ROBOTIC 3D PRINTING OF MINERAL FOAM FOR A LIGHTWEIGHT COMPOSITE FACADE SHADING PANEL

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Abstract. This paper presents the design and fabrication of a lightweight composite facade shading panel using 3D printing (3DP) of mineral foams. Albeit their important role in industrial construction practice as insulators and lightweight materials, only little research has been conducted to use foams in 3DP. However, the recent development of highly porous mineral foams that are very suitable for extrusion printing opens a new chapter for development of geometrically complex lightweight building components with efficient formwork-free additive manufacturing processes. The work documented in this paper was based on preliminary material and fabrication development of a larger research endeavor and systematically explored designs for small interlocking foam modules. Furthermore, the robotic 3D Printing setup and subsequent processing parameters were tested in detail. Through extensive prototyping, the design space of a final demonstrator shading panel was mapped and refined. The design and fabrication process is documented and shows the potential of the novel material system in combination with fiber-reinforced ultra-high performance concrete (UHPC). The resulting composite shading panel highlights the benefits of using mineral foam 3DP to fabricate freeform stay-in-place formwork for lightweight facade applications. Furthermore, this paper discusses the challenges and limitations encountered during the project and gives a conclusive outlook for future research.

Keywords. Robotic 3d-printing; mineral foam; lightweight construction; concrete formwork; facade shading panel.

1. Building with Foam

During the last two decades, large-scale additive manufacturing (AM) in construction gained considerable momentum in the research community and in industry (Lim et al. 2012; Delgado Camacho et al. 2018). These new fabrication technologies can contribute to more sustainable and lean construction processes. Most advancement has been reported in the field of 3D printing (3DP) for load-bearing applications with cementitious materials. However, the availability of sustainable materials in construction 3DP that address other important building-physical properties such as thermal insulation or water permeability remains limited. Only a few researchers investigated porous foam-like materials for this purpose. Expanding polyurethane foam was used to 3DP stay-in-place formwork for a dome structure (Keating et al. 2017) and a single-storey residential building (Furet, Poullain, and Garnier 2019). Other researchers printed with cement foams on existing masonry walls to improve their insulation performance (Lublasser et al. 2018).

Porous materials and in particular foams have a great legacy in architecture and construction because of their lightweight and thermal insulating properties. Already our Neolithic ancestors used natural porous materials like pumice and clay to insulate their dwellings. By the beginning of the 20th century the plastic revolution transformed the building industry with new high-performance materials such as synthetic foams (Engelsmann, Spalding, and Peters 2010; Faircloth 2015). Today synthetic foams such as polystyrene and polyurethane represent more than 41% of the European insulation market. However, synthetic foams come with considerable environmental and health concerns because they are based on finite resources and are highly flammable. In contrast, inorganic solutions such as aerated concrete and mineral foams are more suitable for environmentally friendly and safe construction. Novel sustainable solutions were developed recently and it was demonstrated that they can be used for 3DP (Minas et al. 2016; Dutto 2019).

2. Motivation and Project Focus

Most application methods of foams in contemporary construction practice are time and labor demanding, geometrically limited, and very wasteful. 3DP however, offers a lot of opportunities for automated fabrication of complex objects without extra cost, formwork, and production specific tooling. These advantages can be transferred into construction. This enables for instance geometrically complex freeform building elements made of foam that are impossible or unfeasible to produce with any other technique. The design space of modular foam blocks for architectural envelopes and formwork could be considerably extended. Furthermore, custom foam shapes would be traditionally manufactured with subtractive methods from large blocks, which produces a lot of waste. 3DP of foams would allow to increase the resource-efficiency through the formwork-free direct production of objects with a much higher degree of geometric complexity. The approach of large-scale 3DP with mineral foams in construction opens new perspectives for architectural design and sustainable construction. It fosters not only resource-efficiency but also the invention of novel lightweight building components. The combination of different densities as composite with foam as functional formwork makes building elements lighter and more versatile for different use cases.

