DIGITAL FABRICATION OF GROWTH

Combining digital manufacturing of clay with natural growth of mycelium

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Abstract. In this paper we will demonstrate that a digital workflow and a living material such as mycelium, make the creation of smart structural designs possible. Ceramics industries are not as technically advanced in terms of digital fabrication, as the concrete or steel industries are. At the same time, bio-based materials that use growth as a manufacturing method, are often lacking in basic research. Our interdisciplinary research combines digital manufacturing - allowing a controlled material distribution, with the use of mycelial growth - enabling fibre connections on a microscopic scale. We developed a structure that uses material informed toolpaths for paste-based extrusion, which are built on the foundation of experiments that compare material properties and observations of growth. In this manner the tensile strength of 3D printed unfired clay elements was increased by using mycelium as an intelligently oriented fibre reinforcement. Assembling clay-mycelium composites in a living state allows force-transmitting connections within the structure. The composite named "MyCera" has exhibited structural properties that open up the possibility of its implementation in the building industry. In this context it allows the design and efficient manufacturing of lightweight ceramic constructions customized to this composite, which would not have been possible using conventional ceramics fabrication methods.

Keywords. Mycelium; Clay; 3D Printing; Growth; Bio-welding.

1. Introduction

The interdisciplinary subject of this paper is primarily embedded in the field of architecture, but is also influenced by the latest developments in mycology, bio-based materials, clay and 3D printing. Generally speaking, the overall research goal focuses on finding a viable, long-term solution to the global problem of waste management and CO2 emissions, which also affect the building industry and construction waste management. This research focuses on extraction and utilization of highly accessible and widespread materials, clay and mycelium.

Mycelium is the vegetative part of mushrooms, which consists of a system of filamentous hyphae. It grows on lignocellulosic substrates and can be moulded into lightweight composites. This has been applied in the past decade by several artists and designers in the production of furniture and structures for short-term exhibitions, as well as companies (Ecovative, MOGU, MycoWorks) that launched commercially available products, such as leather, foam, packaging material and acoustic panels. Further to these developments, universities such as IAAC Barcelona (Claycelium 2019), ETH Zürich (MycoTree 2017), CITA (Fungar 2019) and Vrije Universiteit Brussel (Elsacker 2017) have organized workshops, courses and research programs exploring the usage of mycelium composites. One of the important questions to be answered is whether the structural properties of these existing materials, which primarily use mycelial growth as a manufacturing process, can now be improved. Although mycelium composites have a great potential for substituting some building components, the viability of their actual application and manufacturing processes on a large scale is still open.

The utilization of clay in architecture, in terms of digital fabrication, is not as technically advanced as concrete or steel industries are. The production and application of bricks has not fundamentally changed since the introduction of dies in piston extruders in 1855 (Händle 2009). In masonry brick production, firing and drying are the most energy consuming phases. The use of mortar results from correcting production tolerances and ensuring the stability of the single elements within a wall component, while posing an issue of leading to high fossil CO2 emissions during cement production (World greenhouse gas emissions 2005) and resource procurement. As for recycling, fired clay could be used as a chamotte for new products, but since the separation of clay and mortar remains challenging, the two materials are usually discarded as one compound after a building has fulfilled its life expectancy of approximately 60 years (Kleiber and Simon 2006). Until now, only the concrete industry has demonstrated commercial potential in 3D printing of single elements (Hansemann et al. 2020), as well as whole buildings (Khoshnevis and Hwang 2006). 3D printing of clay is currently limited to small size elements (Ugarte et al. 2020) and requires further investigation.

The research presented in this paper is based on references that have already developed techniques for the extrusion of mycelium composites (Soh et al. 2020), material mixtures of mycelium and clay (Digital seismograph 2017), development of bio-hybrid architectural systems (Como and Ayres 2020) and 3D printed material assemblies from cellulose and mycelium (Goidea et al. 2020). The work in this paper extends beyond the existing research by evaluating structural properties of a bio-based and digitally fabricated material, as well as observing material distribution on a microscopic scale. This enables the use of natural growth as an additional parameter in architectural design by assembling the clay-mycelium composites in a living state.

2. Methodology

The method of this research was carried out through material experiments and a design study. A series of material mixtures was created, as well as samples with different geometries that have the aim of elaborating different properties based on the respective material and fabrication process. The research was conducted in four phases: 1) material experimentation, 2) setting up hardware and software, 3) testing and measurement, 4) case study - combined structure.

