

2.3 Examples of Soil 3D Printed Units

3D printing with soil for construction is still an experimental method. Several prototypes have been produced, providing evidence of the feasibility and potential of this construction method. Three key built structures are discussed below, and showed in Figure 2.

Tecla is the largest soil printed built to date, consisting of two interconnected domes. It was built in 2021, with a maximum height is 4.2m and a floor area of 60m2. It was design by Mario Cucinella and printed with a crane system developed by WASP.

Tova was designed by the Institute of Advanced Architecture of Catalonia (IAAC) and built in 2022. The dimensions are 4.5x4x3m, and was also built using a system developed by WASP.

Casa Covida consists of three interconnected domes printed with local soil in USA in 2020. It was designed by Emerging Objects, and printed with a SCARA positioner and a mortar pump. The printing of each dome was done in stages of 500mm height, allowing the material to dry in between sessions. The final build size is 2.6x8x3 meters (Rael and San Fratello, 2020).

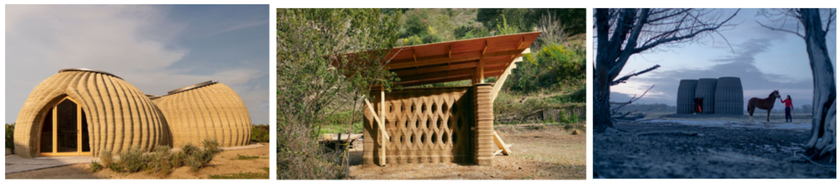

Figure 2. Three examples of soil based 3D printed structures. From left to right: Tecla, Cova, Casa Covida. Source: https://www.mcarchitects.it/en/projects/tecla-technology-and-clay, https://iaac.net/project/3dpa-prototype-2022/, https://www.rael-sanfratello.com/made/casa-covida

3 Methodology

As presented in the previous section, it is demonstrated that although several 3D printing systems for soil pastes exist, and others can be adapted from concrete printing to soil printing, the cost of the systems is unaffordable for low cost construction. This research focuses on the development of a low-cost extruder, which can be attached to a positioner. In the case of this research, a robotic arm is used. However, a low-cost positioner is currently under development.

The methodology involves an iterative experimental process. From an initial extruder concept, the design was progressively refined through five prototypes. The reliability and repeatability of the extrusion was documented in each step.

4 Results

The laboratory setup and formulation of the printing paste are introduced, followed by a discussion of the design of the extruder.

4.1 Description of the Laboratory Setup

The experiments were conducted using a robotic setup consisting of a Kuka KR180, programmed using KUKAPRC in Grasshopper (Fig. 3)

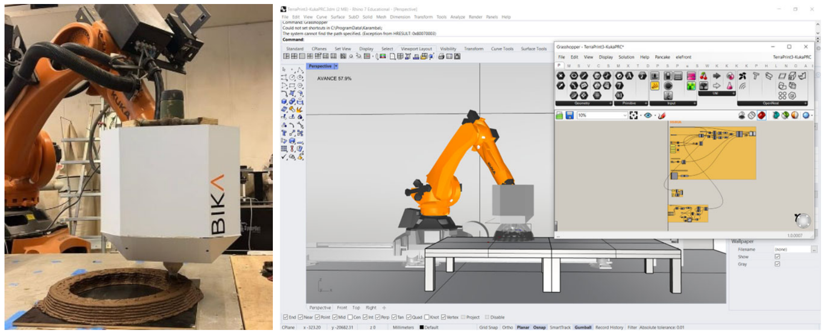

Figure 3. Robotic laboratory used in the experiments, with the final extruder design. Slicing and robotic controlled developed using Grasshopper and KUKAPRC.

4.2 Formulation of the printing paste

The paste used for the extrusion process was formulated based on previous research developed by Max Pazols during his master thesis (2022). The soil was procured locally from the vicinity of the laboratory, located in Santiaga de Chile. The material was sifted with a 4mm sift. The calibrated proportion of the mix is 70% soil and 30% water, which provides and adequate consistency for both the extrusion and the layer buildup. The mix was rested for at least 24 hours before printing. Figure 4 shows manual experiments simulating the buildup process using the formulated paste.

Figure 4. Initial tests of the paste consistency, conducted manually.

4.3 Prototype 1

<u>Design:</u> The first prototype was designed to test if a powertool mixer was an adequate low-cost driver for the extrusion process. The powertool was a 1400W mixer, from the brand Bauker, with a cost of 100 USD. At the end of the mixer,

a screw was attached to push the material. It was then placed in a bucket with a conical plastic funnel and a hole in the bottom (Fig. 5).

Results: This makeshift design was able to extrude material. However, the funnel was weak and the attachment of the powertool to the wood structure unreliable.