Against this background, this project was conceived as a student design thesis and investigated the use of mineral foam 3DP for fabricating brick-sized modules that can be assembled into an architectural-scale structure as lightweight facade application. Key research questions concerned the design of the assembly and modules as well as how the material and fabrication system can be leveraged as paramount design drivers. How can discretization and combinatorics inform modular architectures? How can the modules be joined, interlocked and reinforced? How does the 3DP and post-processing influence the design space? What kind of geometric limitations exist and how could they be overcome? The methods consisted of empirical exploration through prototyping and a final demonstrator. Iterative cycles of experiments combined design and fabrication with qualitative evaluation of the print results. After assessment, the print metrics, material and post-processing routines were optimized and module designs further refined. The evaluation of prototypes was of qualitative nature due to the available equipment, short project period, and anticipated result of a visually impressive architectural-scale demonstrator.

3. Material and Fabrication System

The mineral foam was fabricated based on the formulations developed by FenX AG. Industrial waste-based fly ash particles were mixed with water and modifiers. The resulting suspension was then vigorously foamed using a household mixer. After five minutes mixing, the foam was inserted into printing cartridges. Eventually, foams with wet densities ranging between 500 and 550 kg/m3 were obtained. After printing, the printed elements were dried at room temperature for a minimum of 48 hours and then hardened by sintering in a ceramic kiln. The sintering process consisted of a burnout period (450 °C for 2h) and a sintering period (1100 °C for 3h). The elements were then cooled down to room temperature.

For the robotic 3DP setup (Fig. 1, left), an existing stationary custom syringe extruder was used, which was developed during preliminary extrusion experiments with mineral foam. Decoupling the extruder from the robot allowed for developing it independently without payload or movement constraints. The 6-axis robotic arm used throughout prototyping and final fabrication was an ABB IRB 120 with a maximum reach of 580 mm and a payload of 3 kg. A 400 x 400 mm platform was mounted as a print bed end-effector with the fifth robot axis advantageously oriented downward for maximum payload performance (Fig. 1, right). Furthermore, durable 300 x 300 x 5 mm recrystallized silicon carbide (R-SiC) sintering plates were placed on the print bed for transport and furnace processing. They were chosen for their low weight since other conventional cordierite sinter plates resulted in exceeding the robot payload limitations during printing.

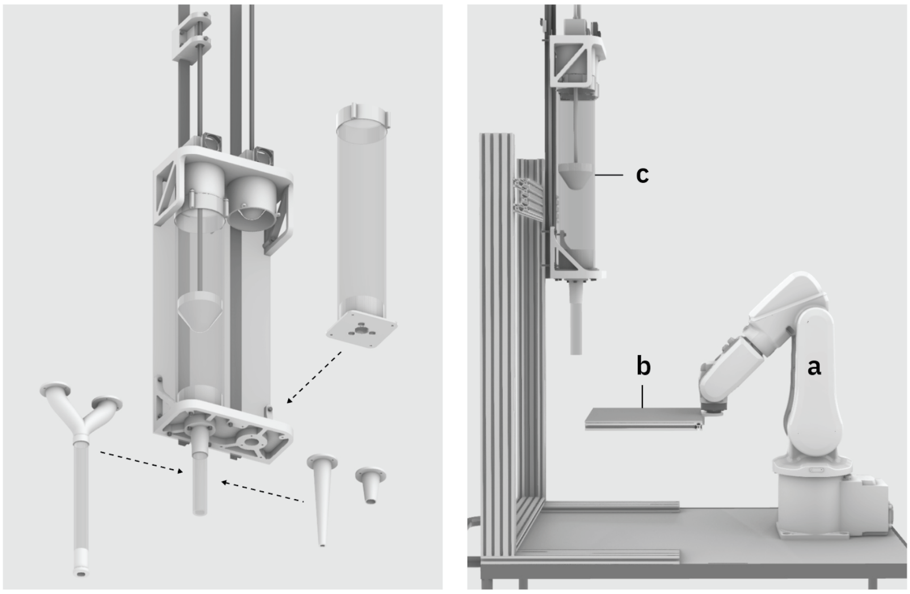

Figure 1. Left: dual syringe extruder with replaceable cartridges and nozzles. Right: robotic fabrication setup with a) ABB IRB 120, b) print bed end-effector, and c) stationary syringe extruder.

