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DEVELOPING A COMPOSITE MYCELIUM-GLASS BRICK UNIT

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DEVELOPING A COMPOSITE MYCELIUM-GLASS BRICK UNIT

A THESIS APPROVED FOR THE
CHRISTOPHER C. GIBBS COLLEGE OF ARCHITECTURE

BY

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What if, every time I started to invent something, I asked,
‘How would nature solve this?’

-Janine Benyus

I dedicate this thesis to all the design enthusiasts working at the intersection of biology and architecture. It has been a privilege for me to work and interact with people from various background, besides my familiar domain of architecture. I hope this thesis helps another environment conscious student designer to take a step further and explore the joy of learning from nature while finding solutions for a sustainable design process.

Acknowledgements

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Abstract

There is an increased need to find sustainable building materials for the construction industry as we face challenges such as, global warming, fast depletion of natural resources and fossil fuels. It is difficult to achieve net zero level energy for buildings. The goal is to look at nature to find solutions. We need building materials that use less energy in their life cycle process. Nature is the best teacher around us, as time and again, it shows us how everything around us reacts at normal temperature and does not need extra energy to occur. All our inventions have already appeared in nature such as the most clever architectural struts and beams reflected in lily pads.

With a focus on Mycelium, the vegetative part of a fungus, this research explores its alternate uses as a living brick. For our project we examine the growth properties of Mycelium by combining it with glass to form a new composite material to use.

Growth is one of the natural processes in any living organism, and our project aims to explore the properties of Mycelium as a living material to provide sustainable design solutions. The organism, Mycelium, grows at room temperature. It feeds on natural local feedstock like husk wheat, corn stock, etc., and it can be naturally developed into a fibrous hardened block of Mycelium material. Incorporating such natural organism behavior as innovations in architecture and design will provide a new approach to using composite materials, moving towards a more sustainable future.

This paper consists of conducting hands-on lab experiments to create a new material, a composite Mycelium-glass brick unit, as well as, exploring other properties of Mycelium. Furthermore, we discuss the uses of glass as an aggregate for the Mycelium substrate.

The tools and methodology used for this research are an experimental continuous trial and error, which involves a student focused lab setting. Presently, the experiment yielded unexpected results, however it provides more insight about the properties of Mycelium and combining it with a different material.

Keywords: Mycelium, glass, bio design, Ecovative, fungi, grown materials, sustainable design, composite, biomimicry, light, transmittance, architecture, bonding capacity, Bruce Goff.

Chapter 1: Introduction

We live in a world which is evolving, past the traditional unsustainable methods of production, towards an era of utilizing renewable and recyclable alternatives. One of the fundamental challenges of the current century is to convert our consumerism into an eco-friendly and self-sufficient society which minimizes energy consumption and taking inspiration from nature builds with carbon emissions. Efficient utilization of resources for less production cost and less waste, must be a conscious effort of the society we live in today. We look to nature to see how life on earth has sustained itself to produce elegant solutions to meet the challenges faced by designers, biologists and engineers every day.

Mycelium-based materials are made from renewable sources and can efficiently replace plastics. Mycelium feeds on organic and agricultural wastes. Structurally, Mycelium is a dense network of thin strands, called hyphae, which grows and fuses together into a solid material. The Mycelium acts like a living three dimensional matrix that binds the substrate particles together to produce a dense rigid structure.

Mycelium-based materials are completely bio-based and can be decomposed at the end of their life cycle without causing environmental pollution. Such natural materials share a key element: Life. This fundamental property of such materials provide them with the qualities of self-organization, self-healing, self-repairing and other adaptable behaviors. Hence there is a gradual shifting trend on using Mycelium as a packaging material in place of plastics and foam in the United States. Artists and designers are adapting this new material in making various sustainable products such as MarsBoot footwear designed by Liz Ciokajlo and Maurizio Montalti[19], MycoComposite planter pot and shipping boxes developed by Ecovative[20], ecological lamp and Sinewave panel by Krown led by Eric Klarenbeek[21]. Temporary architectural installations are also realized by designers utilizing Mycelium, one such example being the Hy-Fi tower by David Benjamin of The Living, New York Architects, which was inaugurated in MoMA's PS1 exhibition space in New York. Looking to future, Mycelium-based materials seem to have the potential of being a structural material that can be used in the building industry and thus help reduce the vast amount of construction industry generated wastes.

Currently Mycelium is tested with different materials or used as an alternate 3D printed material. In many cases it is used singularly to make industrial products. For our research we chose to combine Mycelium with recycled fire glass and investigate the bonding capability of Mycelium with glass as a new composite material, under room temperatures.

Since Mycelium is a new material, no valid life cycle cost analysis comparable to other conventionally used masonry is readily available. Research on the bonding capability and structural performance of Mycelium-based materials is limited for the same reason.

The aim of this project is to conduct an explorative research to determine the bonding capacity of a composite Mycelium-glass brick unit by means of experimental testing and giving more insight on the compressive strength and other properties of Mycelium-based materials. The project aspires to achieve this goal in four subparts:

1) Overview (under Introduction) - Define Mycelium, discuss its properties as a material and its current application in the industry. Explain the reason of choice of glass as a material to bind with Mycelium.
2) Methodology - Clarify the experimental method we used for our research using Mycelium, thus, highlighting the sustainable workflow process. Demonstrate how Mycelium follows cradle-to-cradle approach. Perform hands-on research in a student focused creating-making lab to ascertain if Mycelium binds with glass.
3) Results - Conduct compression tests on samples of composite Mycelium-glass blocks to gain insights on the mechanical and other properties of Mycelium-based products.
4) Discussion – Draw analysis from results and check if our research objective was satisfied. In case not satisfied, point out the direction in which the research on this material can be conducted in future.

1.0 Overview

1.1 Mycelium: A part of Fungi

Figure 1: (left to right) Microscopic view of Mycelium[1]; *Mycelium turns white while growing*[2]

Mycelium is the vegetative (stem, roots and leaves of a plant) part of a fungus or fungus-like bacterial colony. Mycelium has been identified as the largest living organism on earth. Fungal colonies composed of Mycelium are found in soil and other substrates such as rock, sand, etc. Through Mycelium, a fungus absorbs nutrients from its environment. Mycelium is vital in terrestrial and aquatic ecosystems for their role in the decomposition of plant material[1].

Mycelium can form a small or an extensive fungal colony in nature. Through Mycelium, a fungus absorbs nutrients (carbohydrates, fat, protein, water) from its environment. This occurs over a two-stage process. In the first stage, the hyphae secrete enzymes into the food source. This breaks down biological polymers into smaller units such as monomers. In the second stage, Mycelium absorbs these monomers by facilitated diffusion and active transport.[22]

As Mycelium feeds on nutritious organic materials, it transforms and binds the separated particles in a cohesive matter, *acting as a living glue*.

In nature, Mycelium grows quickly. Their growth process is influenced by knowing how and when to alter input parameters (extension of hyphae in reaction to substrate materials, speed of penetration of Mycelium, etc.). Mycelium reaches high efficiencies in normal conditions. Acting as a glue under suitable conditions, Mycelium produces solid blocks at room temperatures.

By introducing alternate natural materials in place of traditional high-energy consumables, we work towards bringing a radical change in the current sustainability standards of the industry.

1.2 Mycelium: Categorization

Sustainability in its basic sense is a broad and complex concept. It has become a significant aspect of all projects in the building industry. The idea of sustainability involves enhancing the quality of life, thus allowing people to live in a healthy environment, with improved social, economic and environmental conditions[3]. A sustainable project is designed, built, renovated, operated or reused in an ecological and resource efficient manner. An ideal project should be (1) Inexpensive to build (2) Last forever with modest maintenance (3) Return completely to the earth when abandoned[3]. While mentioning sustainability, the term "green" materials comes into context. The concept of green materials is known to us but the term itself is ambiguous and vague in nature with no general consensus defining its domain. A study performed by the University of Wolverhampton and the University of West of England[3] concluded that the criteria for defining such green materials are vast and they produced a flowchart reflecting how extensive the term is:

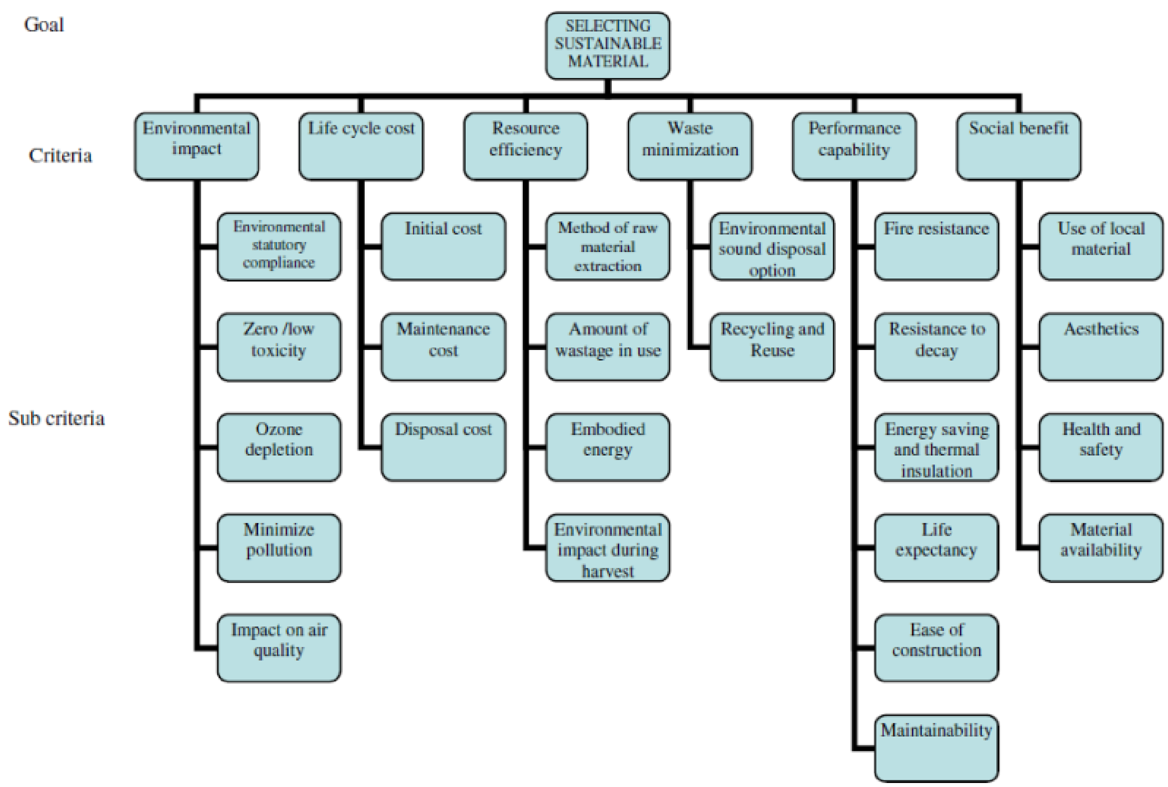

Figure 2: The extensive field of sustainable materials[3]

Mycelium is a sustainable "green" material and it could be categorized under Bio-based materials. A Bio-based material is defined as follows:

"A material of which at least one of the components can be biologically grown and is fully renewable[3]".

