Digital Toolmaking for Earth Building Components

The use of low-cost extruder and 3D printing to develop new fabrication approaches for cob and light earth bricks

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ABSTRACT: This paper reports on ongoing research into innovative methods for extruding cob and light earth building components, aiming to establish a cost-effective fabrication system. The paper provides a brief contextual overview of related work and outlines the research's vision to create a low-cost fabrication system for experimenting with earthen-based composites in low-carbon construction. Various components of the fabrication system are presented, including a piston-based extrusion machine developed by the researchers. The use of low-cost filament 3D printers to create the extrusion profiles (known as dies) is also outlined, with details of printing parameters and die construction approaches. The paper reports on preliminary results of the characterisation of extruded samples in both dense cob and light earth composites, including shrinkage rates and compressive strength. Additionally, the paper presents experiments involving innovative interlocking brick designs and the production of earth bricks with cavities to illustrate the capabilities of the fabrication concept.
KEYWORDS: Extrusion, Toolmaking, Earth Bricks, Cob, 3D Printing

1. INTRODUCTION

Earth-based materials have been used for house building for centuries across in many cultures around the world [1]. Such materials, which is utilised cob buildings and adobe bricks manufacture, is typically a basic mixture of subsoil and fibre. In western culture the use of earthen based building materials almost disappeared in the 20th century, however the emerging climate crisis has spurred a re-evaluation due to their exceptionally low environmental impact [2]. Equally, new digital fabrication technologies are delivering disruptive impact across numerous sectors. This research seeks to combine these developments into innovation opportunities with earth-based building materials to contribute to low-carbon and sustainable construction practices. Specifically, this paper convers ongoing research focussed on developing novel approaches of using 3D printing technology in a toolmaking situation to fabricate extrusion dies to manufacture cob and adobe building components. This approach is tested in combination with a concept for a low-cost hydraulic ram extruder, thus presenting a competitive earth brick manufacturing system.

1.2 Context

Several recent research projects have explored new approaches with cob, focussing on both composition and construction methods. The CobBauge project [2]–[5] has established cob compositions that meet contemporary building performance standards. Notably, the CobBauge team has introduced a dual-composition approach for constructing cob walls. One layer serves as a 'structural layer', meeting loadbearing requirements using a dense earth composite (cob). The other layer, described as a 'thermal layer', is designed to provide insulation and is constructed with a light earth composite. In combination this hybrid cob/light earth wall concept has the capacity to perform to current building regulations standards [2].

The results from the CobBauge team present an exciting potential for re-evaluating the use of cob in contemporary constructions. However, conventional methods of constructing cob buildings remain a time-consuming affair, posing a potential limitation in adopting these new cob compounds. Typically, cob buildings are constructed by stacking cob in layers, known as 'lifts' [6], each 30–60 cm high. The construction process involves gradually building up the structure while tamping and shaping the cob walls to the desired form. Formwork can also be employed to enhance control over the dimensions of the cob wall and increase the speed of construction.

Several projects have explored the integration of digital fabrication and robotic technology earthen constructions. These initiatives encompass investigations into additive layer manufacturing (ALM) using customised Cartesian 3D printing systems [7], [8] or delivery facilitated by multi-axis robotic arms [9], [10].

This research takes a different approach from previous projects seeking to use new digital fabrication technologies, particularly 3D printing, in a *toolmaking* scenario, with profile extrusion as the production approach.

Extrusion is an extremely efficient manufacturing process that is used extensively to produce *fired* ceramic architectural components, such as bricks and tiles. However, in terms of *unfired* earth bricks, the use of extrusion as the manufacturing process appears to be significantly under-researched and underutilised [11], [12]. The underutilisation of extrusion to produce earthen building components could be due to difficulties in processing fibrous composites through extrusion machinery. Additionally, extrusion profiles (*dies*) typically require fabrication in steel by specialised engineering companies, making experimentation with the extrusion process expensive and with limitations to geometries that is achievable through convectional toolmaking technologies. Another potential contributing factor to the limited exploration of extruded earth composites is that industrial extrusion machines (such as those used in the ceramic industry) are costly and typically based on the *auger* principle (see Figure 1). While the auger extrusion approach provides a continuous extrusion flow that is advantageous for mass production, this approach is likely to be susceptible to jamming when exploring fibrous earth composites. An alternative extrusion method, based on the *piston* concept [13], illustrated in Figure 1, offers a simpler principle at significantly lower construction costs. Although the piston approach requires pausing the extrusion process for barrel refilling, it is very useful for experimentation in smaller and less standardised production situations, including trials with earth composite materials.