The stationary syringe extruder was a custom made tool for the controlled extrusion of batch-processed material. The development was inspired by many examples that can be found in the research literature of paste extrusion *(Seibold et al. 2019; Kontovourkis and Tryfonos 2020)*. Executed as a double syringe that is actuated by two independent linear drives, the extruder allowed for precise flow rate control and operations involving one or both material chambers. Each of them measured 90 mm in diameter and 500 mm in height with a volume of 3.2 L. The motors were controlled by an Arduino microcontroller and all extruder operations executed with a GUI application written in Java. No IO signals were sent or interpreted from the robot controller. The robot movement was programmed using the COMPAS framework and the COMPAS_RRC extension for online non-realtime control *("COMPAS" 2020)*. Target frames were generated as a JSON file from the CAD software Rhinoceros3D through a custom Grasshopper Python script. A central script was responsible for establishing the online connection to the robot controller, parsing the JSON robot targets, sending them to the controller and waiting for feedback.

4. Prototyping Observations

On the outset of this project, the empirical data about the capabilities and limitations of the material and fabrication system was limited. Mineral foams are a new material group in large-scale 3DP so far. During three consecutive prototyping phases with specific objectives and methods, the design space for the individual 3D-printed foam modules could be explored and mapped.

The first prototyping phase focused on the individual filament quality and surface artifacts of printed objects (Fig. 2, first row). Identifying the most suitable resolution for the application in this project was the primary objective at this step. To achieve this, different nozzle sizes and print parameters such as extruder flow rates, robot speeds, layer heights and resulting layer widths were tested and evaluated. All nozzles were 3D-printed from PLA on conventional desktop 3D-printers and could be quickly interchanged by loosening three screws at the bottom bracket of the extruder. The first nozzle diameter tested was 10 mm, which resulted in a layer height of 7 mm and width of 15 mm with an extruder flow rate of 3 ml/s and a robot speed of 50 mm/s. These print settings resulted in over-extrusion and a rough surface texture. The second nozzle diameter chosen was 12 mm, which resulted in 8 mm layer height and 18 mm layer width with 1 ml/s flow rate and 10 mm/s robot speed. Here, the results were more promising with less disturbances of the material microstructure, an improved filament quality and a more smooth surface finish. The last nozzle diameter tested was 16 mm, which resulted in 10 mm layer height and 25 mm layer width with 1 ml/s flow rate and 9 mm/s robot speed. Those parameters resulted in the best printing quality. The slow robot movements also avoided vibrations and dragging of the filament. Fabrication speed could be neglected because of the small print sample sizes.

The second prototyping phase targeted to maximize the print height of elements with a footprint of 15 x 25 cm while minimizing elastic buckling of the fresh material (Fig. 2, center row). Methods to achieve this were geometric reinforcement strategies such as adaptive wall thickness and internal bracing structures. First, overlapping filament paths in the form of a double wall were tested and resulted in plastic deformation and tapering. Second, corrugation of the filament path was explored, which led to an improved layer built up until 8 consecutive layers and a final element height of 8 cm without plastic deformation. However, elastic buckling resulted in several print failures and collapses. Third, intersecting filament paths were explored with different cellular print layouts. They were based on triangular and square patterns and the most successful approach for the objective of maximizing height in this prototyping phase.

The third prototyping phase focused on reducing internal material stresses in the 3D-printed cellular foam modules to avoid cracking during drying and sintering. First, square-based cellular patterns with different layer built ups were tested. One foam element was printed with three consecutive layers resulting in 30 mm height and only half of the pattern was continued on top with additional three layers resulting in 60 mm height. Cracks occurred in sharp filament turns and between areas of three and six horizontally deposited layers because of asymmetric loading of the material (Fig. 2, bottom row). Second, circle-based cellular patterns were printed with intersecting and overlapping horizontal layers and a vertical built up of six layers. It could be observed that cracks occurred only in areas where layers did not overlap sufficiently. Third, filament pathing around the circle-based cellular patterns was optimized for sufficient layer overlap of 50 % width and resulted in crack-free foam elements after drying and sintering. The design of the foam modules was iteratively developed throughout the three prototyping phases.

Figure 2. Prototyping evolution. Top row: improving surface quality. Middle row: maximizing print height. Bottom row: reducing cracks.

5. Full-scale Demonstrator

Based on the maximum print heights achievable during prototyping, the design decision was taken for a surface-like assembly of interlocking cellular foam modules that would be bound together by casting fiber-reinforced ultra high performance concrete (UHPC) in between them. This application resembles a lightweight composite panel for a second skin facade that controls light and ventilation. Here, using 3DP allows for the unique customization of the geometrical features of the shading panel in a resource-efficient and waste-free fabrication process. Moreover, mineral foams are particularly suitable because of their low weight and can be used as lost formwork in combination with the strength of cast concrete.