Under selected categorization performed by R.J.J. Lelivelt and published in the paper "The mechanical possibilities of Mycelium materials" [3], Bio-based materials can be sub-divided into the three following categories: (1) Used-as-grown materials (2) Engineered woods (3) Composites. Used-as-grown material requires little or no processing to be used such as wood, bamboo. Engineered woods are made from processed wood, wood-waste or wood-like materials such as MDF, Fiberboard[3]. Composite material consists of a high-strength reinforcement and a high-ductility matrix[3]. The composites are further divided based on their matrices. They are grouped broadly into (i) Mineral matrices (ii) Petroleum-based matrices (iii) Starch-based matrices (iv) Mycelium-based matrices. Thus Mycelium is a Bio-based material belonging to the family of Composites.

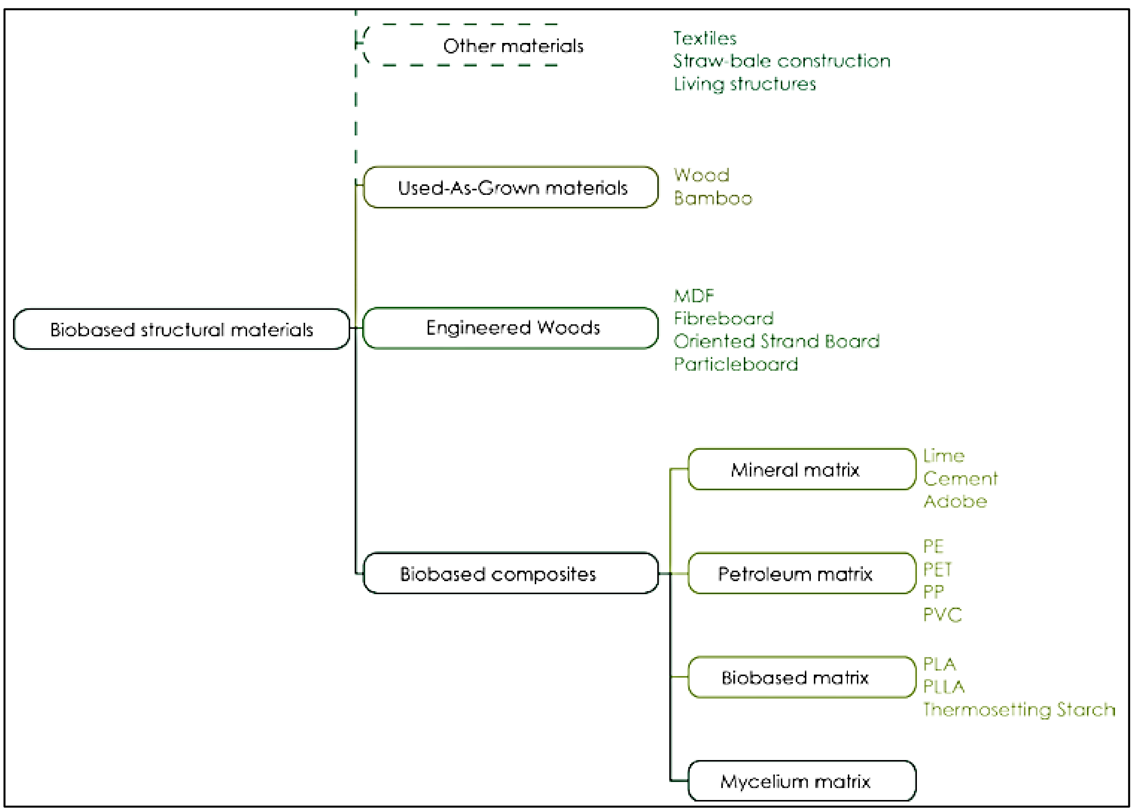

Figure 3: Schematic representation of sub-categories of Bio-based materials[3]

1.3 Mycelium: Structural Composition

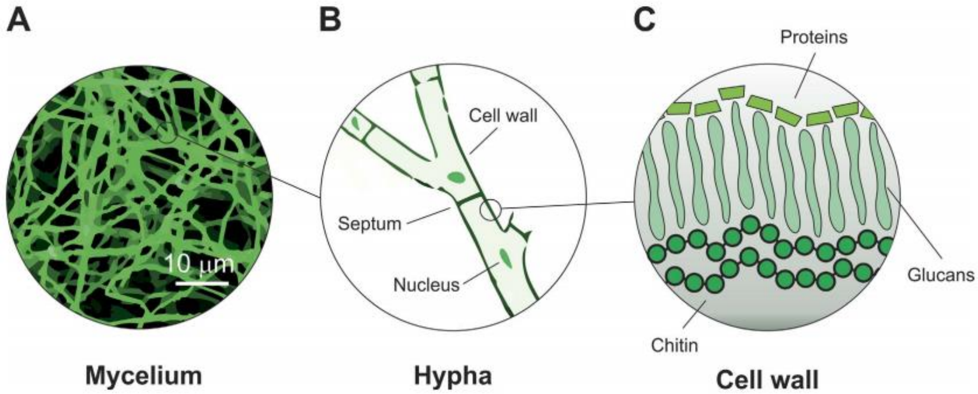

Figure 4: Optical microscopic image of a Mycelium film showing hyphae, septa and cell wall[4]

Mycelium is chiefly composed of [4] -

1) Hyphae - The filaments of the fibrous Mycelium are called hyphae and consist of elongated cells. The growth of hyphae occurs through extension of the cell membrane and cell wall at the hyphal tip. The mass of hyphae is called Shiro.
2) Septa - These cells are separated from each other by internal porous cross walls, named septa.
3) Cell wall – All the parts are enclosed within a tubular cell wall. The cell wall plays several physiological roles in fungi morphogenesis, protecting the hyphae and providing the mechanical strength to the whole mycelium. The cell wall is composed of:
    1. Chitin - A fibrous substance consisting of polysaccharides and forming the major constituent in the exoskeleton of arthropods and the cell walls of fungi.[23]
    2. Glucan - A glucan is a polysaccharide derived from D-glucose, linked by glycosidic bonds.[24]
    3. Protein - An outer layer of proteins such as mannoproteins and hydrophobins.

1.4 Mycelium: Anastomosis, Process of Growth

Anastomosis is the ability of two different hyphae to fuse together when they meet. Anastomosis is fundamental for formation of a fast growing Mycelium as it allows the creation of large networks[3]. Larger networks signify the fact that nutrients can be transported between areas having different concentrations of nutrients due to pressure difference. This phenomenon facilitates a homogeneous growth of the colony in all directions leading to a more homogenous and faster colonization of the substrate[3]. Another benefit of Anastomosis is that it creates a stronger Mycelium[3]. As all the hyphae are interlinked, the resulting mass is more condensed, and able to spread stresses much more efficiently than Mycelium without Anastomosis[5].

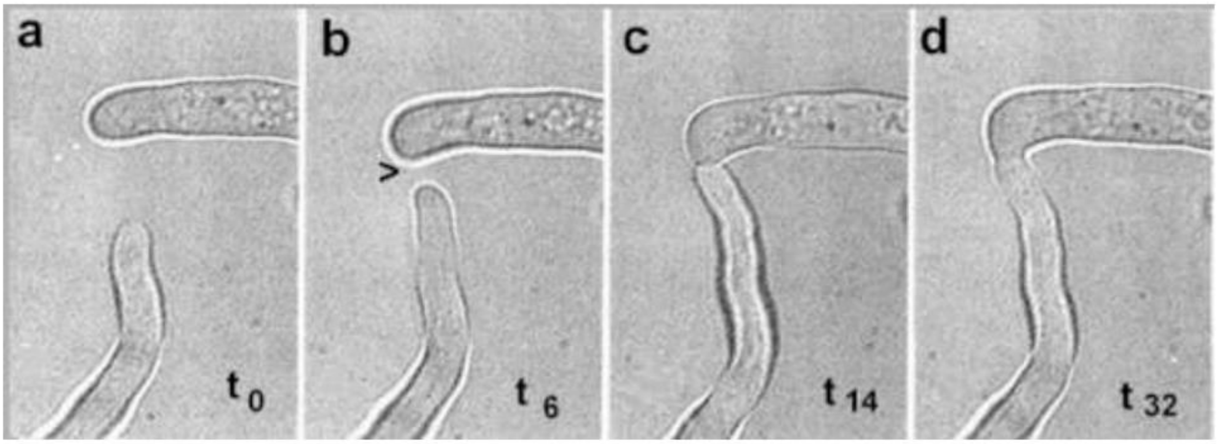

Figure 5: Anastomosis, the process of fusion of two hyphae strands[5]

1.5 Mycelium: as an Adhesive Agent

The single most important property of Mycelium which has been extensively used for our research is that Mycelium acts as an adhesive agent. Being an adhesive agent it helps combine substrate particles together to form a uniform cohesive block. Mycelium bonds itself with its substrate by growing hyphae through the substrate. This creates a more mechanical than chemical bond.

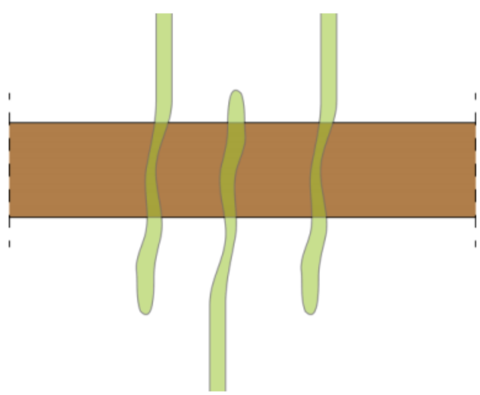

Figure 6: Schematic diagram of hyphae bonding with substrate: mechanical bonding[6]

Mycelium acts as a binding agent functioning as follows:

i. Growth - The growth of hyphae, filament members constituting Mycelium, occurs through extension of the cell membrane and cell wall at the hyphal tip.

ii. Binding - Mycelium has strong binding properties. It processes nutrients from wood, straw, hulls, corn cobs, nut shells, etc. by using enzymes to convert cellulose present in the substrate into chitin, a strong compound found in crustacean exoskeletons, which then binds the substrate particles together.

iii. Breakdown - Mycelium attacks by penetrating the substrate (sawdust, agricultural waste, etc.) by physical pressure and enzymatic secretion in order to break down biological polymer into easily absorbed and transported nutrient, like sugar.[4]

iv. Adhesive agent - The chitin inside the cell wall of Mycelium acts like an adhesive joining substrate particles (sawdust, agricultural waste, etc.) together to form a fiber like network structure which gives shape to various forms.