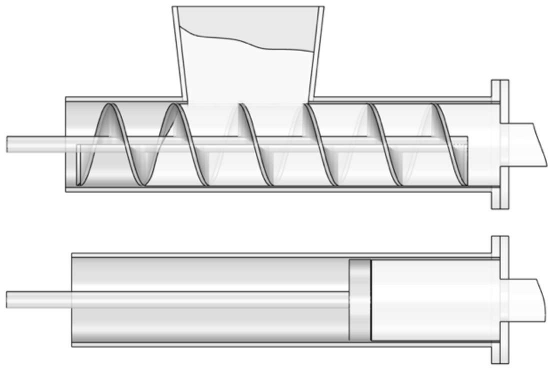

Figure 1: Auger extrusion principle illustrated at the top, with piston extruder illustrated below.

2. RESEARCH AIM, QUESTION AND OBJECTIVES

This research aims to contribute to low-carbon construction by presenting a low-cost production system that enables researchers, architects and builders to utilise digital tools to design and prototype new cob and adobe brick components. The research question could therefore be articulated as: How can 3D printing technologies help facilitate the exploration of new earth-based construction units based on the extrusion production method? The objectives for addressing this research question/aim include the following:

- To test the use of a low-cost extrusion machine for use with earth composites.
- To develop a new toolmaking workflow using low-cost 3D printers to fabricate extrusion dies for earth composites.
- To undertake practical tests of the complete workflow system, including exploration of innovative designs with earth bricks.
- To undertake quantitative studies of the performance of the units produced by the system.

3. RESEARCH EQUIPMENT AND PROCESSES

This research is centred on the use of low-cost equipment with the aim of establishing a workflow that can be relatively easily replicated by other users who wish to explore extrusion of earth composites. The equipment pool consists of standard, consumer level, Fused Filament Fabrication (FFF) 3D printers, a forced action mixer and a piston-based extrusion machine constructed by the researchers.

3.1 Low-cost, piston-based extrusion machine

The extrusion machine utilised in this research has been constructed by the researchers primarily using off-the-shelf components, including a frame made from the Unistrut system [14] and extrusion barrels constructed from standard stainless-steel pipes. While the extruder design incorporated bespoke parts like pipe flanges and plunger brackets, these were fabricated locally by a metal fabricator via laser cutting. The piston's movement is facilitated by a hydraulic power unit capable of supplying the piston cylinder with up to 230 bar of system pressure. Hydraulic systems are ubiquitous for powering all kinds of plant and heavy machinery, and consequently basic hydraulic power systems are widely available at relatively low cost. The parts for the entire extruding machine used in this study come at a cost of around €3000.

Figure 2: Low-cost, piston-based extrusion machine with hydraulic power unit. Photo: T. Jorgensen, 2020.

3.2 3D printing technology and parameters

As a part of the complete design and production workflow developed in this research, low-cost FFF 3D printers play a central role in fabricating the extrusion dies. These dies have been developed a two-part construction approach: the core die body, known as the *pressure plate*, and the second part, the *nozzle,* which is attached with screws. Two different FFF 3D printers were utilised to optimise print quality and speed. For the pressure plates, a Creality CR10 S4 3D printer was used with a 0.8-mm nozzle to facilitate faster printing times. The commonly used Polylactic Acetate (PLA) biopolymer was used as the filament medium, with print settings including 0.6-mm layer heights, 3-layer perimeters, 3-layer top and base and a 20% infill. For the die nozzles, a Bambu X1 Carbon printer with a 0.4-mm print nozzle was used. 'Tough PLA' was selected for printing the extrusion nozzles due to its enhanced durability, particularly as the nozzle was identified as the most susceptible part to fracturing. The print settings for the nozzles included 0.2-mm layer heights, 4-layer perimeters, 4-layer top and base and a 30% infill density. These settings were chosen to ensure a finer surface quality, as any visible layering resulting from the 3D printing process would likely have the most significant impact on this part of the die. The decision to use these specific print settings for the nozzle is informed by the literature on paste extrusion, which highlights the potential impact of die surface texture on extrusion rheology [15].