Figure 3 illustrates the design steps for the full-scale demonstrator. The overall dimensions of the facade panel were determined by the available fabrication time: 6 modules could be produced per week, which resulted in 24 modules in 4 weeks. Circles were chosen as the base unit for the cellular module pattern. First, a generative design tool based on circle-packing was used that distributed a global circle pattern within the design boundary of 500 x 1000 mm. Second, the circle radii parametrically varied as a function of the distance to an arbitrary attractor curve. This allowed to program the permeability of the facade panel for light and ventilation control. Third, the same distance function also affected the print heights from 3 to 6 layers of the circle units. Lastly, the circles were bundled into clusters for individual foam modules with maximum dimensions within the print bed. This step further refined the circle packing scheme and updated path distances for crack-free bonding of overlapping print paths.

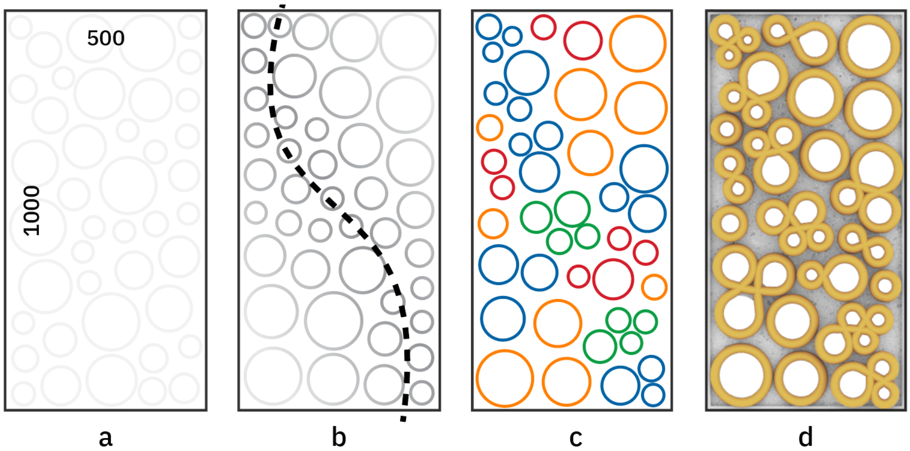

Figure 3. Design steps of final demonstrator: a) boundary condition, b) circle packing, c) module clustering, and d) toolpath bundling .

All 22 cellular foam modules could be produced during the fabrication period of 4 weeks with staged intervals for printing, drying and sintering. The module sizes varied between 60 to 280 mm in diameter and 30 to 60 mm height, which equals 940 mm (3 layers height) to 5060 mm (6 layers height) print path length and 0.2 to 1.2 L of print material. Printing times varied between 8 to 15 minutes with an average of 6 minutes per module. An overall volume of 12.4 L mineral foam was printed. The final step of casting UHPC between the printed foam modules consolidated the composite assembly (Fig. 4). For that, a boundary frame made from 30 x 30 mm steel L-profiles with reinforcement pins served as formwork and could be left in place as a finished edge with mounting details. The resulting panel weighs 15.7 kg, which is comparable to other lightweight ceramic facade claddings. Furthermore, approximately 6.2 kg are printed mineral foam, 6.7 kg UHPC and 2.8 kg steel frame.

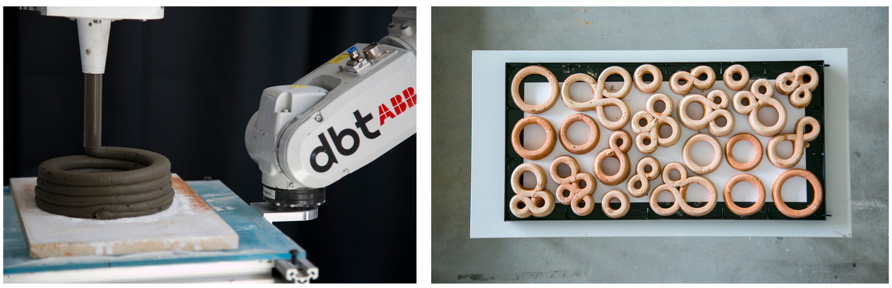

Figure 4. Fabrication of the final demonstrator. Left: 3DP of one module. Right: assembly of sintered modules in steel frame before casting of UHPC.

