Mycelium-Based Bio-Composites For Architecture:

Assessing the Effects of Cultivation Factors on Compressive Strength

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Mycelium-based bio-composites can propose a renewable and biodegradable alternative for architectural construction materials. These biomaterials result from growth of mycelium, fibrous root systems of fungi, on organic substrates in controlled environmental conditions. This paper presents a material study that explores how substrate type and added supplements used for cultivating mycelium affect the compressive strength of mycelium-based composites for use as masonry units in architectural construction. For this purpose, samples grown using Pleurotus Ostreatus (Gray Oyster mushroom strain) on three different substrates (sawdust, straw and a mixture of sawdust and straw) with and without supplementation are tested for compressive strength.

Keywords: *mycelium, biodesign, biomaterials, masonry, compressive strength*

INTRODUCTION

The United Nations projects that 68% of the world population will live in urban areas by 2050. Population growth in urban areas increases the demand for construction. However, with the dominant "produce, use, and discard" framework, AEC (Architecture, Engineering and Construction) industry is far from providing sustainable solutions for the increasing construction demand (Heisel et al., 2017). Moreover, natural resources are getting scarce, necessitating a search for renewable materials and alternative ways for using existing resources. The fourth industrial revolution can bring about a change, and enable to break away from the *discard culture*. Recently, research in the emerging field of biodesign started to offer promising solutions for environmental problems caused by rapid population growth and the accompanying *discard culture*. Biodesign practices incorporate "biology-inspired approaches to design and fabrication" where "living organisms [are] essential components in design" (Myers, 2018). Architects and designers started to collaborate with biologists and material scientists in order to explore how they can design using biomaterials: "materials that are *grown*, rather than manufactured" (Zolotovsky, 2017), and integrate living systems, such as bacteria, algae or fungi, to their design processes in the search for more sustainable solutions.

Along these lines, mycelium-based composites present renewable and biodegradable alternatives for a wide range of design and manufacturing processes, including architectural applications.

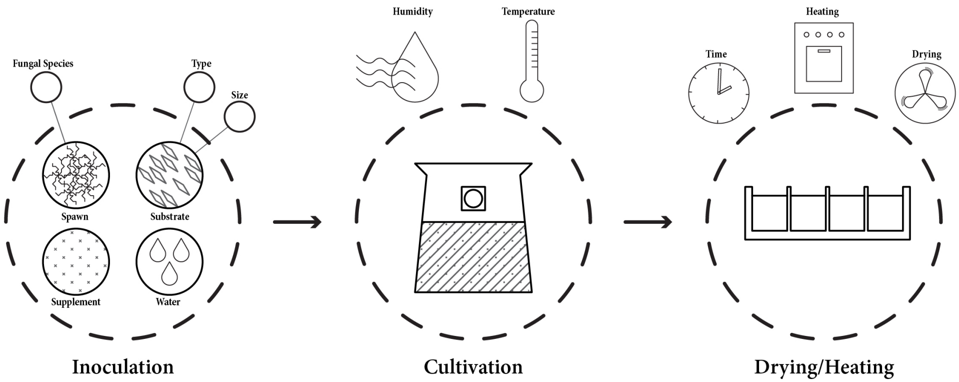

Figure 1
Diagram illustrating the process of cultivation of mycelium-based bio-composites

Mycelium is the fibrous root system of fungi, and mycelium-based composites result from the *growth* of mycelium on organic substrates (i.e. hemp, sawdust, straw). There are many factors that influence the *growth* of mycelium, hence the material properties and performance of resulting mycelium-based composites. Among these are the strains of fungi used for inoculation, the substrate type, environmental conditions during growth (i.e. humidity, temperature, supplementation), and forming and processing techniques as illustrated in Figure 1. While there is already a growing body of work exploring the effects of these various factors on the technical properties of the cultivated composite materials (Heisel et al., 2017; Yang et al., 2017; Appels et al., 2019; Girometta et al., 2019), the main focus of this paper is on the use of mycelium-based composites as masonry units in architectural construction. The paper presents the initial stages of an interdisciplinary research that explores various uses of mycelium-based composites in architecture as a sustainable, renewable and biodegradable alternative to conventional building materials that produce waste and rely on natural resources. As part of this initial stage, in collaboration with mushroom scientists, a systematic material study is realized to assess the effects of different substrate mixtures (sawdust, straw, sawdust+straw; with and without supplementation) on the growth and compressive strength of mycelium-based composite blocks. The results of the compressive strength tests on the block samples demonstrate that the straw-based bio-composites are not capable of bearing loads and the sawdust-based bio-composites show potentials to be used as substitutes for traditional masonry units in architecture if adequate reinforcement is provided.