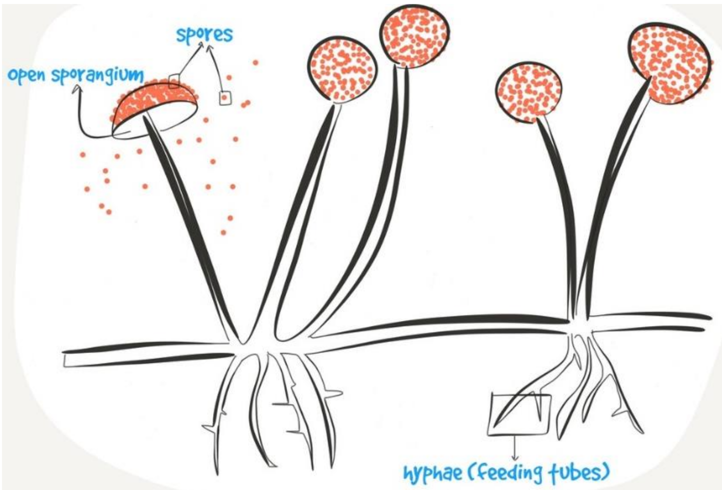

Figure 7: Schematic representation of the parts of a fungi[7]

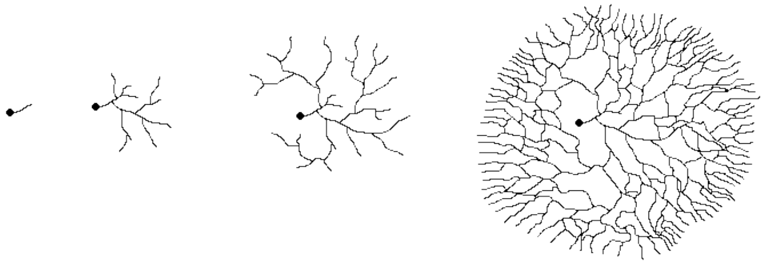

Figure 8: Growth of Hyphae tip[8]

1.6 Process of Substrate Penetration

Mycelium penetrate their feeding substrates by physical pressure and enzymatic secretion thus facilitating the breakdown of biological polymers into simple elements that could be easily absorbed. It grows due to its symbiotic relationship with the materials that it feeds on, forming entangled networks of branching fibers. [4]

1.7 Ecosystem

Mycelium is vital in terrestrial and aquatic ecosystems for their role in the decomposition of plant material. They can be re-used over and over again. At the end of their life cycle they mix with the soil and become a part of the Mother Nature. As they mix with the soil at the end of their life cycle, their decomposition releases carbon dioxide back into the atmosphere.[9] Fungi transform organic matter into forms that can be utilized by other decomposers, and into food for plants.[25]

1.8 Symbiotic Relationship

Mycelium grows by symbiotic relationship with the materials that feed on it, forming entangled networks of branching fibers. Symbiotic relationships are a special type of interaction between species. They can be beneficial, or harmful. But these relationships are essential to many organisms and ecosystems. They provide a balance that can only be achieved by working together.[26] Mycelium grows by a symbiotic relationship with other materials (sawdust, agricultural waste, and wood-stock) on which it feeds forming branching fibers. Symbiotic relationship in fungi or symbiosis are associated with plant roots. This relationship is mutually beneficial because fungi facilitate the transfer of nutrients from the soil into plant roots, and in turn receive carbon from the plant. Carbon is stored by fungi in the soil and used to build hyphae that extend into the soil.[22]

1.9 Selection of Fungi

There are various species of fungi available to use. The criteria for selecting the appropriate fungi depends on (1) The rate of growth of fungi that produces dense Mycelium(2) The availability of fungi (3) The conditions required to grow the fungi. For example Mycelium obtained from Oyster mushrooms grows under relatively simple conditions while Champignon mushrooms are difficult to produce without special equipment and expert knowledge[6]. For our research we obtained Mycelium commercially from the company Ecovative, New York. The type of fungi used by Ecovative is P. Squamosus.

	Possible fungi	Source
	P. Ostreatus (Oyster mushroom)	Used by designer Maurizio Montalti [37]
	C. Versicolor (Turkey tail)	Recommended by substrate cultivator Mycobois [43]
	G. Lucidum (Reishi mushroom)	Used by artist Philip Ross [37]
	P. Squamosus (Dryad's saddle)	Used by packaging company Ecovative [44]

Figure 9: Illustration of types of Fungi used currently in industry[6]

1.10 Selection of Substrate

The selection of appropriate substrate plays a significant part in the process of growth of Mycelium. Some of the selection criteria are (1) The substrate should possess high cellulose content. Fungus receives its nutrition from glucose. A fundamental difference between fungi and other organisms is that fungi can break cellulose into glucose. This refers to the fact fungi grows rapidly in cellulose-rich environment unlike other organisms. Using a cellulose-rich growth environment helps prevent contamination by other organisms[6]. Thus agricultural feedstock is a good choice for substrate as most agricultural crops have cellulose as their structural compound. (2) The substrate needs to be locally available. If the substrate material needs to be shipped from a far-way place the process cannot be sustainable. (3) The substrate needs to be chemically compatible with the chosen fungi. Some plants have special compounds to prevent the growth of fungi inside them. Other plants, such as hemp have a natural anti-infecting wax layer that makes them less susceptible to malicious micro-organism and lowers the need for sterilization[6].

1.11 Process of Growth of Mycelium-Based Material

For our research we purchased Mycelium-based material from Ecovative, New York. The ordered Mycelium comes in a bag with a filter patch which allows Mycelium to respire. There are three basic steps that the company manual recommends users to follow[27] (1) Shake it: This involves adding flour and water to the dry Mycelium bag, at room temperature. This reanimates the Mycelium. The amount of water and flour to be added is generally specified on the surface of the bag of Mycelium and depends on the type of blend used. The mix of Mycelium, flour and water is then thoroughly shaken inside the bag so that no dry part of Mycelium is left untouched. The bag is then sealed tight with clips, making sure to keep the filter patch uncovered[27]. (2) Make it: (4-5 days) This is the stage which involves giving shape to the moist Mycelium mix in desired growth containers. The Mycelium is taken out of the bag and again mixed with flour in a large mixing bowl. It is necessary to break chunks of Mycelium into smaller parts and form a uniform mix. Then the mix is poured in the molds. The top surface of the mold is covered to prevent contamination with bacteria leaving a few holes on the surface to allow air exchange. All equipment and work surface used at this stage is sterilized[27]. (3) Bake it: (5-6 days) The Mycelium block, which should by this time grow and harden to form a white solid mass, is taken out of the molds and heated in an oven for 3-4 hours at 250 degree Fahrenheit or under the sun (in places having a good exposure to sunlight), to stop further growth of fungi. The baked Mycelium block is ready to use[27].

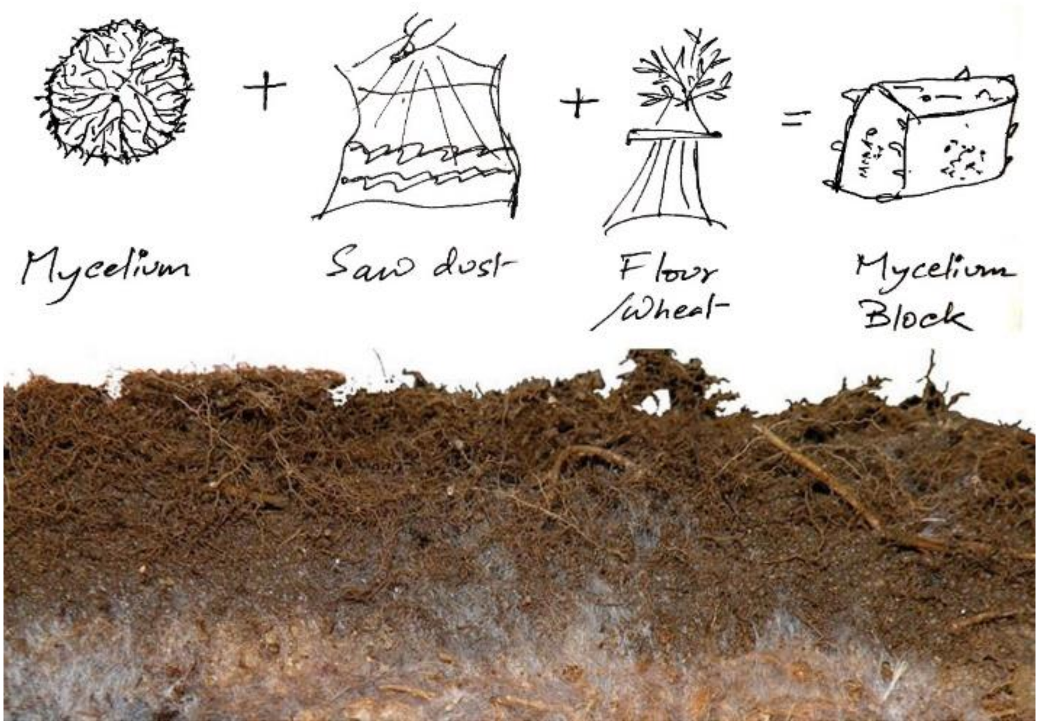

Figure 10: Process of mixing of Mycelium with substrates

The following steps further detail out the reactions performed by Mycelium at every stage:

1) Shake it: Due to the vigorous shaking & mixing the dormant Mycelium starts absorbing nutrients from the flour and spreads root-like hyphae. Growing from moist particles, the individual white strands intertwine to bind particles together. With each passing day the bag turns whiter as Mycelium colonizes and covers the entire surface of the bag. Condensation occurs in the bag as Mycelium respires, converting glucose and oxygen into carbon dioxide, water, and ATP (Adenosine Triphosphate) [27].

Figure 11: Opening and mixing a bag of Mycelium-based materials/Stage 1 [9]

2) Make it: This is the step where fabrication of the mix occurs. A large amount of stress is developed when the contents of rehydrated Mycelium mix is broken into smaller parts. It is important to provide extra nutrition to Mycelium by adding extra flour[27]. They go into making the bonds stronger. When poured into the growth containers the Mycelium grows exponentially and fills in all the gaps of the container, binding the loose particles like a natural glue. Sanitization is an important step in this process to prevent growth of external bacteria.

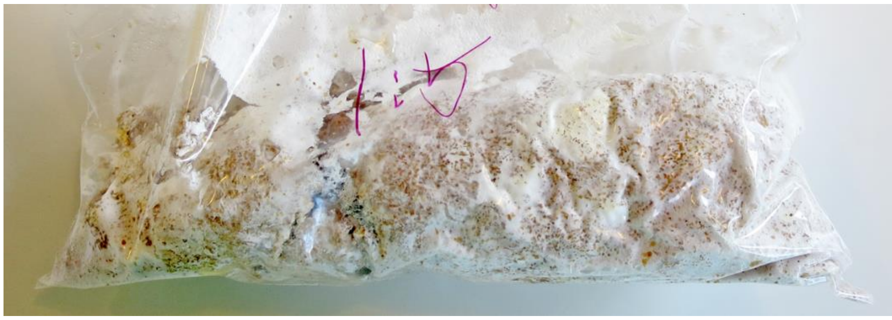

Figure 12: Growth of Mycelium after Rehydration/ Stage 2 [9]

3) Bake it: Heating and drying the Mycelium block removes all the moisture and eliminates the ability of Mycelium to grow further. In general the heating is done in a normal baking oven at 250 degree Fahrenheit for 3-4 hours. In case an oven is not available, it is also possible to dry the moist Mycelium block by placing it under the sun or a fan[27]. However care should be taken to prevent humid condition in the environment at this stage which could reanimate the Mycelium.

