# CLAY-MYCELIUM COMPOSITE

*Using Mycelial Growth as Fibre Reinforcement for Unfired Clay*


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## Abstract

This paper presents the first results of a basic research on a new composite made of inorganic and organic material by using unfired clay and mycelium, the vegetative part of mushrooms that grows on bio-waste. The use of cement in the building industry has a high significance in global greenhouse emissions, is resource-intensive and has an unresolved disposal problem. Finding sustainable alternatives to reduce the need for cement is one of the major global challenges. Our composite called "MyCera" has exhibited notable structural properties that open up the possibility of implementing this composite in the building industry. Our scientific contribution is the successful development of a bio-processed material mixture which is suitable for digital fabrication and facilitates the natural process of mycelial growth on low-cost raw materials. The 3D printed samples of this mixture show a notable increase of tensile strength compared to the same mixture without mycelial growth by enabling fibres to connect on a micro scale and act as a fibre reinforcement. This material shows potential to be a viable alternative to constructions that relies on mortar and deserves further research.



**Keywords:** composite material, clay, mycelium, bio-waste material, 3D printing


## Introduction

In the last couple of years, several artists and designers have developed mycelium-based materials and designed prototypes for exhibitions. Also, some alternative products such as leather, foam, packaging material, furniture or acoustic dampers had become commercially available. Applied projects in the field of architecture were developed at various universities, e.g. IAAC Barcelona [1], ETH Zürich [2], CITA [3] and Vrije Universiteit Brussel [4]. University projects were frequently a part of experimental design studios. Based on those results, there is currently a tremendous interest in research of mycelium as sustainable material in the building industry.

In architecture, clay is mostly used in the form of bricks, tiles or sanitary appliances. In terms of digital planning and digital fabrication, the clay industry is not as technically advanced as concrete or steel industries are. The production and application of bricks has not fundamentally changed since the beginning of using dies in piston extruders in 1855 [5]. 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. However, mortar poses another issue, as it leads to a high fossil $CO_2$ emission due to the production process of cement and resource procurement [6]. 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 usually get discarded as one compound after a building fulfills its life expectancy of approximately 60 years [7].

With this research, a combination of clay and mycelium is explored, where mycelium acts as a reinforcing component within/or between individual unfired clay elements.

## Methodology

The methodology of this research was carried out through experiments and design studies. A series of novel composite 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 three phases: (A) experimentation with material, (B) setting up hardware and software and (C) testing and measurement.

### *A. Material experimentation*

The composite material "MyCera" consists of inorganic parts − clay and water, and organic parts − mycelium and substrate. The main challenge in the material experimentation phase was finding an optimal substrate type and optimum ratio of organic and inorganic material with the following requirements:

1) using as much organic material as possible to achieve enough nutrition for homogeneous mycelial growth that influences higher porosity left by the organic components after the firing process;
2) the mixture must retain the required viscosity and elasticity for the 3D printing fabrication process.

A decision was made to use black clay, type Nigra 2002 of company Sibelca to ensure a better visual distinction between clay and mycelium. 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.

The goal of the first set of experiments was mixing clay and different substrate types to choose the one optimal for mycelial growth. Those substrates were sawdust, along with bleached and unbleached cellulose.

Two types of mycelium strains were used in the beginning, *Pleurotus ostreatus* and *Ganoderma lucidum*. After several experiments, *Ganoderma lucidum* was abandoned due to contamination problems. The naming system (Table 1.) used for the samples is determined as followed: material composition – inorganic component – organic component – mycelium strain – sample number (MM mixed material, CP clay powder, FS sawdust, CS1 bleached cellulose, CS2 unbleached cellulose, PO *Pleurotus ostreatus*).

TABLE 1. SAMPLES WITH MIXTURES OF CLAY AND THREE SUBSTRATE TYPES IN SEVEN DIFFERENT RATIOS

| CP:MM volume | CP:MM weight | sawdust size <2 mm | bleached cellulose size 1-4 mm | unbleached cellulose size 1-4 mm |
|---|---|---|---|---|
| 1:8 | 1:4 | MM-CP-FS-PO-01 | MM-CP-CS1-PO-01 | MM-CP-CS2-PO-01 |
| 1:6 | 1:3 | MM-CP-FS-PO-02 | MM-CP-CS1-PO-02 | MM-CP-CS2-PO-02 |
| 1:4 | 1:2 | MM-CP-FS-PO-03 | MM-CP-CS1-PO-03 | MM-CP-CS2-PO-03 |
| 1:2 | 1:1 | MM-CP-FS-PO-04 | MM-CP-CS1-PO-04 | MM-CP-CS2-PO-04 |
| 1:1 | 2:1 | MM-CP-FS-PO-05 | MM-CP-CS1-PO-05 | MM-CP-CS2-PO-05 |
| 2:1 | 4:1 | MM-CP-FS-PO-06 | MM-CP-CS1-PO-06 | MM-CP-CS2-PO-06 |
| 4:1 | 8:1 | MM-CP-FS-PO-07 | MM-CP-CS1-PO-07 | MM-CP-CS2-PO-07 |

After a series of experiments and elaboration of mycelial growth, sawdust was chosen as a substrate. In order to prepare this material for printing, a series of different experiments was done to find optimal material viscosity for the 3D printer with a 4 mm nozzle.