BACKGROUND ON DESIGNING WITH MYCELIUM-BASED BIO-COMPOSITES

What is a Mycelium-based Bio-Composite?

Mycelium is the vegetative part of fungi made of a mass of *hyphae*. Hyphae are the long, branching filamentous structures of fungi that act as growth agents. The primary role of mycelium in nature is to decompose organic waste: with enzymes secreted from hyphae, mycelium break down the bio-polymers to simpler bodies and then digest carbon-based nutrients. This process let the "hyphae grow out of the substrate into the air creating a fluffy or compact layer covering the substrate", called *fungal skin* (Appels et al., 2019). Fungal colonies made of mycelium can be found inside or on the surface of organic substrates such as soil, sawdust, paper and any other carbon-based matter.

Pure mycelium can be extracted from natural processes: it is "the result of complete degradation of substrates", called *colonization*. During colonization, mycelium cements the substrates and partially replaces them with the tenacious biomass of the fungus. Pure mycelium is also obtainable by removing the fungal skin from substrates (Appels et al.,2019). Mycelium-based composites, on the other-hand, emerge when fungal growth is stopped during colonization through drying or heating the mycelium: drying the mycelium leads to its hibernation, which means mycelium can restart growing when environmental conditions allow it; heating the mycelium kills it and stops its growth permanently. The outcome of either of these processes is a *mycelium-based composite*. Mycelium-based composites can be shaped by using non-carbon-based formworks.

Existing research suggest that the properties of both pure and composite mycelium depend on fungal species used for inoculation, substrates and additives used, growth conditions, and processing and forming techniques. According to various studies, mycelium-based bio-composites have 1) a relatively low density when compared to plastics, 2) a relatively low compressive strength when compared to conventional materials used in masonry construction, 3) a lack of tensile strength, and 4) a strong dependency for curing process for durability (Appels et al., 2019; Yang et al., 2017; Attias et al., 2017; Haneef et al., 2017; Islam et al., 2017; Jones et al., 2017). In this study, we assess the effects of substrates and additives used to cultivate *Pleurotus Ostreatus* based composites on their compressive strength with the aim to explore ways to improve compressive strength of mycelium-based composites.

The Use of Mycelium-based Composites in Design and Architecture

While mycelium have been used for more than a century in medical industry to produce enzymes and small molecule compounds such as antibiotics and organic acids (Wosten, 2019), initial explorations on the use of mycelium-based composites as biomaterials date back to 1980s when Japanese scientist Shigeru Yamanaka explored the binding power of mycelium to produce paper and certain building materials (Girometta, 2018). Later on, Stamets (2005) presented evidence on the environmental benefits of mycelium in decomposing toxic wastes and pollutants in soil and water. Recently, designers and architects started to explore the use of mycelium in product design, fashion, and architectural design as sustainable alternatives to conventional materials (Figure 2 and Figure 3). Among these are synthetic leather, kitchen utensils, packaging items, various furniture, wall and ceiling panels, and masonry units.

Figure 2
Examples of mycelium use in product design

Synthetic leather cultivated using mycelium and agricultural byproducts by companies MycoWorks and MOGU is sustainable, flexible, durable and waterproof, and performs like leather (Figure 2-A). Kitchenware developed by Officina Corpuscoli as part of the project "Future of Plastics" are biodegradable alternatives to single-use plastics (Figure 2-B). Similarly, Ecovative, the first start-up company working on the industrialization of mycelium-based products, produces mycelium-based packaging as an environment-friendly alternative to plastic-based foam packaging (Figure 2-C). Lightweight mycelium-based composites, despite their load-bearing capability and durability led the designers to explore designing various furniture by cultivating mycelium. Among these are the works by Erik Klarenbeek (Figure 2-D) and Phil Ross (Figure 2-E).