Figure 13: (left to right) Baking oven in Lab; Mycelium block after baking [9]

Figure 14: : (left to right) Demonstration of the process of making a Mycelium planter [2]

1.12 Cradle-to-Cradle Approach of Mycelium: Sustainability

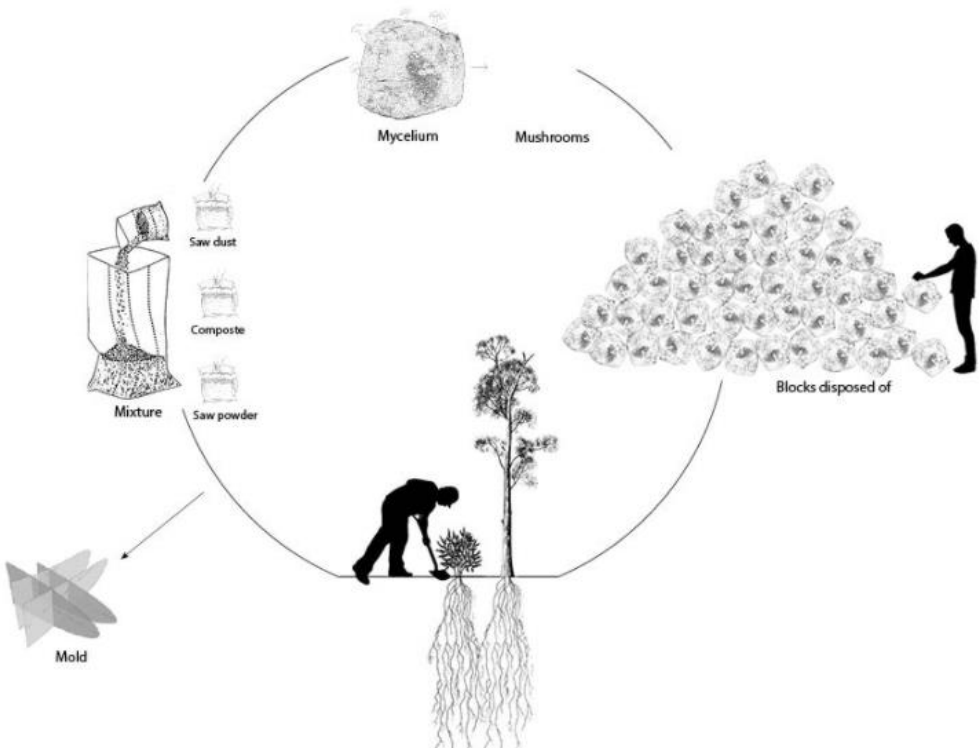

Figure 15: Life cycle of Mycelium [10]

The aim of this project, among others, is to highlight the sustainable properties of Mycelium and demonstrate how it follows a cradle-to-cradle life cycle process adding value to the environment.

Cradle to Cradle (C2C) concept (by William McDonough and Michael Braungart (2002): Cradle to Cradle®: Remaking the Way We Make Things;) is an approach for designing intelligent products, processes and systems taking into account the entire life cycle of the product, optimizing material health, recyclability, renewable energy use, water efficiency and quality, and social responsibility[28].

The design takes its inspiration from nature, in which all materials used can provide "nutrition" for nature or industry, maximize material value and safeguard ecosystems[28]. The purpose of the Cradle to Cradle design is to restore continuous cycles of biological as well as technical nutrients with long terms positive effects on profitability, the environment and human health[28]. A C2C product is designed so that all of its materials are selected to safely cycle within either a biological or technical metabolism and to be reused or recovered at their highest possible value[28].

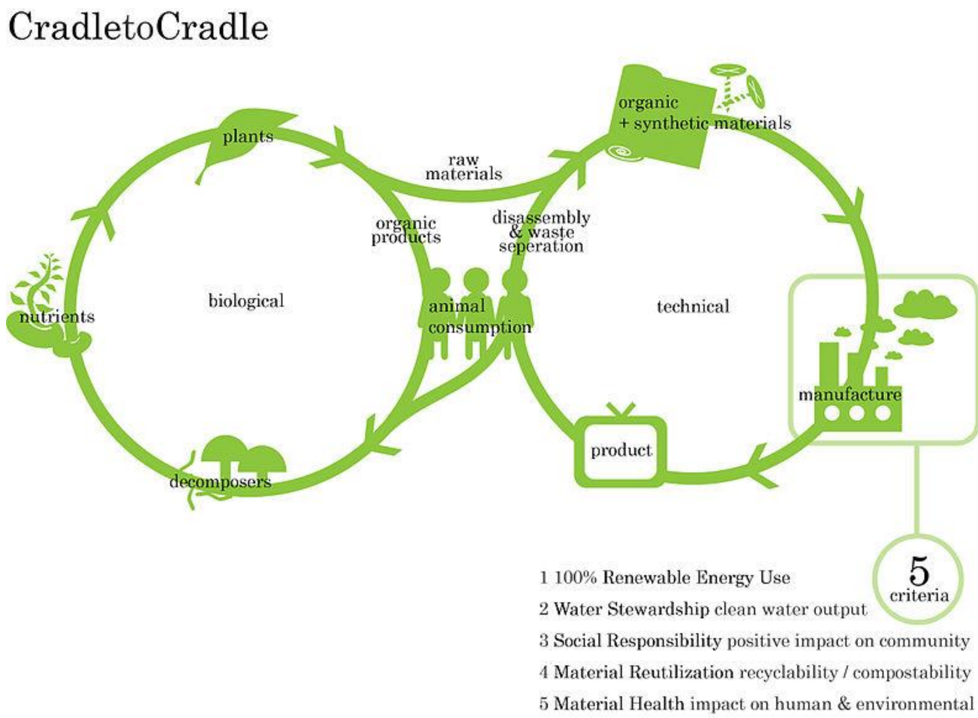

Figure 16: Cradle to Cradle design, McDonough and Braungart model[11]

Mycelium-based materials are natural polymeric composites (chitin, cellulose, proteins, etc.) that require minimum energy for production (self-growing), and their characteristics can be changed by modifying their nutrient substrates[4].

Mycelium are agricultural products of biological origin and can be grown on agricultural wastes, agro-industrial wastes or even industrial wastes. It can play major roles in decomposition and nutrient cycling making it an element of significant value in terrestrial ecosystems. The substrate on which Mycelium feeds can be obtained locally. This makes the product ideal for manufacturing all over the world. The raw inputs of the material are selected based on regionally available agricultural byproducts[29]. By manufacturing regionally, and using local feedstock, transportation of raw and finished materials could be minimized thus making the production process sustainable. After its use at the end of the life cycle, Mycelium-based materials could be conveniently left in the backyard to get decomposed in a few weeks. Hence the material is completely bio-degradable. Mycelium breaks down when exposed to the atmospheric conditions facilitating decomposition. Being all organic, the material gets composted easily. Thus Mycelium successfully follows a C2C life cycle.

For our research, we used recycled fire glass, a by-product from industries, to combine with Mycelium. The broken glass at the end of its life cycle could be reused again and goes back into the system. Hence the composite material as a whole is never wasted and represents a complete C2C cycle.

1.13 Advantages of Using Mycelium

1. Natural Adhesive

   Mycelium is a microscopic fibrous network of fungus that binds itself to its food source creating a strong, resilient matrix in any shape desired. This adhesive property of Mycelium can be utilized in making bricks at room temperature to replace the traditional brick masonry units which require high temperatures and need to be fired in kilns. Mycelium is a natural binding agent that can work with agricultural products and wastes such as oat husks to make an incredibly durable material that could replace Styrofoam and polystyrene in practically every application[29].

2. Easily available raw materials

   The raw materials needed to produce Mycelium bricks are corn stalk (waste material from farms), saw dust, agricultural waste, etc. which are locally available and eco-friendly[9].

3. Low-cost

   Structures grown out of Mycelium are low-cost as it requires raw materials which are easily available and uses indigenous manufacturing processes. This could help serve diverse communities with low income groups and create low-cost housing options in places having economically lower classes of people.

4. Less construction expertise

   The process involved in making Mycelium bricks is simple and straightforward. It does not involve high technology or expertise. This could be advantageous allowing people with no expertise in construction techniques to build their own homes.

5. Comparison with conventional brick masonry

   The manufacturing process of conventional masonry brick (a) Requires a very high temperature kiln firing (900-1000 0 C)[30] and (b) Releases a substantial quantity of greenhouse gases (Ahmari & Zhang, 2012). Manufacturing of glass bricks produces two types of air emissions: (i) Those from the combustion of fuel for operating the glass-melting furnaces, and (ii) Fine particulates from the vaporization and recrystallization of materials in the melt. The emissions from fuel combustion include greenhouse gasses like sulfur oxides (SOx), nitrogen oxides (NOx), and particulates, which contain heavy metals such as arsenic and lead[31].

   On the other hand, Mycelium brick units can be (A) Produced at room temperatures and (B) Do not require firing. Notably, (C) Mycelium does not release any harmful toxic gases pre or post production. (D) Mycelium bricks decompose at the end of their life cycle by mixing with the soil and (E) Do not cause any pollution at the end of its life cycle.

6. Short span of manufacturing time

   Bricks of size 8/4/2 inches can be grown in two weeks, and the process produces no waste or carbon emissions. However the manufacturing time will depend on the size of the molds.

7. Cradle-to-Cradle Life Cycle

   When a structure made of Mycelium is taken down at the end of its life cycle, the building components can be composted and turned into fertilizer for the soil. Thus every component returns back to the soil and adds nutrients.

1.14 Current Uses of Mycelium in Construction

1. Manufacturing companies such as Ecovative[32] in New York uses Mycelium in places where compressive strength is important but tensile, flexural, and torsional strength are not, such as in packaging material and insulation.

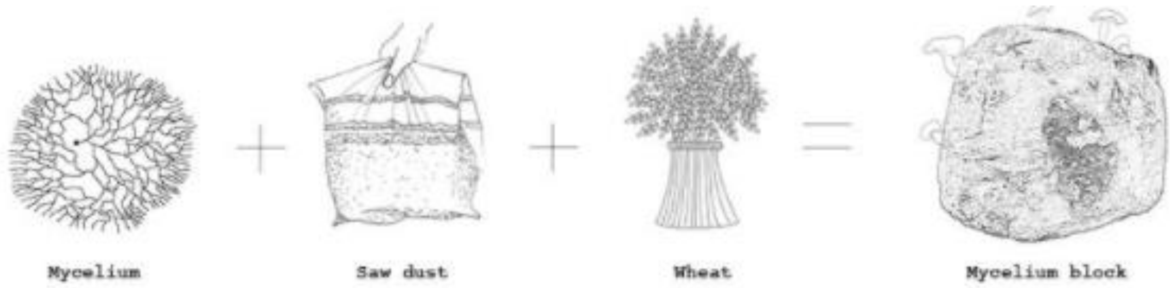

Figure 17: Process of mixing of Mycelium with substrates to form a solid block [10]

2. Application of Mycelium in the form of construction of an organic brick structure has been made in the "Hy-Fi" tower inside the Museum of Modern Art, New York by architect David Benjamin of New York Architects.