Figure 5. First prototype of the extruder and the mixed with the screw.

4.4 Prototype 2

Design: The second iteration of the extruder aimed to solve the problems with the inclusion of a 3D printed nozzle which provided support for the screw.

Results: The reliability of the extrusion flow increased significantly (Fig. 6.). As the equipment was left extruding continuously, the importance of a better refill process became evident.

Figure 6. Second prototype of the extruder and extrusion results.

4.5 Prototype 3

Design: The third iteration improved the refilling process and the structure of the hopper. A wider design made with galvanized steel sheets was tested (Fig. 7).

Results: The extruder maintained a consistent flow of the paste, and the wider hopper allowed for an easier refilling process.

Figure 7. Third prototype of the extruder and extrusion results. On the left, a turntable to simulate the printing process before mounting the extruder to the robot.

4.6 Prototype 4

Design: Following the consistent flow of material, the third extruder prototype was modified to be attached to the robotic arm. The tool was mounted and calibrated in the robot (Fig. 8).

Results: A simple wall section design of 1000mm (l) x 150mm (w) x 100mm (h) was prepared and tested. The process parameters calibrated: the powertool RPM dial was set at the maximum, the robot speed at 100mm/s and the layer height at 10mm.

Figure 8. Fourth prototype of the extruder and extrusion results.

4.7 Prototype 5

Design: The fifth and final prototype improved the attachment to the robot, reinforced the overall structure and improved the general appearance of extruder (Fig. 9). The design included an 18mm plywood structure, which hold the hopper, nozzle and powertool, and a aluminum composite casing. A 3D model of the final design and the cutting file for its parts are included in this link: https://www.dropbox.com/scl/fi/if22nrug5sh4158n059rg/BIKA-FinalModel.3dm?rlkey=a0zti7hs3d3cwigq0l8x0kgtz&dl=0

Results: The several printing tests were conducted with the extruder, which deposited material consistently. Final experiments are discussed in the following section.

Figure 9. Fifth extruder design, plywood structure and exterior appearance.

4.8 Final Printing Tests

Three printing experiments were conducted using the final extruder design (Fig. 10). The first experiment consisted on a wall section 1000mm long, 150mm wide and 120mm tall. The printing time was 4 minutes and achieved a height of 120mm. The printing process was successful.

The second experiment consisted on a twisting ribbed dome 800mm diameter. The printing time was 6 minutes. The curvature of the dome required cantilevering, which was accomplished in the prototype but visible deformations appeared in the lower layers. T

The third and final experiment consisted on a double wall dome, 600mm diameter and 150mm height. The printing time was 9 minutes. With the double layer strategy, the print was significantly sturdier and accomplished a larger height without visible deformations.

The three experiments were printed successfully, but stopped at a maximum height of 120-150mm, height at which the structure starts to lose stability because the weight of the buildup over the bottom layers that did not have time to dry and harden. In larger prints, at the final architectural scale, this problem would be reduced as each layer would take significantly more time to be completed and therefor more time to dry. Additional experiments on sequencing of prints to achieve taller structures is needed.

Figure 10. Final printing experiments using a wall design, a ribbed dome and a double layer dome.

5 Discussion

The development of a reliable and functional low-cost extruder provides a step towards additive manufacturing in architecture for developing countries, where building shortage are most pressing. However, the path toward a complete system requires significant development. The limitations of this research and future research is presented.

5.1 Limitations of this research

The extruder solution presented in this paper has cost of 200 USD in materials, making it very competitive when compared with commercial alternatives. Future development for this functional low-cost extruder for earth-based pastes should consider the following improvements:

- Better design of the nozzle mount to facilitate its maintenance and the addition of interchangeable nozzle geometries.
- Detailed study of the design of the screw (diameter, variable pitch, feed zone, material, barrel size and compression rates).
- Universal mount for the power tool mixer.
- A study of the extruder performance for soils from different regions.
- Assessment of the impact of addition of short fibers of different lengths to the printing paste.
- Universal mount for different positioner systems.

5.2 Towards a low-cost soil-based 3D printer for architecture

The scalability and implementation of this extruder in real life scenarios require future research:

- Development of a low-cost positioner to replace the robotic arm is necessary. Gantry systems for DIY CNC equipment can provide a starting point, but the larger loads associated with the soil printing process have to be carefully considered.
- Development of sequencing strategies to allow dehydration of previous layers to accomplish taller structures is an important matter, addressed by previous research (e.g. Rael and Sanfratello, 2020) but had not been tested with the proposed extruder.
- Incorporation of continuous fiber reinforcement or timber structures for improved seismic resistance is an important next step, not only for this research but for all soil-based construction.
- Durability and degradation of soil printed architecture requires further study.

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