Figure 3
Examples of mycelium use in architectural context

Following these design explorations, over the past couple of years, the use of mycelium-based composites has also started to be explored in architectural applications. Mycelium-based composites have good insulation performance, and are safer and more fire-resistant than the commercially available thermoplastics used in the building and construction industry (Jones et al., 2017). In order to replace petroleum-based materials used for insulation, MOGU has developed mycelium-based wall and ceiling panels (Figure 3-A). On the other hand, masonry units cultivated from mycelium propose a biodegradable alternative for construction of small structures. There are a few architectural projects built using mycelium-based blocks over the past couple of years, among which are the *Hy-Fi Tower* (Figure 3-B), the *Mycotecture Alpha* (Figure 3-C), and the *MycoTree* (Figure 3-D). The *Hy-Fi Tower* is designed by David Benjamin from Living Studio as a temporary structure in 2014 for MoMA's PS1 courtyard. The tower has the form of three intersecting cylinders of 13 meters tall, and is built with 10,000 mycelium blocks that are cultivated using Ecovative's growth mixtures (Slavin, 2016). The tower remained erected for three months during the Summer of 2014 and was then disassembled, mycelium blocks were broken to be composted. This design experiment is a testimony for the durability, resistance and biodegradability of mycelium-based masonry units. *Mycotecture Alpha*, is a small-scale pavilion designed and built by Phil Ross, the co-founder of *MycoWorks*, using around 350 mycelium blocks. The structure consists entirely of mycelium blocks, with a mycelium floor, and a simple barrel vault that holds the structure through the compressive strength of the blocks (Karana et al., 2018). In a more recent project, Block Research Group at the ETH Zurich, in collaboration with Karlsruhe Institute of Technology, designed and built *MycoTree* for the 2017 Seoul Biennale of Architecture and Urbanism. *MycoTree* is a spatial branching structure built with mycelium-based bio-composites that are molded into special formworks designed by 3D graphic statics method. This project shows "how regenerative resources in combination with informed structural design have the potential to propose an alternative to established, structural materials for a more sustainable building industry" (Heisel et al., 2017). Besides the use of mycelium-based composites as masonry units, there are recent attempts at using mycelium as substitutes for architectural membranes and columns. The *Shell Mycelium* pavilion designed and built by Yassin Areddia and Beetles 3.3 is an effort to explore the use mycelium as a reliable substitute for concrete in small-scale and temporary construction projects (Figure 3-E). The pavilion has been built for 2016 Kuchi Muziris Biennale in India. Gruber and Imhof (2017) also exemplify innovative uses of mycelium to cultivate columns (Figure 3-F) and minimal surfaces (Figure 3-G).

Research on the use of mycelium in architecture is rapidly advancing with the aim to discover the constraints and affordances of mycelium-based composites. One of the most important tracks in this line of research is to find ways to enhance the mechanical and chemical properties of mycelium-based compos-

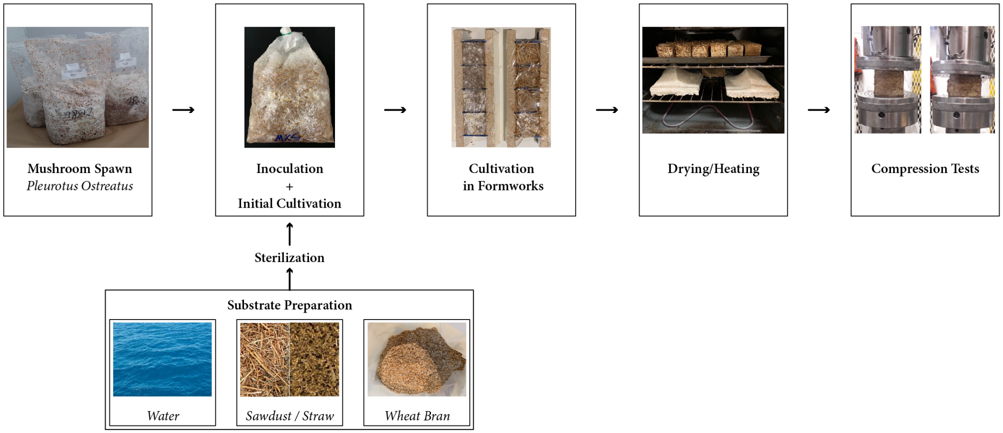

Figure 4
Experiment workflow.