Figure 18: Mushroom Tower by David Benjamin [12]

3. Dutch designer Eric Klarenbeek uses 3D printing technology to make furniture out of fungus. Working with the University of Aachen, Klarenbeek developed a way to 3D print with living cells instead of plastic or metal.

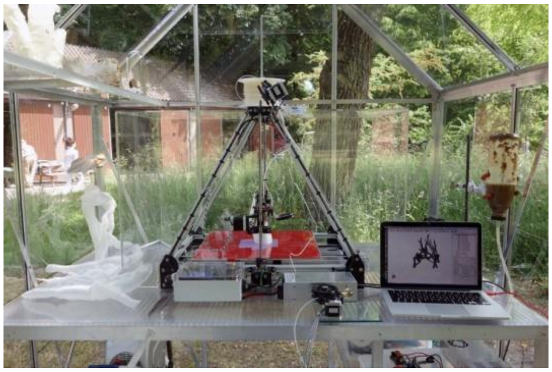


Figure 19: (left to right)Mycelium 3D printer; 3D printed chair, Klarenbeek [13]

4. Philip Ross, an artist and architect of Mycoworks[33], San Francisco, has been exploring uses of Mycelium combining with leather to make various products in a more sustainable way than how it is produced traditionally from animal hides.
5. Others working with Mycelium include :
   - Designers, Grace Knight and Danielle Marino, who set the mushroom stage for Synbiobeta 2018. Having industrial Design degrees, they both chose to work with this material. The woodworking knowledge of Grace and CNC router molding expertise of Danielle helped shape the stage.
   - Théo Chauvirey, doing Masters in Design, Concordia University, Montréal, QC, investigates the use of Mycelium as a material to be used in public transport system – as an alternative to plastic for making chairs in metro trains.
   - Merjan tara Sisman and Brian Mcclellan (students who make chairs and pendant light fixtures)
   - Ford Motor Company (who is teaming with Ecovative to replace plastic and foam car parts with mycelium material)
   - Shigeru Yamanaka (who filed the first patent in 1989 for using mycelium to bond fibers together into a fabric or paper)
   - Jonas Edvard (whose MYX lamp shade made of oyster mushrooms grown on hemp and linen grows mushrooms which can be eaten a few weeks after it is purchased).

1.15 Literature Review

Plastic as a waste for construction

As we look around today, the most noticeable feature in our daily lives is the existence of plastics, Styrofoam boxes or cups. It is compelling to note that how inspite of having knowledge of the corrosive effect plastic brings to the environment we have reluctantly grown dependent on using them, creating a huge toxic circle of plastic waste encapsulating us. Plastics still dominate the entire process of production and supply in most of the working industries in today's world. Some 18 billion pounds of plastic waste flows into the oceans every year from coastal regions, which is equivalent to five grocery bags of plastic trash sitting on every foot of coastline in the world. 40 percent of plastic produced in packaging is used just once and then discarded[14].

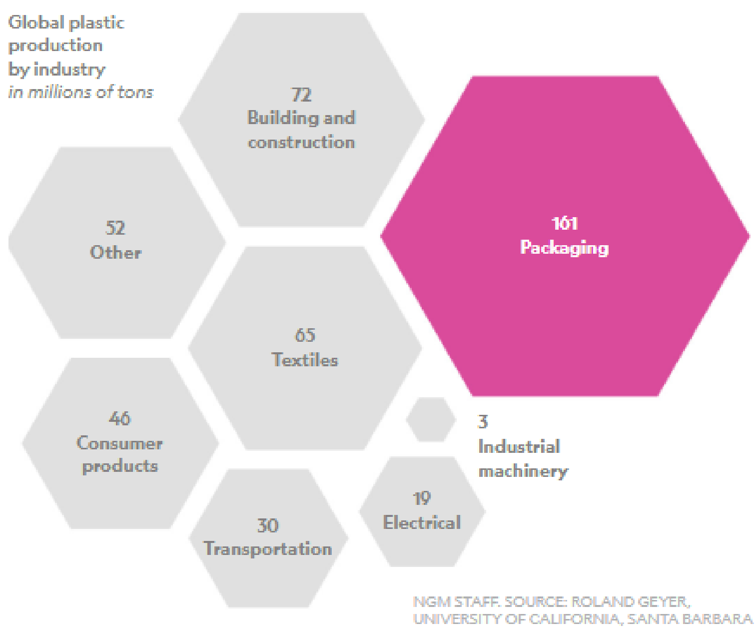

Figure 20: Global Plastic production by Industry [14]

Now looking towards the Construction industry, in a report published by the Construction Dive[34] analyzed from Transparent Market Research data, the volume of construction waste generated worldwide every year will approximately double to 2.2. Billion tons by the year 2025. Construction waste as classified in the report includes materials from excavation, roadwork and demolition, as well as complex waste like plastics, metal, ceramic and cardboard. According to the report, wastes consisting of building materials such as wood, shingles, asphalt, concrete and gypsum add upon a large part of the construction waste[35]. The disposal of such construction waste is hazardous and harms the environment by increasing pollution. The construction debris consisting of paper, plastic, cartons, etc. pile up to create a permanent impermeable layer on our topsoil.

Waste management in the construction industry should be top priority. Managing wastes at the production level as well as on job-site is critical. Proper management of waste is necessary to create a safe and healthy environment for the population. Cost savings from a project can also be increased if there is proper waste management on site that can lead to reusing resources and valuable materials.

Figure 21: Proposed uses of Mycelium to replace plastics

Biomimicry

One of the first educators in the concepts of Biomimicry who pointed out the importance of learning from nature is Janine Benyus. In one of her interviews she explained Biomimicry (from bios, meaning life, and mimesis, meaning to imitate) as a science that studies nature's best ideas and then imitates these designs and processes to solve human problems[36]. Janine thinks of Biomimicry as "innovation inspired by nature" [36]. In her book Biomimicry in Architecture[37], she reflects examples of natural organisms seeking environmental solutions through innovative biological methods. The author explains how Nature can be our mentor and instead of extracting from nature to fulfil our needs we can learn from it to solve our problems. The book spells out that the wisdom to live sustainably is not only indigenous to the aboriginal tribes of our countries but also to species that have lived on Earth far longer than humans. Janine shifts her argument to design by discussing, how the central air conditioning system that surrounds us 24/7 has already been used indigenously by cooling termite towers. Even the first ever humane produced Ford car wheels was already prevalent in the tiny rotary motor that propels the flagellum of the world's most ancient bacteria[37].

Our paper has Biomimicry at its very core. We use the indigenous growth properties of a natural object and incorporate those behaviors to make a composite sustainable material.

In the paper titled "Patterns of Growth—Biomimetics and Architectural Design" [38] the author discusses the experiment conducted using two different species of fungi: Reishi and Oyster, cultivated on shredded recycled materials of straw, wood, and paper. It indicates how Mycelium is one of the most incredibly fastest growing organisms found on the earth surface and thus grow in abundance. Being renewable, it's potential for use in the construction industry seems enormous.

Industry application of Mycelium

There are predominantly two companies in the United States who are conducting research on Mycelium. They are either using it as a packaging material or making various products out of it. (1) Ecovative, a company based in New York, uses Oyster mushroom mycelium by growing them on local agricultural waste products (2) MycoWorks, in San Francisco Bay area, produce materials using Reishi mushroom feeding on sawdust, textiles or industrial waste under the guidance of designer Philip Ross. Investigating the effects of pressure, gas exchange and air filtration on the strength of Mycelium the artist and designer Philip Ross has earned the patent of using this product back in 2012 (US Patent 20120135504 A1). [9]

In the Netherlands, designer Eric Klerenbeek is 3D printing mycelium by combining it with bioplastic to create new objects as a substitute for PLA. As per their website [39] Studio Klarenbeek and Dros are exploring ways of 3D-printing living organisms, such as Mycelium, in combination with local raw materials to create products with a negative carbon footprint. Instead of using plastics, they collect local land-waste, and use Mycelium to bind it all together. Their 3D printers are self-built consisting of X, Y, Z axes and print objects by using Mycelium substrate mix as a fluid, thus building by layers.

In the Netherlands, Maurizio Montalti, the founder of Officina Corpuscoli, is actively collaborating with different groups of professionals to give rise to alternate advancement in society. In his "Growing Lab" he is using Mycelium and other natural life forms to create new opportunities for the design industry.

Figure 22: Products manufactured in the Growing Lab by Maurizio Montalti[40]

Studio Murmur, Chicago

A materials research team from Studio Murmur [9] explored the uses of Mycelium for construction. In the paper titled "Mycelium Material Study" by Studio Murmur, the study investigates the formation of a new material by using various cellulose rich waste material substrate such as straw, sawdust, grain hulls, etc. with Mycelium and letting each composite to grow together. The spawn used is from the Reishi mushroom which grows onto the substrate and forms Mycelium. The paper explores the effects of different substrates and different mesh-like support materials on the strength and tactile qualities of the new material formed with Mycelium. According to the report published by Studio Murmur, the process took 2 weeks in the inoculation stage and another eleven (11) days for final colonization on the support material viz. metal meshes like hardware cloth and poultry netting. [9]

Defining its properties, the report by Studio Murmur [9] explained Mycelium as the vegetative part of fungi composed of thin hyphae, the root-like structures which allow the fungus to absorb nutrients from its substrate. It is known from the experiment conducted by Studio Murmur that Mycelium has strong binding properties and processes nutrients from wood, straw, hulls, corn cobs, nut shells, etc. by using enzymes to convert cellulose in the substrate into chitin, a strong compound found in crustacean exoskeletons. As explained before, the chitin, acting like an adhesive, joins substrate particles together to form a cohesive block.

Mycelium as an alternate renewable source

In the article published in Scientific Reports in January 24 2017 titled – "Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties" [4] the author talks about how in today's world with the growing needs of people to turn to renewable resources of energy, different kinds of polymer are made from natural resources like cellulose, lignin, pectin, plants, proteins, polyesters from bacteria, etc. materials which are biodegradable. The downside for manufacturing such materials is that their process of production is expensive and longer which takes more time and is difficult to extract from bio resources which makes them costly in production and to be manufactured in smaller scale. For these reasons even if they are eco-friendly they cannot be manufactured for being so expensive and having limited uses. The paper talks about a different strategy of overcoming the defects of the above processes and inventing a new material using composite biomaterials and controlling their properties at the time of growth while reducing the expensive costs of production or finer manufacturing processes. It discusses about the application of such strategy by using Mycelium.[4]

Glass: an ancient material in use

Glass is a material that dates back to the ancient times. It first appeared as glass beads in the fourth millennium B.C. in the Egyptian Tombs. Used in terms of a decorative or structural element glass has an important place in the history of building and architecture[41]. Glass being viscous can be molded into any shape and have been used by masons in construction since ages to reflect light into the interiors. It is made essentially by heating ordinary sand to high temperatures until it turns into a liquid and is then solidified into different shapes and transformed into brilliant architectural forms and materials. Apart from having obvious aesthetic values and flexibility in design, glass represents a symbol of progress and modernity. As we look around us almost every building façade and interior incorporates glass as one of its most vital building element.