For the final material mixture, sawdust was sieved to ensure a particle size <2 mm to not 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 is 7:1. 35% water was added for printing, measured from the weight of the mixture. In the final step of material preparation, the wet mixture was filled into the material tanks, closed airtight to prevent any moisture loss, each containing a material volume of up to 4600 cm³. The chosen geometry was 3D printed and inoculated by distributing the mycelium spawn on the 3D printed samples.

*B. Setting up hardware and software*

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

A custom Grasshopper script for Rhino 3D was developed to use the 3D printer in the most flexible manner. This way, designing and providing machine data is directly connected within one software and allows an efficient workflow.

*C. Testing and measurement*

The following experiments refer to the paste-based extruded material mixture stated in *A*. All tests were conducted at the Institute of Technology and Testing of Building Materials at Graz University of Technology. Two kinds of tests were performed: 1) tensile strength along the extrusion axis; 2) binding force between the printed layers. Additionally, an experiment was carried out to observe the growing depth of mycelium through clay.

*C.1. Tensile strength along the extrusion axis*

Samples for testing tensile strength along the extrusion axis were printed from the material mixture described in *A* in dimensions 60x170x15 mm. They were then dried and sterilized and half of them were inoculated. The incubation was terminated after 14 days and the samples were dried once again. Finally, all samples were sanded to have identical dimensions before testing.

The test results show an increase of the average maximum tensile strength of 66,62% for the samples with fungal growth.

| Name | Maximum_Kraft | Maximum_Dehnung aus Strecke |
|---|---|---|
| Parameter | Gesamter berechneter Bereich | Gesamter berechneter Bereich |
| Einheit | N | % |
| 12 | 178,37 | 0,14748 |
| 13 | 112,52 | 0,17075 |
| 14 | 83,08 | 0,16744 |
| 15 | 92,84 | 0,17746 |
| 16 | 146,21 | 0,18079 |
| Durchschnitt | 122,60 | 0,16878 |
| Standardabweichung | 39,4234 | 0,01303 |
| Bereich | 95,2900 | 0,03331 |

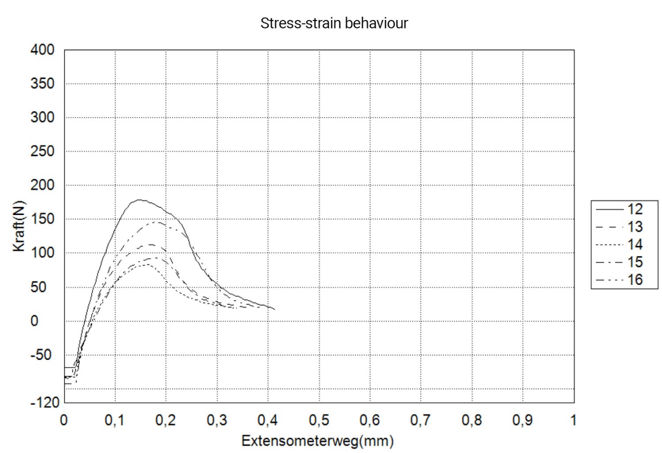


Fig. 1 Load curves regarding tensile strength along the extrusion axis of the individual samples without mycelium

Samples without fungal growth showed an average maximum tension of 122,60 N (Fig.1) with a top value of 178,37 N, while samples with 14 days of fungal growth showed an average maximum tension of 204,28 N with a top sample of 278,30 N (Fig.2). There is no significant change of elongation behavior in these samples.

*C.2 Binding force between the printed layers*

The hypothesis proposes that printed layers reinforced by mycelium have better binding connection than the 3D printed layers without mycelium. This assumption was based on the fact that mycelium acts as an additional binding agent that connects two adjacent layers.

| Name | Maximum_Kraft | Maximum_Dehnung aus Strecke |
|---|---|---|
| Parameter | Gesamter berechneter Bereich | Gesamter berechneter Bereich |
| Einheit | N | % |
| 12 | 278,30 | 0,25744 |
| 13 | 254,81 | 0,20419 |
| 14 | 178,70 | 0,20085 |
| 15 | 162,05 | 0,18413 |
| 16 | 147,52 | 0,15081 |
| Durchschnitt | 204,28 | 0,19948 |
| Standardabweichung | 58,5057 | 0,03869 |
| Bereich | 130,780 | 0,10663 |