Figure 3: 3D printing of extrusion dies. Photos: T. Jorgensen, 2023.

4. TEST SET-UP AND INITIAL FEASIBITITY RESULTS

Initial feasibility experiments were carried out to test whether the cob recipes established by the CobBauge team [3] could be extruded using the set-up. Initial tests focused on experiments with the light earth mixture. This composite was prepared with a commercial terracotta clay body (Valentine VC1D), which was mixed with additional water to create a clay slip with a consistency of 14 cm in diameter using a clay slip puddle test approach [2]. Using a forced action pan mixer, this slip was then mixed with hemp shiv with a ratio of 3 to 1 (hemp to clay slip by volume). The extruder was set up with a 250-mm pipe and a die with a square profile of 100 mm by 100 mm. The pressure plate section was initially designed to have a relatively short depth of 100 mm with sides tapering from the 100-mm square profile out to a round profile matching the extrusion barrel wall.

4.1 Establishing extrudability of light earth mixture

The initial tests utilised the CobBauge team's recipe for a light earth mixture. However, this 3:1 hemp-to-clay slip ratio was found to be too fibrous and would jam in the extrusion die. Experiments with extrusion die geometry were undertaken to remedy the issue. The depth of the pressure plate was extended to 150 mm and 200 mm to provide a more gradual taper. However, these alterations still failed to solve the issue of the mixture's extrudability. The slightly layered texture, which is characteristic of 3D printing, was also hypothesised to inhibit the flow of the earth composite but smoothing the surface of extrusion die with filler and subsequent sanding still failed to remedy the problem. Addressing the extrudability of the light earth composite was concluded to be unattainable through changes to extrusion die geometry or by improving the die surface. Altering the recipe of the composite appeared to be the only viable option to achieve extrudability. Several tests were undertaken in which the clay slip content of the mixture was gradually increased. Through these experiments, it was found that a ratio of 4 hemp shiv to 3 clay slip (57.4%–42.4% by volume) achieved a mixture that would extrude well. It was observed that adjusting the consistency of the clay slip had a positive impact on extrudability. Adjustment to the consistency of the clay slip was also found to aid the extrudability with a 'wetter' slip (determined by 14cm in the puddle test) found to separate from the hemp shiv in the extrusion situation. A 'drier' slip (8-10cm puddle test) was found to create a more extrudable composite. The initial tests in this investigation were carried out using a standard hemp shiv grade with pieces of up to 22 mm. However, a finer hemp shiv of 3.5 mm pieces was explored and found to improve the extrudability even further. This finer hemp shiv allowed for an even greater ratio, achieving 60% hemp shiv to 40% clay slip.

4.2 Extrusion of the standard cob mixture

Initial extrusion experiments focused on the use of light earth composite with adjustments to the hemp-to-clay slip ratio having to be implemented to ensure extrudability. Challenges in terms of extruding the denser cob mixture were expected, but the standard recipe used by the CobBauge team was found to extrude very well without any adjustment to the recipe. This recipe consists of clay (47.5%), sharp sand (51.7%) and 2.5% straw (barley) – all dry weights. The clay utilised was a commercial stoneware body (Sibelco HZ 3215) with the 'cigar test'

[16] used to determine the suitable addition of sand. Water was added for the mix to achieve a consistency that adhered to the 'drop ball test' [17]. This test requires achieving a 21-cm diameter when a 2-kg cob ball was dropped from a height of 1 m.