2.1. EXPERIMENTATION WITH MATERIAL MIXTURE

The composite ”MyCera” consists of inorganic parts - clay and water, and organic parts - mycelium and substrate. The main challenge in this phase was finding an optimal substrate type and optimum ratio of organic and inorganic parts, which have following properties: 1) using a high proportion of organic material ensures enough nutrition for homogeneous mycelial growth that influence the effective porosity left by the organic components after the firing process, 2) using a high proportion of clay ensures the specific viscosity and elasticity required for a 3D printing fabrication process.

To restrict the number of samples with various material combinations, common modelling clay, type Nigra 2002 of company Sibelca was used. The material is composed of 65.50% SiO_2, 1.10% TiO_2, 21.50% Al_2O_3, 8.9% Fe_2O_3, 0.30% CaO, 0.80% MgO, 1.80% K_2O, 0.10% Na_2O, 0.4% Mn. Black clay enables the visual differentiation between clay and mycelium and is highly obtainable. Finally, the very fine chamotte increased the plasticity without causing too much abrasion inside the 3D printer, which would be the case with a rougher chamotte.

The goal of the first set of experiments was mixing clay and different substrate types in order to choose the one optimal for mycelial growth (Figure 1). Those substrates were sawdust, bleached and unbleached cellulose, which were obtained from the Austrian paper producer Mayr-Melnhof Karton. The used sawdust consists of mixed wood types with a majority of hardwood that has less resin. It is therefore a suitable additive for mixing with clay and also feasible as a substrate for mycelium.

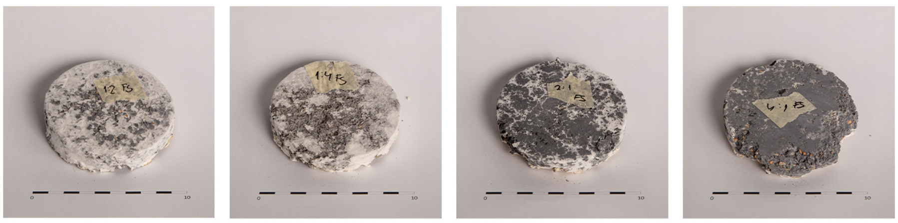

Figure 1. Samples with a different clay:substrate rate: a) 1:2, b) 1:4, c) 2:1, d) 4:1.

Two types of mycelium strains were used, *Ganoderma lucidum* and *Pleurotus ostreatus*. After several experiments, *Ganoderma lucidum* was abandoned because of frequent contamination problems. *Pleurotus ostreatus* was used, because it has the ability to digest a great variety of lignocellulosic substrates (Elsacker et al. 2020), has a fast growth rate and becomes denser in its second growth phase (Ghazvinian et al. 2019). A series of samples with clay and the three substrate types were blended into seven different ratios of organic and inorganic components. The rate of *Pleurotus ostreatus* was 10% of the material mixtures' weight for all samples. Distributing more spawn would have accelerated the growth, but would not have influenced the quality of the final outcome.

After a series of experiments and evaluation of mycelial growth, sawdust was chosen as a substrate. Compared to cellulose, wood has a better local availability and a higher control of the grain size is possible. To prepare the material for printing, a series of different experiments was performed to find optimal material viscosity for the 3D printer. The quantity of water added to the mixture does not affect the dried geometry but rather the printing workflow. It was necessary to keep it as low as possible while retaining required viscosity for printing. A high water percentage decreases the possibility for an overhanging geometry, while also increasing drying time and problems related to shrinkage. The sawdust was sieved to ensure a particle size <2 mm not to block the nozzle of the 3D printer. Both components were mixed in a dried and pulverized state to achieve a homogeneous distribution and were then blended with water by a mixing machine. The weight ratio of the final mixture from clay to sawdust was 7:1. 35% water was added for printing, measured from the weight of the mixture. In a final step of material preparation, the wet mixture was filled into material tanks, each containing a material volume of up to 4600 cm^3 and closed airtight to prevent moisture loss. Once the material was printed and then sterilized, inoculation was carried out differently, depending on the geometry. The mycelium spawn was dispersed on the surface of the solid objects, whereas the hollow ones were filled. The mycelium spawn quantity added to the mixture was higher than that usually added to purely organic composites, since the material mixture mainly consisted of inorganic components. Inoculating the printing mixture before extrusion was tested out as well, but due to elaborate preparation of maintaining sterility during printing, this method was discarded. The approach of printing the elements firstly, then sterilizing and inoculating them was considered to be a more efficient method.