ites for increased durability and strength against potential fatigue and humidity threats. In the next sections of this paper, we present the workflow and results of an experimental material study realized to assess the effects of cultivation factors on compressive strength of mycelium-based composites. The study proposes ways to improve compressive strength of mycelium-based composites for use in masonry construction.

EXPERIMENTAL MATERIAL STUDY AND ANALYSIS METHODS

The experiment setup consists of several stages, starting with substrate preparation. The prepared substrates are first sterilized in autoclave chambers before being inoculated with *Pleurotus Ostreatus* (Gray Oyster mushroom) strain. Sterilization provides a clean slate for cultivation and prevents unwanted contamination. Inoculated substrates are then placed within growth chambers where adequate environmental conditions (humidity and temperature) for cultivation are provided. When enough mycelium cultivation is achieved over the course of two weeks, cultivated mycelium samples are transferred within 5x5x5 cm3 plastic formworks to initiate the second phase of growth. Here, mycelium growth makes the mixture denser taking the form of the plastic formworks. At the end of day 3, cubic samples are taken out from the formworks and heated in the oven in order to *kill* mycelium and stop the cultivation process. The resulting samples are the mycelium-based bio-composites. Finally, mycelium-based bio-composite samples are tested for compressive strength using a 22 kips Instron test machine. Figure 4 illustrates this process, which is explained in detail in the sub-sections below.

Substrate Preparation

The first stage consists of preparing the substrates on which mycelium will grow. Six substrate mixtures have been prepared as part of the study using: 1) sawdust (SDP), 2) sawdust with supplement (SDS), 3) straw (STP), 4) straw with supplement (STS), 5) a combination of sawdust and straw in equal amounts (MXP) and 6) a combination of sawdust and straw with supplement (MXS). The supplement used is wheat bran, which provides more carbon and nitrogen for the cultivation process. Substrate badges of 5 kg have been prepared with moisture contents of 67.5±2.5%. These badges are divided in autoclavable bags for sterilization: STP, STS, MXP and MXS badges are divided into three bags of 1.6 kg each

CODE	CONTENT	HUMIDITY	BAGS	SPAWN
SDP	100% Sawdust	69.4	2*2.4 kg	64 g
SDS	90% Sawdust/ 10% Wheat Bran	65.6	2*2.4 kg	64 g
STP	100% Straw	69.7	3*1.6 kg	42 g
STS	90% Straw/ 10% Wheat Bran	69.2	3*1.6 kg	42 g
MXP	50% Sawdust/ 50% Straw	67.3	3*1.6 kg	42 g
MXS	45% Sawdust/ 45% Straw/ 10% Wheat Bran	67.5	3*1.6 kg	42 g

Table 1
Six substrate mixtures

and SDP and SDS badges in two bags of 2.4 kg due to the difference in their volumes. Before sterilizing the bags, three samples of 40 g from each badge are collected for humidity measurement. These samples are placed in the autoclave chamber to be completely dried and are weighed in order to calculate the amount of water lost during autoclave process. Table 1 summarizes the characteristics of substrate mixtures and Figure 5 shows the badges and the bags.

Figure 5
Badges and bags of substrate mixtures

Figure 6
Formworks.

Sterilization of Substrate Mixtures

Due to the sensitivity of mycelium to be contaminated with other organisms living in the substrates, it is necessary to sterilize the substrate mixtures and the working environment before inoculation. The sterilization takes place in autoclave chambers. The bags are autoclaved for 45 minutes in 121 degrees Celcius. Since heat kills the spawns and prevents their growth process, samples are cooled down in room temperature overnight prior to inoculation.