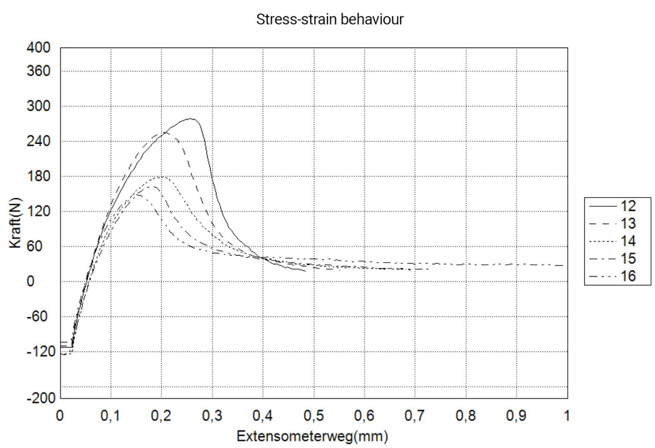


Fig. 2 Load curves regarding tensile strength along the extrusion axis of the individual samples with mycelial growth

To evaluate the increased strength of the consolidated layers, samples in a cylindrical form were prepared. The printing path consists of three concentric circles per layer, each with alternating starting points. Further on, those are randomly shifted per layer to avoid a weak seam along the object. The samples have 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.

For testing, the central void was filled with a wooden cylinder and the whole 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 transfer the force on the acrylic glass once it is being pulled. The samples were tested using a Shimadzu AG-X plus testing machine (Fig. 3).

Fig. 3 Cylindrical test samples

The test results confirmed the hypothesis of an increased average maximum tensile strength of 32,34% in favour of specimens with mycelium. Samples without fungal growth showed an average maximum tension of 83,80 N with a top value of 93,14 N, while samples with 14 days of fungal growth showed an average 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 is no significant change of elongation behavior in these samples.

*C.3 Observation of growing depth*

To evaluate the maximum wall thickness of clay that mycelium can grow through, samples with wall thicknesses ranging from 2,5 mm to 9,5 mm have been produced and infiltrated by mycelium (Fig.4).

Fig. 4 Some of the samples to test maximum growth depth into clay

Pieces of 10 mm were broken out and taken from different positions within the previous samples. To observe the superficial growth of mycelium on clay, an Eschenbach stereo light microscope with a maximum magnification of 90 was used. Successful mycelial growth through a 3D printed clay wall of 9,5 mm is evident.

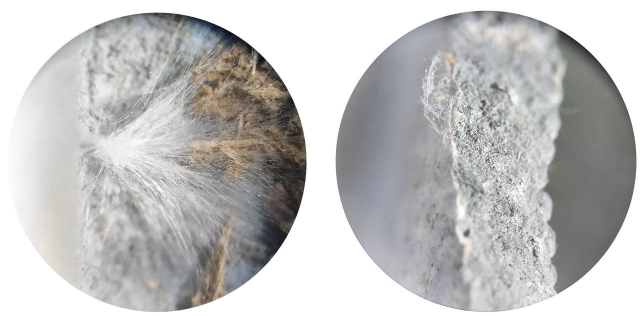

Fig. 5 20x magnification of mycelial advancement after growing through a printed sample and reaching out for nutrients (left). Superficial mycelial growth on a printed sample (right)

## Conclusion

A composite material consisting of clay and sawdust was prepared for 3D printing and subsequently inoculated with mycelium. After a sufficient growing process, the elements were fired, whereby all organic elements burned up leaving an effective porosity through a branching inner structure in the ceramic. In the second phase, the single chambers of the elements were again filled with mycelium. Multiple elements were then assembled in a state where mycelium still continues to grow (Fig.6). The elements are connected through the expansion of the hyphal network, until they fully dry out under atmospheric conditions. In this manner, the mycelium fibres form connections, which are able to transmit forces between adjacent elements by penetrating the inner structures of the fired elements as a fibre reinforcement.

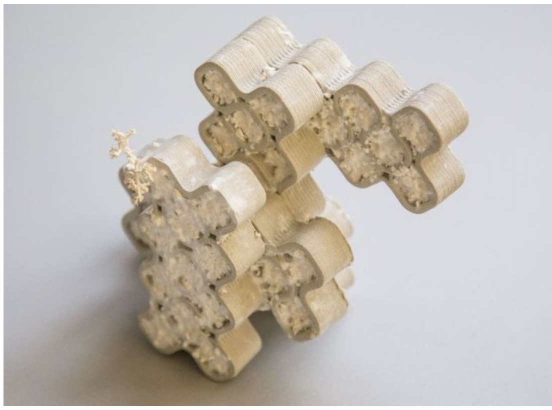

Fig. 6 One of the structures bound by mycelial growth

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 between the 3D printed layers. It can be concluded that 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.

## Future work

To verify the assumption of an intelligent fibre distribution, a comparison of grown mycelial fibre reinforcement and common fibres that are used to increase tensile strength, such as basalt and glass fibres [8], is planned. The future work will include creating a multi nozzle system for working with different material qualities within one element, e.g. cellulose and lignin as addition to clay.

Fig. 7 First promising example with cellulose and single nozzle

For further examination of mycelial growth on a microscopic scale, samples will be scanned with an electronic microscope. Implementing growth as a design parameter in 3D software is being prepared for the next research phase. This way, simulating and visualizing mycelial growth will be possible. Furthermore, a comparison of fired clay with and without mycelial infiltration will be examined.

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