2.2. SETTING UP HARDWARE AND SOFTWARE

Customizing the standard hardware and developing new software for direct transmission of Rhino 3D Geometry into G-Code was necessary in order to 3D print the composite mixture. New material tanks of hard anodized aluminium and a rastered printing bed were added to the 3D Clay printer Delta WASP 40100.

2.2.1. Hardware

A 4 mm nozzle was chosen for extruding the mixture. Nozzles with a smaller diameter (1-2 mm) caused an occasional blockage, whereas bigger sizes presented a less precise option. A constant pressure of 6 bar on the material tank was necessary for printing. Another influence on the physical design was the available printing area, which is defined by the printer model. The maximum area was 40 cm in diameter and 100 cm in height.

2.2.2. Software

A custom Grasshopper script for Rhino 3D was developed for using the 3D printer in the most flexible manner. By this means the designing and providing of machine data is directly connected in a single software allowing a highly efficient workflow. The printing paths were created through curves that are discretized and divided in parts where the control points are transferred into a G-Code with specific printing speeds and material flow values. A single-lined spiralized printing path was introduced for the cylindrical objects. Solid elements were printed along alternating directions of the printing paths for each layer in order to have a crossed structure and more stability. The spiralized toolpaths reduce printing time by not having to start and stop the extrusion for each layer, while also creating the smoothest possible surface. A method of having a variable speed and factor of extrusion - extrusion flow - was developed in order to allow a variable wall thickness within a single printed line. A simulation of extruded volume and the movement of the printer head was included to predict potential geometrical collision.

2.3. TESTING AND MEASUREMENT

The following experiments refer to the paste-based extruded material mixture described in the previous chapter. All tests in the context of tensile strength were conducted at the Institute of Technology and Testing of Building Materials at Graz University of Technology. Two kinds of tests were carried out: 1) tensile strength along the extrusion axis, 2) binding force between the printed layers. Additionally, an experiment was carried out to observe the growth depth of mycelium through clay. The hypothesis was that printed layers with mycelium have better binding connection than the 3D printed layers without mycelium. This assumption was based on the examination of mycelium acting as an additional binding agent that connects two adjacent layers.

2.3.1. Tensile strength along extrusion axis

Samples for testing tensile strength along the extrusion axis were printed from the material mixture described in the previous chapter in dimensions 60x170x15 mm, whereby all printing paths were created in parallel to the stress axis. These were then dried and sterilized and one half were inoculated. The incubation was terminated after 14 days and the samples were dried once again. Finally, all samples were sanded down to have identical dimensions before testing.

The test results show (Figure 2) an increase of the average of maximum tensile strength values of 66.62% for the samples with mycelial growth. Samples without mycelial growth showed an average value of maximum tension of 122.60 N with a top value of 178.37 N, while samples after 14 days of mycelial growth showed an average value of maximum tension of 204.28 N with a top sample of 278.30 N. There is no notable change of elongation behaviour in these samples. Some of the samples were damaged during the fixture in the testing machine due to internal bending behaviour of clay while drying. The test objects showed no recognizable crack pattern after reaching maximum tensile force.

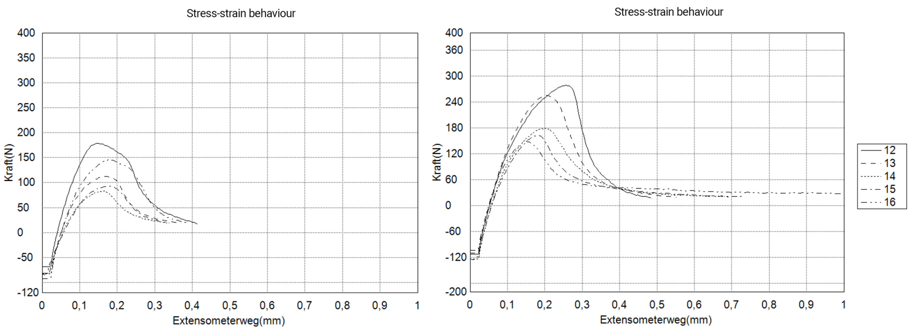

Figure 2. Comparing the load curves regarding tensile strength along the extrusion axis of the individual samples without (left) and with (right) mycelial growth.