1.16 Proposed applications of Mycelium

1. Interior construction

   Mycelium can be used as an interior feature wall.
2. Temporary installations

Mycelium has been used in making temporary installations such as the Hy-Fi Tower. However the life-span of such structures is a question that needs to be delved further.

3. Low-cost Housing

   Mycelium structures utilize local materials and cheap labor. No special expertise or equipment are necessary. So Mycelium can be used as an excellent alternate material for low cost housing. Nonetheless, the safety and living conditions of people living inside such structures over a certain span of time needs to be investigated further.

4. Computational Design and Fabrication

   Mycelium blocks can be customized and fabricated by computational design and used for research demonstration in building a pavilion. Lever, who leads the Sustainable Construction Unit at Karlsruhe Institute of Technology, and Block, who founded the Block Research Group at ETH Zurich, have created a tree-shaped structure consisting entirely of Mycelium.[15]

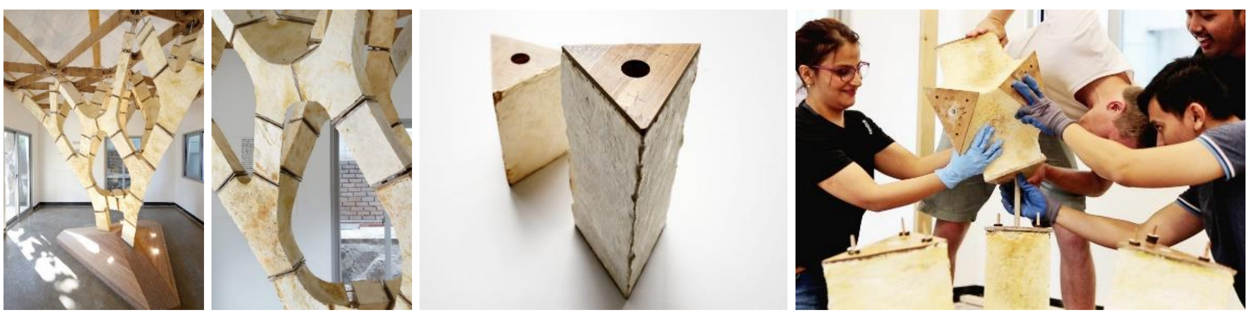

Figure 23: MycoTree, an installation, consists of dozens of mycelium components that support each another in compression. These components are attached to one another with a system of bamboo endplates and metal dowels – but it is the Mycelium that is taking all the load[15]

1.17 Reason for Choice of Glass

We chose to combine Mycelium with glass for our research. The hypothesis is to give rise to a composite brick having reflectance properties. The contextual relevance was drawn from the design pedagogy of Bruce Goff, an American architect native to Oklahoma's soil, who introduced recycled colored (blue "culled") glass in most of his projects to create an eclectic design identity. Historically, glass has been proven to symbolize innovation and advancement in construction. For our research we use recycled fire-glass with Mycelium and propose to create a composite translucent brick unit which could be used as an interior feature wall reflecting light.

The aim is to be able to pass light through the composite Mycelium-glass brick and into the interior spaces of a structure. It is proposed that using glass with Mycelium would help substitute for other conventional masonry such as glass bricks and reduce pollution besides making it less expensive.

For our research we used recycled broken glass ordered from Amazon (it is recommended to use broken glass available from car factories locally which was not available in this case). We know that light reflects when it hits a glass surface. This happens due to the reflectance properties of glass. A part of the ray of light which falls on a glass surface gets reflected, a part gets transmitted and another part gets absorbed. This transmittance property of glass is proposed to be utilized for our research. It is assumed that the composite Mycelium glass brick formed will be able to transmit light through its surface.

Figure 24: Christ Redeemer Church designed by Bruce Goff in Bartlesville, Oklahoma[42]

Figure 25: Christ Redeemer Church designed by Bruce Goff in Bartlesville, Oklahoma[42]

Figure 26: Illustration showing similar uses of blue "culled" recycled glass: Christ Redeemer Church designed by Bruce Goff in Bartlesville, Oklahoma, and the glass brick grown in lab

Chapter 2: Methodology

The adhesive property of Mycelium forms the basis of our research process. The methodology we use for our research involves experimental hands-on continuous trial and error process. This happens in a student-focused learning lab setting called the Creating_Making Lab under the College of Architecture at the University of Oklahoma

Materials required: The basic ingredient, (1) Mycelium, required for this experiment was obtained from Ecovative, a company based in New York, which spearheads the current market scenario in commercially selling mycelium. Various experiments were performed to explore the properties of Mycelium which are divided as per workflow sequence in this section.

For our research we used two separate blends of Ganoderma sp. Mycelium (a) Hemp blend and (b) Aspen blend, ordered from Ecovative as mentioned before. The other required ingredients include (2) Recycled Fire Glass, ordered from Amazon (3) All - purpose flour: 2-3 bags (2 lbs. each) and (4) Water.

Lab accessories: The accessories used include (1) Measuring cup with spout 16 oz.; Quantity: 1 (2) Closure items such as clips to tie the filter bag for rehydration during growth of Mycelium; Quantity: 5-10 (3) Growth container or molds to facilitate directed growth of Mycelium mix, both fabricated in the Lab and pre-ordered from Ecovative at different stages of the process. Growth form material includes – foam, plastic, chipboard, cardboard, paper, plaster of paris, rubber; Quantity: mentioned before every experiment (4) Latex gloves for hand protection during inoculation; Quantity: 2 boxes of 40 each (5) Isopropyl (/Rubbing) alcohol with 71% ethyl alcohol for sterilization; Quantity: 3 bottles (6) Paper napkins; Quantity: 4-5 rolls (7) Weights, used to facilitate Compression test on bricks while testing them on UTM(Universal Testing Machine); Quantity: mentioned later, to be used as per requirement of UTM (8) PLA(Polylactic Acid) filament, used to mock-up 3D printed models; Quantity: as per required (9) Scissors; Quantity: one pair (10) Tape; Quantity; 2 (11) Measuring Tape; Quantity: 1 (12) Stapler; Quantity: 1 (13) Cooking spoon; Quantity: 1 (14) Plastic cover, to wrap the mold packed with Mycelium and prevent moisture loss from the mix; Quantity: 2 (15) Sharp objects such as sharp scissors or needle, to drill holes on the surface of plastic wrap to allow Mycelium to respire; Quantity: 1 (16) Spray bottle, to sterilize the growth containers and work surface; Quantity: 1(17) Mixing bowl, to mix the Mycelium with flour in the second stage of rehydration process; Quantity: 2 (18) Baking tray and aluminum foil, for drying the Mycelium blocks; Quantity: 2 each (19) Stir instruments, to help mix all ingredients; Quantity: 1 (20) Digital Calipers and Scale, to measure change in thickness of Mycelium brick units while testing for Compression under the UTM.

Equipment: The required equipment include: (1) Conventional baking oven, available at Creating_Making Lab, University of Oklahoma: for baking bricks at last stage of growth process (2) Digital weight scale, available at Creating_Making Lab, University of Oklahoma: for measuring weight of bricks at different stages of the drying process (3) Universal Testing Machine(UTM), available at Fears Lab, University of Oklahoma: for conducting compressive strength test on bricks (4) Craftbot 3D Printer, available at The Edge, University of Oklahoma: to print a mock-up model of self-supporting lattice structure grown out of Mycelium(5) Laser Cutter, available at Creating_Making Lab, University of Oklahoma: to fabricate a latticed formwork made from cardboard of 0.5 inch thickness to form the matrix to allow growth of Mycelium.

The process in which Ecovative collects, prepares and sells mycelium is as follows–

1. Agricultural Waste + Mycelium = Mycelium Material [38]
2. Agricultural waste is sourced from local farms and processed to size for use.
   Some of them are most commonly used such as wheat straw, paddy straw, rice straw, rice bran, molasses, coffee straw, banana leaves, tea leaves, cotton straw, saw dust etc. [43] Mycelium can be cultivated using sawdust. Sawdust itself is often not nutritious enough and needs to be supplemented with a nitrogen source such as bran, urea, sunflower seed and horse manure. [43]
3. The agricultural waste is sterilized and the mushroom grain spawn is added to the material. Grain Spawn is mushroom Mycelium grown into certified organic rye grain which is ideal for inoculating sterilized substrates, or for use in unsterilized totem or bed-style inoculations. Grain spawn is the industry standard for high volume commercial production.[44]
4. The material is dehydrated in Ecovative factory and tested by the quality control team to ensure the mushrooms will grow well at home[38].
5. The tested dehydrated Mycelium is packed in filter bags and thus becomes ready to be sold commercially to different parts of the world[38].

2.1 Growth Test

Experiments were conducted in five broad sections each divided into three basic steps. Each section is divided depending on the type of Mycelium blend (hemp or aspen or both) used, the type of test performed, the quantity of bricks grown and the use of glass.

Test I

Aim: To grow solid Mycelium blocks using different types of growth containers (glass not used).

Type of Mycelium used: Grow-It-Yourself (GIY) Mycelium (Hemp) material purchased from Ecovative

Type of Mold used: (1) Six types of mold used were prepared in the Lab. They were made of six different materials: chipboard, foam, plywood, paper, plastic, and plaster of paris. They were shaped in square boxes of dimension 6x6 inches. (2) Plastic Ice cube trays (3) Plastic bowl

Hemp Mycelium material	Dry bag: $13.00/bag (Hemp blend) Shipping: $20.00 (on total purchase) One bag of Hemp material was purchased
Dry weight of Mycelium material	0.9 lbs./bag
Dry volume of Mycelium material	207 in^3/bag
Note: It was calculated from the volume of the dry Mycelium material present, that one bag of Hemp blend Mycelium material can make 3 solid bricks of conventional U.S. brick size: 8x4x2 inches	

Table 1. Summary of specifications of materials used for Growth Test I

Figure 27: Grow-it-yourself (GIY) Mycelium material obtained from Ecovative [16]

Total time period for experiment – 2 weeks approximately.

Stage I: Process of Rehydration: The bag of mycelium was mixed with 6tsps of flour and 5 cups of water. The contents within the bag were mixed well, the top was covered with clips, and made sure that filter patch on the bag remains unblocked, for Mycelium to respire while growing. The bag was kept untouched for 5-6 days in the Lab which had air filters.

Figure 28: Grow-it-yourself (GIY) Hemp Mycelium material after rehydrating

Stage II: Mold preparation: In this stage the contents inside the bag of Mycelium were taken out and mixed with flour (5-6 tsps.) in a mixing bowl, making sure all the media was sterilized and clean. Next the molds were sterilized. It was found difficult to sterilize molds made of paper, plywood, foam, chipboard and plaster of paris. Molds made of plastic were easiest to sterilize. The Mycelium mixed with flour was poured into the molds to fill them. The top surface of molds were covered with plastic wrap to avoid growth of bacteria but with a few holes punched on the surface to allow the mycelium to breathe as it grew. Then the assemblies were allowed to grow and kept untouched for 6-7 days.