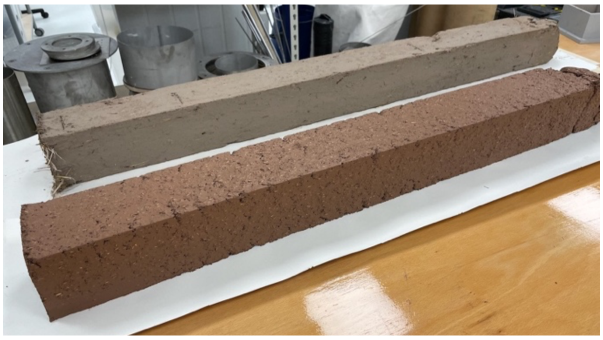

Figure 4: Extrusion tests with both standard cob mixture as well as light earth mixture. Photo: T. Jorgensen, 2020.

4.3 Effect of die geometry on surface resolution

After establishing the parameter of an extrudable light earth recipe and testing the extrudability of the cob mixture, tests on the effect of the extrusion die geometry on the surface fidelity of the extruded cob units were carried out. In particular, the impact of the length of the extrusion nozzle was investigated. Tests with 50-mm, 100-mm and 150-mm nozzles were undertaken, and it was found that there was clear visual evidence of improved surface fidelity with longer nozzles. The impact of the geometry of the pressure plate (the taper ratio in particular) was found to be less clear, and further testing is required to determine how this may affect the extrude parts.

Figure 5: Tests with various extrusion nozzle lengths to improve surface fidelity. Photos: T. Jorgensen, 2023.

5. CHARACTERISATION OF SAMPLES

A full range of characterisation tests of extruded samples are now underway to determine the effects of the extrusion process on the earth brick units produced. These tests include compressive strength, flexural strength, shear strength, dry density and thermal conductivity. While some of these tests are still in process, some preliminary results concerning shrinkage and compressive strength can be reported, which have some noteworthy results.

5.1 Shrinkage ratio of extruded earth brick units

One of the most surprising test results is the shrinkage rate in earth bricks produced by the extrusion process. Measurements were taken at the wet forming stage and compared with measurements of the units in a completely dry state. The tests were carried out by making marks 1000 mm apart on extruded test bars with a square cross section of 100 mm by 100 mm. Measurements of both light earth and cob mixtures showed surprisingly different shrinkage ratios in relation to the extrusion direction. For the cob mix, the shrinkage along the length of the extruded forms was under 1% (992 mm = 0.8%). In contrast, the cross section had an average of 7% shrinkage (93 mm). For the light earth composite, the shrinkage along the length of the extruded bars was recorded at 1.5% (985 mm). Measurements of the cross section recorded an average of 92 mm, indicating an 8% shrinkage. In conventional use of earth composites for in-situ construction (cob) or manufacture of adobe bricks, shrinkage rates of 1–4% have been reported [18]. The high level of shrinkage in measurements taken *across* the direction of extrusion and the difference in this rate compared with the shrinkage rate along the *length* of the extruded parts is significant and surprising. Additional tests on other extrude samples have been undertaken to validate these readings, with similar findings being recorded. The reason for this difference is not immediately clear, and further research is required.

5.2 Compression strength tests

Assessments of the structural performance of the extruded earth bricks produced in this research are not fully complete, but some recordings have been undertaken with results of potential significance. Samples for both the cob mix and the light earth mix were subjected to compression strength tests. Samples were produced with a 100 x 100 mm square profile extrusion die and then dried and cut into 100 mm lengths. The samples were tested for compressive strength in both the vertical and horizontal orientations in relation to the extrusion direction. The cob mix performed best, with the samples being oriented horizontally in relation to the extrusion direction, with a maximum of 19.68-kN load recorded. With the samples placed in a vertical orientation, the performance was slightly lower at 19.13 kN. The light earth mix recorded a maximum of 12.01-kN load in the horizontal orientation and 11.62 kN in the vertical orientation. All figures are based on an average of recordings from 3 test samples.

Both the performance of the cob and the light earth mixtures are far better than commercial earth brick products manufactured by pressing or moulding in frames [19], [20]. The structural performance of the extruded samples also far exceeds that reported from in-situ cob building [5].

Similar to the results of the shrinkage tests, the findings from the compressive strength tests are surprising and potentially significant. The inherent alignment of clay particles and fibres in the extrusion process is hypothesised to be the core reason for this high level of performance.