2.3.2. Binding force between printed layers

To evaluate the increased strength of the consolidated layers, the samples were prepared in a cylindrical form. The printing path consisted of three concentric circles per layer, each with alternating starting points. Subsequently, these were randomly shifted per layer to avoid a weak seam along the object. The samples had a height of 40 mm, a diameter of 45 mm and a void with a diameter of 20 mm, thus a wall thickness of 12.5 mm. The samples were prepared by filling the central void with a wooden cylinder and the total volume was capped with a piece of acrylic glass, which was glued only to the ceramic surface. An anchor was drilled into the wooden piece to transmit the force to the acrylic glass once it had been pulled. The samples were tested using a Shimadzu AG-X plus testing machine.

The test results confirmed the hypothesis by showing an increase of average of maximum tensile strength values of 32.34% in favor of specimens with mycelium. Samples without mycelial growth showed an average value of maximum tension of 83.80 N with a top value of 93.14 N, while samples after 14 days of mycelial growth showed an average value of maximum tension of 110.90 N with a top sample of 174.82 N. The fracture at maximum tensile force occurred between the top two layers at all samples. There was no notable change of elongation behaviour in these samples.

2.3.3. Observation of growth depth

Samples with wall thicknesses ranging from 2.5 mm to 9.5 mm have been produced to evaluate the maximum extent of mycelial growth through clay. Pieces of 10 mm width were broken out from different positions within the samples. To observe the superficial growth of mycelium on clay, an Eschenbach stereo light microscope, with a maximum magnification of 90, was used to examine the surface of fracture.

Successful mycelial growth through a 3D printed clay wall of 9.5 mm is evident (Figure 3, left). The 9.5 mm wall is seen on the left side of the picture and mycelium reaching for nutrients. Displaying hyphae within the area of fracture was not possible using a light microscope. The expected effective porosity is assumed to take place on a much smaller scale. Further investigation of the inner porosity caused by hyphal growth is required by scanning through an electron microscope.

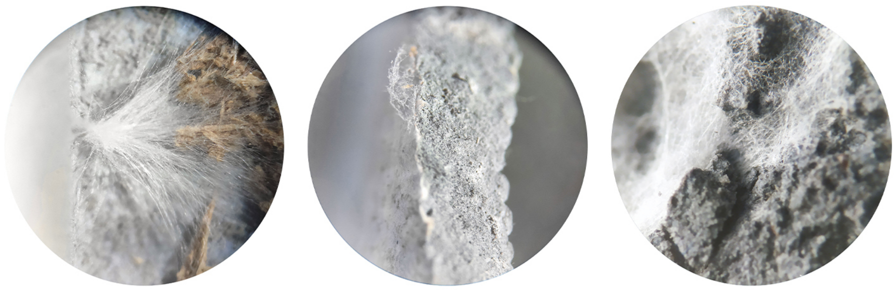

Figure 3. Mycelial advancement through the 3D printed clay wall (9.5 mm) at 20x magnification (left). Surface growth on a 3D printed clay wall (2.5 mm) at 20x magnification (middle). Hyphae connection between two elements at 30x magnification (right).

2.4. CASE STUDY - COMBINED STRUCTURE

The main goal of the design study was incorporating material design in the structural properties of an architectural element. Two types of elements were designed to fulfill different static requirements: 1) bar elements which consist of fired clay and primarily bear pressure loads (Figure 4, right), 2) node elements that consist of unfired clay and a large amount of mycelium, which have more capacity of bearing tensile and torsion loads (Figure 4, left, middle). Both of these element types were 3D printed from the same material mixture consisting of 87.5% clay and 22.5% sawdust. The following step was preparing the elements for inoculation, which was achieved by wrapping them in a tear resistant aluminum foil and autoclaving at 117-120°C at 0.8-1 bar for 120 minutes. After the elements cooled down to room temperature, inoculation commenced.

Figure 4. Inoculated node (left, middle) and bar (right) elements after 14 days of growth.

Cylindrical objects were filled with mycelium spawn. For the node elements, the spawn was evenly dispersed on the surface. The objects were then moistened with sterilized water. The inoculated elements were incubated in microfilter bags (PP75/BEH6/V37-53, SacO2) at 24°C and 80% relative humidity in a dark environment. After two weeks, the bars were removed from the growing environment, dried at room temperature and then fired at 600°C for 6 hours, followed by 960°C for 2.5 hours. During that process, all organic elements burned up leaving an effective porosity through a branching inner structure in the ceramic. The node elements were kept in the same growing conditions, without firing, with the aim of establishing enhanced mycelial growth.