Figure 29: (left to right) Hemp Mycelium showing visible growth turning white; Mycelium packed in plastic bowl growth container at Stage III

Stage III: Baking: The Mycelium blocks were taken out of the molds (the molds were discarded in this case) and baked in an oven at 250 degree Fahrenheit for 2-3 hours to stop further growth of fungus. The blocks were taken out of the oven after 3 hours and the solid Mycelium blocks were ready for use.

Figure 30: Hemp Mycelium blocks formed at the end of Stage III

Test II

Aim: To grow composite Mycelium-glass bricks.

Type of Mycelium used: Grow-It-Yourself (GIY) Mycelium material (Aspen) purchased from Ecovative. Aspen Mycelium blend is the heaviest blend available with Ecovative. Two (2) bags of Aspen blend were purchased.

Type of Mold used: (1) One (1) brick growth form purchased from Ecovative; made of recyclable PETG (Polyethylene Terephthalate Glycol-Modified) plastic (2) One plastic pail (3) Two plastic bowl(s)

Type of glass used: One (1) bag of Recycled Copper blue star fire Flame 10-Pound, 1/2-Inch (Fire Glass) Rich-Copper Reflective; purchased from Amazon.

Aspen blend Mycelium	Dry bag: $15.00/bag (Aspen blend) Shipping: $20.00 (on total purchase) Two bags of Aspen blend were purchased
Dry weight of Mycelium material	1.44 lbs./bag
Dry volume of Mycelium material	0.12 ft^3(207.36 in^3)/bag
Compressive Modulus at 15% compression	236 psi
Compressive Stress/Strength at 15% compression	26 psi
Brick growth form (8" x 4" x 2")	1 brick form: $7.5 Shipping: $20.00 (on total purchase)
Recycled Copper blue star fire Flame 1/2-Inch (Fire Glass)	Cost of 1 bag of glass: $35.88 (with shipping) Weight of 1 bag of glass: 10 lbs.
Notes: It was calculated that two (2) bags of Aspen material will make total six (6) composite Mycelium-glass bricks.	

Table 2. Summary of specifications of materials used for Growth Test II

Figure 31: Grow-it-yourself (GIY) Mycelium Aspen blend purchased from Ecovative [17]

Total time period for experiment – $2^{1/2}$ weeks approx.

Stage I: Process of Rehydration: The bags of mycelium were mixed with 8 tsps. of flour and 5 cups of water (as per instructions on the bag of Mycelium obtained). The contents were mixed well within bag and the top was covered with clips, making sure that filter patch on bag remains unblocked, for Mycelium to breathe in while growing. The bag was kept untouched for 5-6 days.

Figure 32: Grow-it-yourself Rehydrated bag of Aspen Mycelium after Stage I

Stage II: Mold preparation: In this stage the contents inside the bag of mycelium were taken out and mixed with flour (5-6 tsps.) in a mixing bowl, making sure all the media was sterilized with rubbing alcohol along with the workspace, to help prevent external bacterial growth. The contents were mixed and large chunks of Mycelium were broken down to form a uniform mixture of smaller particles of Aspen. The molds were made ready by sterilizing them thoroughly with rubbing alcohol.

Figure 33: (left to right) Plaster brick made out of growth forms; Starfire copper blue glass

Figure 34: Growth forms packed with Mycelium-based materials at the end of Stage II

The glass pieces were sterilized (by soaking them in a bowl of rubbing alcohol), and packed into the growth forms along with the contents of Mycelium material. The volume of glass packed in with the mix was not measured at this stage. The top surfaces of mold were covered with plastic wrap to avoid growth of external bacteria leaving a few holes on surface to allow Mycelium to breathe as it grew. The assembly was kept untouched for 5-6 days.

Stage III: Baking: The Mycelium blocks was taken out of the molds and baked in an oven (at 250 degree Fahrenheit for 3-4 hours). The recycled fire-glass did not cause any difficulty while heating in the oven.

Test III

Aim: To grow composite Mycelium-glass bricks. Mycelium will be tested with different percentages of glass at this stage. The bonding capacity of Mycelium shall be checked for specific percentage of glass used.

Type of Mycelium used: Grow-It-Yourself (GIY) Mycelium material (Aspen) purchased from Ecovative. Eight (8) bags were purchased in all for this Test. It was proposed to use Five (5) bags of Mycelium for first phase of the experiment and Three (3) bags for second phase. Thus the whole process (with 3 steps) was repeated twice. The reason for conducting the whole experiment into two phases is because of the limited availability of space to bake the bricks and molds to be used. Dividing the test into two phases ensured sufficient time was available to bake each block for the required length of time.

Type of Mold used: The molds in this case were custom-fabricated using Computer Numerical Control (CNC) machine present in the Lab at the University of Oklahoma. The material chosen was foam. One (1) sheet of 8x4 ft. foam-board was purchased from Forest Building Materials, Norman of 2" thickness.

Type of glass used: One (1) bag of Recycled Copper blue star fire Flame 10-Pound, 1/2-inch (Fire Glass) Rich-Copper Reflective; purchased from Amazon.

Aspen blend Mycelium	Dry bag: $15.00/bag (Aspen blend) Eight (8) bags of Aspen blend were purchased Total cost: $120 (free shipping)
Dry weight of Mycelium material	1.44 lbs./bag
Dry volume of Mycelium material	0.12 ft^3(207.36 in^3)/bag
Compressive Modulus at 15% compression	236 psi
Compressive Stress/Strength at 15% comp.	26 psi
Foam Board from Forest Building Materials	1 Sheet of 2" thick 8/4 feet size Cost: $60
Recycled Copper blue star fire Flame 1/2-Inch (Fire Glass)	Cost of 1 bag of glass: $33.00 (10 lbs.) 3 bags (30 lbs.) of glass was purchased Total cost: $101 (free shipping)
Notes: The experiment was divided into two (2) phases. The first phase used five (5) bags of Aspen Mycelium material and the second phase used three (3). In total 28 bricks were made at the end of two phases.	

Table 3. Summary of specifications of materials used for Growth Test III

Total time period for experiment – 6 weeks approx. (in total for two phases of the experiment)

Phase I

Five (5) bags of Aspen blend Mycelium material used at this phase.

Stage I: Process of Rehydration: The bags of mycelium were mixed with 8 tsps. of flour and 5 cups of water (instructions specified on the surface of bags). The contents within bag were mixed well and the top surface was rolled and tied with clips, making sure that the filter patch on bag remains uncovered. As before, the bag was kept untouched for 5-6 days.

Figure 35: Sealed bags of Aspen Mycelium material at Stage I

Figure 36: 2" thick Foam Board purchased from Forest Building Materials Norman

Stage II: Mold preparation: One (1) sheet of foam board was broken into four parts, each part being of size 4/2 ft. Brick molds to be cut out of foam were designed using Rhino and RhinoCAM. Each of the 4/2 ft. sheet was CNC milled incorporating those designs. Each sheet could accommodate 16 brick mold forms of size 8x4x1.8 inches. The depth of the brick molds were kept 1.8 (instead of 2 inches as per conventional depth of US brick used) inches as that is the maximum depth the CNC milling tool can cut through after leaving a minimum base material of thickness 0.2 inches. CNC router was used for faster and accurate formation of brick molds.

Calculation of percentages of glass used: The foam board was also used to cut through volume cups of sizes that could contain 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70% and 80% of glass respectively. The mass of glass molds to be cut out was calculated with respect to the volume of bricks molds. These cut out volumes of foam served as measuring cups for using specific percentages of glass for the rest of the experiment.

Calculations used for determining the volume of foam to be cut by the CNC:

5% glass- 2.88 cubic inches (of the total volume of one brick – 8”x4”x1.8” = 57.6 cubic inches).

10% - 5.76 cubic inches

20% - 11.52 cubic inches

30% - 17.28 cubic inches

40% - 23.04 cubic inches

50% - 28.8 cubic inches

60% - 34.56 cubic inches

70% - 40.32 cubic inches

80% - 46.08 cubic inches

Thus the foam molds were made ready. Continuing with the process of growing Mycelium at Stage II, the contents inside the bags of Mycelium were taken out and mixed with flour (8 tsps.) in a mixing bowl, making sure all the media was sterilized and clean. The contents were mixed carefully to ensure no large lumps of Mycelium remained.

Process of laying glass inside the brick molds: We tested for two different methods for laying glass in the molds. (1) With cardboard sheet: The foam molds were sterilized (as much as possible) along with the workspace. One layer of Mycelium mix was laid flat inside the mold, a thin sheet of corrugated cardboard was placed on top of that layer. The glass pieces were sterilized. The foam cup measuring 5% by volume was filled with glass. Then a few sterilized glass pieces from the cup was laid on top of the piece of cardboard. Another layer of Mycelium material was poured above the layer of glass. Again a sheet of cardboard was placed on top of that. A few more glass pieces were laid on top of that. The process was repeated as long as the whole volume of foam mold was filled. (2) Without cardboard sheet: The foam molds and workspace was sterilized. One layer of Mycelium material was laid flat inside the mold. No cardboard was used this time. A layer of glass was laid flat directly on top pf Mycelium mix. The steps were repeated.

The whole process with two methods was repeated using different percentages of glass. Half of them were prepared following method (1) as stated above and the rest following method (2). The blocks were left untouched for 5-6 days.

(Hypothesis: We chose to add cardboard in between layers because (i) Mycelium is believed to feed on the cardboard sheet eventually. (ii) With time there will be no trace of the cardboard left in the mold. (iii) The placement of glass over the corrugated cardboard sheet would also help ensure the glass stays in position and forms a uniform horizontal layer across the length of the mold that would help in light transmitting through it.)

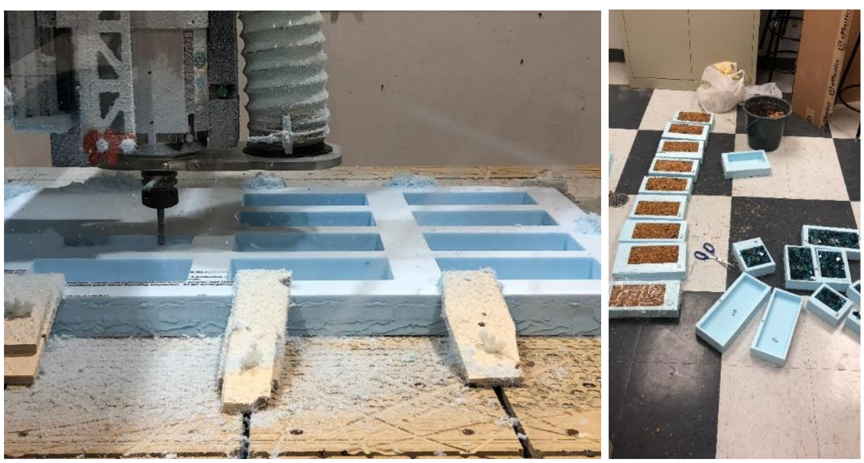

Figure 37: (left to right) CNC router cutting through foam to give shape to brick forms; Mycelium material packed in molds with glass)

Figure 38: (left to right) Glass filled measuring cups cut out of foam; Mycelium material at the end of Stage 2 after being inoculated, turns white ensuring complete growth of Mycelium.