Inoculation and Initial Cultivation

Pleurotus Ostreatus (Gray Oyster mushroom) spawn, one of the most common fungal species, is used to inoculate the substrate mixtures. Biohoods provide sterile conditions for inoculation through laminar flows that prohibit germs and other living organisms to enter the environment. Using 8% of water content of each bag (64 g for sawdust samples and 42 g for straw and mixed samples) *Pleurotus Ostreatus* spawns have been added to the substrate bags. Bags are then placed within growth chambers that have 99% relative humidity and a temperature of 24±1 degrees Celcius for cultivation for a total of 14 days.

Mycelium growth in straw bags was faster than in sawdust bags. This is due to the difference of the chemical content of straw and wood and their capacity to feed mycelium during cultivation. The glucans forming wood are more complex than the ones forming straw, resulting in faster digestion of straw by mycelium and faster growth. The bags supplemented with wheat bran also grew faster than the ones without supplements. Mycelium, in addition to carbon, needs nitrogen for cultivation and wheat bran supplement provides mycelium with more nitrogen, increasing the cultivation speed.

Cultivation in Formworks

After 14 days in growth chambers, cultivated mycelium are transferred from bags to formworks to initiate the second phase of growth. Formworks are cubes of 5x5x5 cm3 made of plastic covered MDF and plexiglass (Figure 6). Before transferring the mycelium matter, formworks are sterilized with alcohol. The transfer is done in a sterile environment in four stages and contents are hand-pressed between each stage wearing latex gloves in order to prevent contamination. Afterwards, the formworks are covered with plastic wraps and are kept in a dark environment that has a temperature of 24±1 degrees Celcius for about 3 days.

Drying and Heating

After 3 days in formworks, the samples are taken out of the formworks and weighed. The samples are left to dry on a drying rack for 6 hours using a fan, which led the samples to lose 1/3 of their weight. Consequently, they are placed in the oven for 90 minutes in 90 degrees Celsius, which killed the mycelium and evaporated the water in the samples until another 1/3 of their weight is lost. By measuring the weights and volumes of the samples, and by taking their weight over volume ratio the densities of the samples are calculated. Samples are cooled down overnight before the compression tests.

Compressive Strength Tests

The tests for the compressive strength of mycelium-based bio-composite samples are conducted with a 22 kips Instron test machine. The samples are loaded in the machine as slowly as possible in order to study their behavior in compressive loading and then unloaded to observe their reaction (Figure 7). To evaluate the elastic behavior of the bio-composite samples, their compressive strengths are measured based on the amount of compressive stress which made the samples strain for 20% of their height. The ultimate compressive strength of samples, which is the largest stress they can bear before crushing, are also reported. Table 2 presents the results of the compression tests.

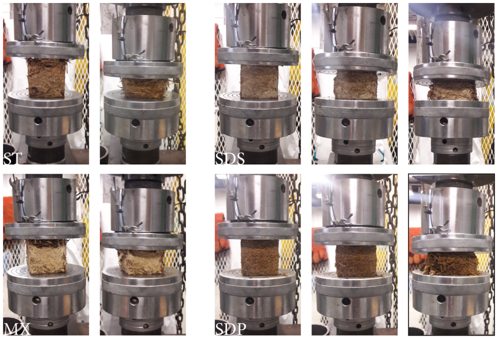

Figure 7
Testing the compressive strength of mycelium-based bio-composite samples

RESULTS AND DISCUSSION

When the densities of the mycelium-based composites are compared, as shown in Table 2, it is clear that the composites cultivated using denser substrates ended up having a higher density: sawdust, being denser than straw, resulted in denser composites. On the other hand, when the densities of the composites cultivated using the same type of substrates with and without supplements are compared, the ones that are cultivated with supplements showed a lower density. This indicates a better growth of mycelium on the substrates, and a relatively higher compressive strength. The stronger nature of the supplemented material was also visually evident before the second cultivation process within the formworks: The supplemented bags were better integrated, with their inner and outer parts homogeneous and coherent, whereas the mixtures without supplements were not. Their outer parts were more coherent however their cores were incoherent and unconfined.