In order to design a structure that reflects the possibilities which result from material qualities and digital fabrication, a “combined structure” was developed. The geometry was defined by a topological optimization algorithm (via Topos plugin for Grasshopper). Exemplary support and load conditions were applied within a 380x380x380 mm boxed space. The result was then abstracted to an axis diagram, in which the axes were rebuilt with cylindrical objects and nodes as streamlined meshes (via Kangaroo plugin for Grasshopper).

The structure was assembled by putting the two types of elements together in a state where mycelium continues its growth. Mycelium fibres of the still growing node elements formed connections through expansion of the hyphal network and bio-welded adjacent elements together. The mycelial connections were able to structurally connect bar and node elements. After a minimum growth duration of 14 days, the structure was dried under atmospheric conditions and the assembly was finished. The material showed two important aspects after the assemblage: 1) it is able to fill out the gaps that occur while assembling and it tolerates an uneven contact between two surfaces - the same way as mortar, 2) it developed a connection within multiple elements by expansion of the hyphal network.

The combined structure (Figure 5, right) was designed and built to be a showcase for the exhibition *Steiermark Schau 2021 (Styrian Show)* starting in April 2021 at Kunsthaus Graz. The exhibition objective is to present research to the public, to connect art and science and to make all of this work accessible to a non-academic audience.

To visualize mycelial growth in the design phase, the Metaballs algorithm was used. It creates n-dimensional isosurfaces that are characterised by their ability to meld together when in close proximity, to form contiguous objects (Figure 5, left). This algorithm is often used for digital modelling of organic objects (Martinez 2017). Threshold of this melding is set according to previous observations of how far the hyphae reach out in mid-air. For the current stage of the research, this algorithm is a useful tool to visually propose a grown structure.

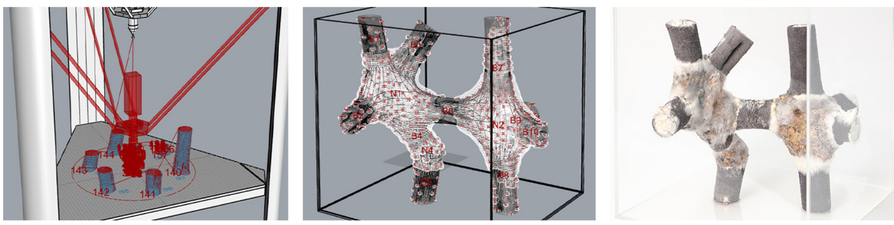

Figure 5. Software setup showing the simulation of printing (left) simulation of mycelial growth (middle) and realization of the combined structure (right).

3. Conclusion

We developed a composite material and produced two different 3D printed types: 1) bar elements based on fired clay to deal with pressure forces; 2) node elements based on mycelium to deal with tension and shear forces. Both types consist of a mixture of clay and sawdust inoculated with mycelium. After a sufficient growing process, the bar elements were fired, whereby the organic elements burn up leaving an effective porosity through a branching inner structure. The growth process of the node elements was terminated where mycelium remained as a fibre reinforcement. The two element types were assembled in a state during which mycelium was still growing, until it fully dried out under atmospheric conditions. In this manner, we built a combined structure in which mycelium fibres formed connections, which are able to transmit forces between adjacent elements by penetrating the tube-like inner structures of the fired elements.

The composite "MyCera" shows notable structural properties when compared to the same material mixture without mycelium. This has been proven on a set of samples tested for tensile strength along the extrusion axis, as well as within connections between the single 3D printed layers. Mycelium enhances tensile strength along the extrusion axis by 66.62% and the connection between the single layers by 32.34%. It is assumed that the high increase of tensile strength is caused by the growth process which takes place after printing. This kind of intelligent fibre distribution could not have been achieved with a non-growing material. Currently, the main limitation is preserving a sterile fabrication process.

4. Perspectives

After accomplishing sufficient research, the proposed material composition could replace cement based binders. Furthermore, utilizing this new material and fabrication method, which increases tensile strength, ceramic elements in architecture can be assembled in less solid configurations. To verify the assumption of an advantageous structural effect of grown fibre connections, a comparison of mycelial fibre reinforcement and other fibres that are commonly used to increase tensile strength, such as basalt and glass fibres (Naughton and Grennan 2017), is planned. The question of the actual application and durability of the material after a long-term exposure to atmospheric conditions still remains open. Another open topic is the possibility of introducing coatings such as Xyhlo Biofinish (van der Berg and Konings 2019) (made from the *Aureobasidium pullulans* fungus) and sodium silicate (Stark and Wicht 2000) to extend its lifespan until it matches the one of a standard ceramic brick.