6. EXPLORATION OF INNOVATIVE BRICK DESIGN APPROACHES

The extrusion process presents the potential for fast design exploration of geometries not easily achieved with traditional earth brick shaping methods, which typically utilise wooden frames or moulds [1]. To provide an initial exemplar of the new design possibilities using 3D printed dies in earth brick production via extrusion, initial design concepts explored interlocking bricks to facilitate rapid construction of earth buildings (see Figure 6).

Figure 6: Experiments with interlocking earth brick designs. Photo: T. Jorgensen, 2023.

This approach is proposed with either wet or dry brick units. Employing consumer-level 3D printing technology for die creation allows for the rapid exploration of a broad range of geometries at an exceptionally low cost. with material cost of a die approximately €15. This presents the potential of exploring innovative constructions approaches utilising different earth composites there, building on the hybrid wall layer approach established by the CobBauge team (design concept example illustrated in Figure 7).

Figure 7: Extruded earth brick design concept, Photo: Simon Regan, 2023.

6.1 Exploration of extruded earth bricks with cavities

Using extrusion to create earth composite bricks presents a good opportunity for creating units with hollow sections. These cavities are created using cores suspended in the extrusion dies. This is a method that is widely used for conventional ceramic bricks, as this approach presents several advantages, including reduction in material use, quicker dying times, increased thermal performance and easier transport and handling. To create hollow sections in extruded parts, die cores must be suspended by a frame/bar commonly known as a *bridge.* The principle of crating hollow sections in extruded parts relies on the ability of the extrusion medium to be separated by a bridge and then forced together again through pressure so seamless walls can be achieved. To ensure thorough reunification of the extrusion medium, the bridge is typically designed to be positioned as far as possible from the extrusion orifice. For ceramic extrusion, significant structural integrity is required by the bridge element, and the polymer used for standard 3D filament printing does not have anywhere near structural performance of the tool steel, which is normally used for the bridge element. To overcome this issue, a hybrid approach was taken in this research with the 3D printed dies designed to incorporate a stainless-steel metal bar on which 3D printed cores could be suspended. This die design is illustrated in Figure 8.

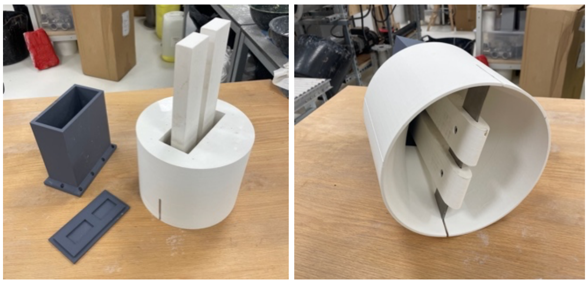

Figure 8: 3D printed extrusion dies with cores fitted to create earth bricks with cavities. Photo: T. Jorgensen, 2023.

Several experiments with the light earth mixture were undertaken with dies that incorporated cores, all with a good level of success.

Figure 9: Experiments with cavities in extruded earth bricks. Photos: T. Jorgensen, 2023.

7. PRELIMINARY CONCLUSIONS AND DISCUSSION

The research has successfully demonstrated a solid proof-of-concept that low-cost 3D printers can be used effectively in a toolmaking scenario for the extrusion of earthen-based brick units. A key aspect of the manufacturing concept developed in this research is the low cost. A complete extrusion set-up, like the one utilised in this research, can be acquired for less than €5000. Based on the low cost the authors argue that the using 3D printing for creating earth brick extrusion dies presents innovation opportunities for the design of cob and adobe buildings. The research also seems to indicate that the extrusion process delivers unexpected material characteristics in the resulting earth bricks. Some of these characteristics may pose challenges, such as high shrinkage rates across the width of the extruded parts. Other characteristics, such as high compressive strength, present significant advantages. The remaining characterisation tests should provide a clearer picture of the overall potential of the extrusion process to deliver innovation in the quest to deliver low-carbon and more sustainable construction approaches.

ACKNOWLEDGEMENTS

The research has been facilitated via funding from the Arts and Humanities Research Council (UK) and Research England. Many thanks to Atul Vadgama, Max Tillotson and Hazel Luff for their valuable contribution to the testing and characterisation of the samples.

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