The overall results of the tests did not show significant difference in strength between the mixtures of straw and straw+sawdust, which suggests that straw is more dominant in determining the compressive strength of the composites.. The composites cultivated with straw were able to bear lower

CODE	DENSITY (G/CM³)	STRENGTH (KPA)	ULTIMATE STRENGTH (KPA)
SDP	0.552	145.9	1018.4
SDS	0.493	188	1380.6
STP	0.277	20	72.7
STS	0.192	27	169.2
MXP	0253	29.7	105.9
MXS	0.234	30.5	116.1

Table 2
Results of compressive strength tests

loads compared to the ones cultivated with sawdust, however, they showed elastic behavior - they gained their original length after unloading-, which shows their potential for utilization in other purposes, such as being used as foam substitutes. The sawdust-based composites have significantly higher compressive strength, however, they are not strong enough to be utilized as alternative materials for masonry construction and they would need to be reinforced. Further addition of sawdust to the sawdust+straw composites may make them stronger and have better mechanical characteristics.

When the samples were unloaded, sawdust samples without supplement disintegrated, indicating inhomogeneous cultivation. Their inner part was weak whereas their fungal skin was bearing the load. Sawdust samples with the supplement, on the other hand, deformed but did not disintegrate. Moreover, having a variety of substrate sizes within the composite can affect the integrity and workability of mycelium-based bio-composites, similar to having a variety of grains as aggregate in concrete applications. A complete range of small, medium and large parts in substrates can improve the mechanical behavior of the material. For instance, adding wood chips in various sizes to the sawdust mixture can help to achieve a better integrity and load-bearing capacity in mycelium-based bio-composites.

Another factor that can impact the material strength is the environmental conditions during cultivation. Controlling the humidity and water content in the mixture during cultivation in the formworks are decisive of the resulting material strength. Allowing the material to be cultivated in the formworks for a longer period may also enhance the load-bearing capacity and elastic behavior of the mycelium-based bio-composites.

CONCLUSIONS

Mycelium-based bio-composites, as studied in this paper, are potential substitutes for masonry material in architecture with some desirable features, such as their lightweight, bio-degradability and renewability. In this study the compressive strengths of mycelium-based composites cultivated using different substrates (sawdust, straw, sawdust+straw) are compared. *Pleurotus Ostreatus* (Gray Oyster mushroom), as one of the most commonly available fungal species around the world, is used to inoculate the substrates. The effects of using supplements (wheat bran) on the growth of mycelium and consequently on the load-bearing capacity of mycelium-based composites are also presented. The results show that although the straw-based and mixed specimens show a quite well elastic behavior, their compressive strength was very low to be used in masonry constructions. Moreover, while the sawdust-based specimens yield higher compressive strength, they are also not strong enough to replace conventional masonry materials without introducing any reinforcement.

As previously discussed, the mechanical properties of mycelium-based composites are highly dependent on many factors, including the fungal species used for inoculation, substrates and additives used, growth conditions, cultivation time, and processing and forming techniques. Therefore, this paper presents the initial stages of a more extensive exploration on the potential of mycelium-based composites as an alternative construction material. Future studies can explore the use of other commonly available and fast-growing fungal species, such as *Ganoderma* and *Trametes Multicolor*, to study how they affect compressive strength. Furthermore, the effects of having a variety of substrate sizes during cultivation can be studied. Environmental and process related parameters, such as relative humidity, temperature, and time of cultivation should also sought to be optimized. The process of drying/heating to stop the growth of mycelium and processing techniques can also be investigated.

While the research presented in this paper is a straightforward material study, working with living systems in design fields proposes a novel ontological and epistemological framework for design. First, because the materials are generated - *grown* - by designers themselves: Designers can control and tweak material properties as part of the design process. This implies a design process where the form is not imposed on the material from above but the *growth* parameters and resulting material properties can help determine the form. Second, because *growth* processes are predominantly unpredictable: The inherent uncertainties of these *growth* processes can inform the design process, unexpected discoveries can be made which can benefit the final outcome.

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