6. Conclusions & Outlook

The main advantages of the proposed 3DP procedure are the simplicity of the foaming process and the applicability of mineral foams as ink material in construction scale. There are still many process parameters to work on, in terms of the 3DP setup and material system, which could enable easier processing and better material quality in the print results. In particular, the energy-intensive consolidation process of sintering in a ceramic kiln impacts the sustainability of the material system dramatically. Furthermore, the drying and sintering processes showed an increased sensitivity for cracking. Both steps are time demanding and slow down the fabrication speed. Improvements in the print setup could include the transfer of the ink in a continuous manner from foaming to printing, instead of filling a cartridge. Similarly, a moving printing plate could be detrimental for the shape retention, which eventually limits the printable height. Of course, further integration of the extruder tool head with the mechanical system e.g. industrial robot would facilitate the real-time control and synchronization of both and increase the process robustness.

Figure 5. Full-scale demonstrator. Overall impression and closeups.

Large-scale 3DP with mineral foam for freeform construction is a novel approach with promising applications for sustainable, resource-efficient and innovative building elements. For the first time this project showed how mineral foam 3DP can be used for an architectural scale object that leverages the advantages of the automated formwork-free fabrication method for bespoke freeform geometries (Fig. 5). All 3D printed foam components that composed the demonstrator in this study are unique. Consequently, the significance of mineral foams for lightweight architectures could be shown to be extended with 3DP particularly in the domain of bespoke facade elements that are designed for a specific local building context. Beyond that, mineral foams exhibit a very high thermal resistance and can be used with 3DP for freeform insulating building elements in future research. The empirical exploration of the design space with the current material and fabrication setup is an important contribution to future research. Furthermore, an architectural outlook as a building-scale application based on the demonstrator shading panel was proposed (Fig. 6). For this preliminary design and fabrication study, sintered mineral foams were used as stay-in-place functional formwork and UHPC was used as a filler. Considering the high cement content in this concrete, a more sustainable option would be a cement-free material. This opens a new chapter for future sustainable construction with 3DP of functionally graded mono-material building elements made entirely from mineral foams - *a new kind of monolithic.*

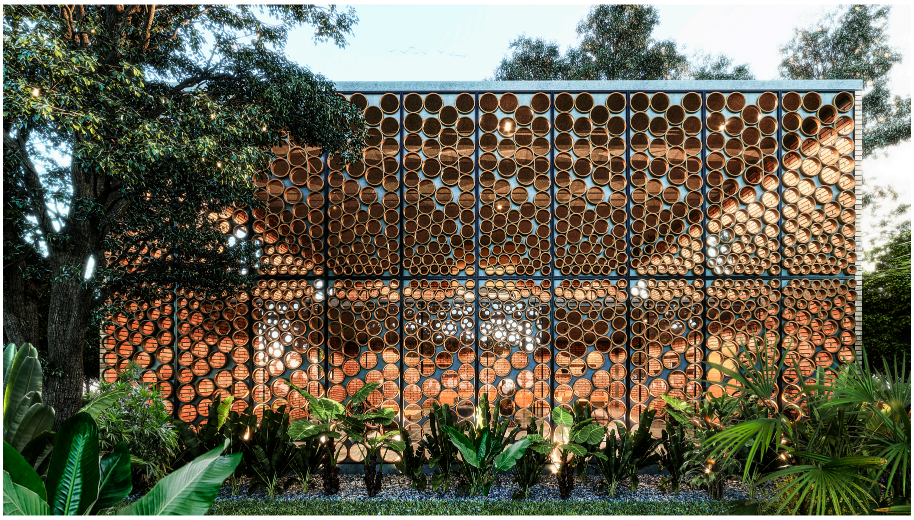

Figure 6. Visualization of a building-scale application of the shading panel.

7. Authorship

This project was part of a larger research collaboration between Digital Building Technologies at ETH Zurich and FenX AG. It was briefed as a 10-week long design thesis for the ETH Master of Advanced Studies in Architecture and Digital Fabrication. The work presented in this paper is the thesis project of Dinorah Martinez Schulte in collaboration with Patrick Bedarf (tutor), Ayça Şenol and Etienne Jeoffroy (material development). All photographs were taken by Dinorah Martinez Schulte.

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