Future work is planned based on the results of this research: 1) creating a multi nozzle system to distribute different material properties within one element, 2) scanning samples with an electronic microscope, 3) implementing growth as a design parameter in 3D modelling software.

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References

“World greenhouse gas emissions” : 2005. Available from <https://www.wri.org/resources/charts-graphs/world-greenhouse-gas-emissions-2005> (accessed 22nd October 2020).

“Digital seismograph” : 2017. Available from <https://designbydata.org/project/digital-seismograph-adrien-rigobello> (accessed 09th December 2020).

“Mycotree - Block Research Group” : 2017. Available from <https://block.arch.ethz.ch/brg/project/mycotree-seoul-architecture-biennale-2017> (accessed 27th November 2020).

“Elsacker, E. - Architectural Engineering Lab of the Vrije Universiteit Brussel” : 2019. Available from <https://www.vub.be/arch/people/elise-elsacker> (accessed 27th November 2020).

“Fungar - Royal Danish Academy” : 2019. Available from <https://royaldanishacademy.com/news/forskere-skal-skabe-levende-svampearkitektur> (accessed 27th November 2020).

“Claycelium - Institute for Advanced Architecture of Catalonia” : 2019. Available from <http://www.iaacblog.com/programs/claycelium/> (accessed 22nd October 2020).

J. van den Berg and B. Konings (eds.): 2019, *Material Atlas; Materialen Atlas; The Growing Pavillon*, Company New Heroes, Amsterdam.

Brian, D. and Händle, F.: 2007, *Extrusion in Ceramics*, Springer Berlin Heidelberg, Berlin.

Colmo, C. and Ayres, P.: 2020, 3d Printed Bio-hybrid Structures – Investigating the architectural potentials of mycoremediation, *eCAADe*.

Elsacker, E., Vandelook, S., Van Wylick, A., Ruytinx, J., De Laet, L. and Peeters, E.: 2020, A comprehensive framework for the production of mycelium-based lignocellulosic composites, *Science of The Total Environment*, **725**, 138431.

Ghazvinian, A., Farrokhsiar, P., Vieira, F., Pecchia, J. and Gursoy, B.: 2019, Mycelium-Based Bio-Composites For Architecture: Assessing the Effects of Cultivation Factors on Compressive Strength, *eCAADe*.

Goidea, A., Andreen, D. and Floudas, D.: 2020, Pulp Faction: 3d printed material assemblies through microbial biotransformation, *Fabricate*, London.

Hansemann, G., Schmid, R., Holzinger, C., Tapley, J., Kim, H., Suskovic, V., Freytag, B., Trummer, A. and Peters, S.: 2020, Additive Fabrication of Concrete Elements by Robots, *Fabricate*, **4**, 124-129.

Khoshnevis, B. and Hwang, D.: 2006, Mega-scale fabrication by Contour Crafting, *International Journal of Industrial and Systems Engineering*, **Vol.1**(3), 301-320.

Kleiber, W. and Simon, J.: 2006, *Verkehrswertermittlung von Grundstücken*, Bundesanzeiger Verlag.

Martinez, F., Martinez, F. and Hernández, C.: 2017, Organic-Shaped Structures Design Using Genetic Algorithms and Metaballs, *Contemporary Engineering Sciences*, **Vol.10**(21), 1001-1010.

Naughton, P. J. and Grennan, R. M.: 2015, The strength of fibre reinforced clays; La force de l’argile renforcées par des fibres, *XVI European Conference on Soil Mechanics and Geotechnical Engineering*.

Soh, E., Chew, Z.Y., Saeidi, N., Javadian, A., Hebel, D. and Le Ferrand, H.: 2020, Development of an extrudable paste to build mycelium-bound composites, *Materials and Design*, **195**, in print (Article 109058).

Stark, J. and Wicht, B.: 2000, *Zement und Kalk; Der Baustoff als Werkstoff*, F.A. Finger-Institut für Baustoffkunde der Bauhaus-Universität Weimar.

Ugarte, J. P., Mhatre, S., Norman, S. and Bechthold, M.: 2020, Extruded Tessellations: A novel structural ceramic system at the intersection of industrial ceramic extrusion and CNC fabrication, *SIGraDi 2020: XXIV International Conference of the Iberoamerican Society of Digital Graphic*, Medellín.