Stage III: Baking: The Mycelium blocks were taken out of the foam mold and baked in the oven at 250 degree Fahrenheit for 2-3 hours. The foam molds had to be discarded at the end of the Test as they broke apart while taking the Mycelium brick out of them. Bricks layered in two different processes were observed closely before and after drying them in the oven.

Phase II

The remaining three (3) bags of Mycelium were used in this phase.

Stage I: Process of Rehydration: The bags of Mycelium were mixed with 8 tsps. of flour and 5 cups of water (instructions specified on the surface of bags). The contents within bag were mixed well and the top was rolled and tied with clips, making sure that the filter patch on bag remains uncovered, for Mycelium to breathe while growing. As before, the bag was kept untouched for 5-6 days.

Stage II: Mold preparation: The contents inside the bags of Mycelium were taken out and mixed with flour (8 tsps.) in a separate mixing bowl, making sure all the media was sterilized and clean. As before, large pieces of Mycelium material was broken into smaller parts to be easily packed into the molds.

Process of laying glass inside the brick molds: At this phase, only method (2) as described before was used to lay the glass. The use of cardboard seemed redundant after Phase I results. As before, the foam molds and workspace was sterilized. One layer of Mycelium material was laid flat inside the mold. A layer of glass was laid on top of the Mycelium material across the length of the mold. Another layer of Mycelium material was poured on top of it. The whole process was repeated till the whole volume of mold was covered using the desired amount of glass. It was repeated using different percentages of glass, making a set of 9 Mycelium bricks having different percentages of glass. The blocks were left untouched for 5-6 days.

Figure 39: Mycelium material packed with glass in molds; Half of two sets of bricks being inoculated, other half already grown

Stage III: Baking: The Mycelium blocks were taken out of the foam mold and baked in the oven at 250 degree Fahrenheit for 3-4 hours. At the end of the baking process, the composite bricks were ready to use. The foam molds were discarded after the Test. The bricks were observed closely before and after drying in the oven.

Test IV

Aim: To grow Mycelium bricks and test them for (1) Compressive strength (2) Water Absorption (3) Water retention (4) Adhesive property (5) Joinery systems. No glass was used at this Test.

Type of Mycelium used: Grow-It-Yourself (GIY) Mycelium material (Aspen and Hemp) purchased from Ecovative. One (1) bag of Hemp Mycelium blend and three (3) bags of Aspen Mycelium blend were purchased. In the first phase, One (1) bag of each of Hemp and Aspen blend was grown to test for (1) Compression test and (2) Water absorption. In the next phase the remaining bags of Aspen were grown to test for (3) Water retention (4) Adhesive property (5)

Joinery systems. Some extra bricks were also made with the remaining amount of Mycelium material.

Type of Mold used: (1) Ten (10) brick growth forms purchased from Ecovative; made of recyclable PETG (Polyethylene Terephthalate Glycol-Modified) plastic (2) Two types of ice cube trays ordered from Amazon: (i) 2 pack large square ice cube molds (ii) 3 pack mini ice cube mold with lid (3) One Plastic salad bowl from Walmart (4) Sheets of Cardboard for testing adhesiveness, used from leftover stock in the Lab. A few old bricks having glass was also tested for Compression along with the new solid Mycelium bricks made at this stage.

Aspen blend Mycelium	Dry bag: $15.00/bag (Aspen blend) Three bags of Aspen blend was purchased Total cost: $45.00 (shipping free)
Dry weight of Aspen Mycelium material	1.44 lbs./bag
Dry volume of Aspen Mycelium material	0.12 ft^3(207.36 in^3)/bag
Hemp Mycelium material	Dry bag: $13.00/bag (Hemp blend) One bag of Hemp material were purchased
Brick growth form (8" x 4" x 2")	1 brick form: $7.5 Ten (10) growth forms were purchased Total cost: $75
2 pack large square ice cube molds	Cost: $8.00
3 pack mini ice cube mold with lid	Cost: $16.00
Plastic salad bowl	Cost: $10.00
Sheets of Cardboard	Thickness: 0.5 inch (leftover stock)
Notes: At the end of Phase I end, a total of 7 bricks were made, 3 from Hemp Mycelium material and 4 from Aspen Mycelium material. For Phase II the remaining bags of Aspen were used to make (1) Smaller cubes for testing joinery system in Mycelium blocks, (2) A curved Mycelium bowl for testing for water retention and (3) With cardboard to check for adhesiveness.(4) the remaining Mycelium material was used to make more solid bricks	

Table 4. Summary of specifications of materials used for Growth Test IV

Total growth time – $2^{1/2}$ weeks approx. for each phase

Phase I

Two (2) bags of each of Aspen and Hemp blend Mycelium material used at this phase.

Stage I: Process of Rehydration: The bags of Mycelium were mixed with 8 tsps. of flour (for Aspen blend) or 6 tsps. of flour (for Hemp blend) and 5 cups of water (or as specified on the surface of bags). In a separate mixing bowl, the flour and water were added to form a uniform mix. Then the viscous liquid was poured in the bags of Mycelium material. The contents within the bag was mixed well by shaking it. The top was rolled and tied with clips, making sure that the filter patch on bag remains uncovered, for Mycelium to respire while growing. As before, the bag was kept untouched for 5-6 days.

Figure 40: GIY Aspen and Hemp Mycelium material undergoing rehydration

Stage II: Mold preparation: The contents inside the bag of Mycelium were taken out and mixed with flour (8/6 tsps. as specified for each) in a mixing bowl, making sure all the media was sterilized and clean. As before, the large lumps of Mycelium material was broken into smaller parts and mixed well with the flour added. Then the uniform mixture was packed into brick plastic molds. The Hemp and Aspen Mycelium material covered 7 brick growth containers.

Figure 41: Aspen and Hemp Mycelium material packed in brick molds/ Stage II starts

Stage III: Baking: The Mycelium blocks were taken out of the plastic brick molds. Then they were put in the oven at 250 degree Fahrenheit for 2-3 hours to dry. At the end of 3 hours, the bricks were ready to use for Compressive Strength test.

Figure 42: (left to right) Mycelium growing in brick molds/ during Stage III; Aspen & Hemp blend respectively

Figure 43: (left to right) Mycelium bricks taken out of molds and ready to be baked; A single brick before drying

Figure 44: (left to right) Oven in Creating_Making Lab used for baking; Bricks inside oven

Figure 45: (left to right) Bricks after baking being dried in open by external fan

Phase II:

Two (2) bags of Aspen Mycelium material used at this phase.

Stage I: Process of Rehydration: The bags of Mycelium were mixed with 8 tsps. of flour and 5 cups of water. In a separate mixing bowl, the flour and water were added to form a uniform mix. Then the viscous liquid was poured in the bags of Mycelium material. The contents within the bags were mixed well by shaking it. The top was rolled and tied with clips, making sure that the filter patch on bags remain uncovered, for Mycelium to respire while growing. As before, the bags were kept untouched for 5-6 days.

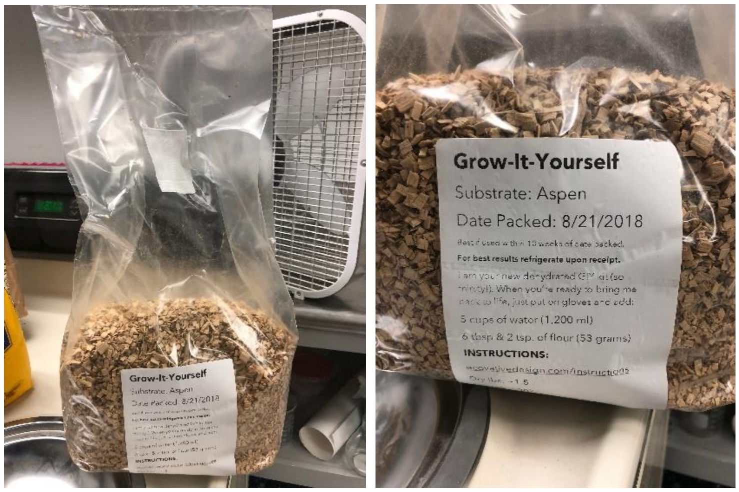

Figure 46: Dry GIY Aspen Mycelium-based material

Figure 47 : (left to right) Rehydrated GIY Aspen Mycelium/ Stage I begins; After 3-4 days of rehydration, water droplets form on the surface of the bag showing air exchange by Mycelium and the bag turns white

Stage II: Mold preparation: (1) Ice cube trays and (2) Plastic bowl, were sterilized before use. For the (3) Adhesive test, cardboard mold was prepared by cutting a few small parts from a large sheet of cardboard. Each small part was randomly designed to give shape to a 3-dimensional structure, attached with each other by slits cut across the pieces. The sheets were not sterilized as external bacterial growth was of less priority in this case. The cardboard block will not be baked at the end. After preparing the molds, the contents of the bags of Mycelium were taken out and mixed with flour (6 tsps.) in a separate mixing bowl, making sure all the media was sterilized and clean. As before, large pieces of Mycelium material were broken into smaller parts and mixed well with the flour added. Then the uniform mixture was packed into (1) The ice cube trays and (2) Plastic bowl (3) The remaining amount of Mycelium mix was sprinkled on top of the cardboard structure. All the molds were covered in plastic wrap leaving a few holes on the surface for Mycelium to breathe. The whole system was kept untouched for 5-6 days.

Figure 48: Rehydrated GIY Aspen Mycelium at the end of Stage I

Figure 49: Aspen Mycelium material packed in molds/ Stage III starts

Stage III: Baking: The Mycelium blocks were taken out of the molds (1) and (2). Their weights were measured. Then they were put in the oven at 250 degree Fahrenheit for 2-3 hours to dry. The weights were checked at the end of 2 hours. The process was repeated until it was ensured that the blocks were completely dry by making sure that their weights do not change even after further heating. The Mycelium packed with cardboard was left untouched and allowed to grow further.

The following tests were performed with the blocks formed which have been discussed separately later in this section: (1) Water retention test was conducted with the bowl shaped Mycelium block (2) Small cube blocks of Mycelium were kept separately to explore Joinery system in Mycelium (3) The cardboard 3D matrix was kept untouched and allowed to grow further for one week more to check for Adhesiveness.

Figure 50: Mycelium material growing in molds, 4-5 days after start of Stage II

Figure 51: (left to right) Small cubes/ hexagonal blocks/bowl shaped block of Mycelium respectively/ end of Stage III

Test V

Aim: The objective is to make a self-supported structure out of Mycelium. It was proposed this could be achieved by designing a small scale model using Mycotecture (Mycelium made blocks). The hypothesis at this stage is, that, if Mycelium can bind with cardboard it can grow to form a self-supported structure. The basis for this hypothesis is that Mycelium acts as a natural glue. As it grows consumes the cardboard and grows into a 3-dimensional structure along the lines of the cardboard form. The validity of binding capacity of Mycelium with cardboard was confirmed after the results obtained from Adhesive Test.

Process: To achieve this (1) A small-scale cardboard structure was designed with a notching system. A single notch of a sheet of cardboard was designed to intersect with the notch of another sheet forming a stable self-supporting latticed structure. The hollow pockets created by the latticed structure were filled with the Mycelium mix and allowed to grow. (2) It was assumed Mycelium would feed on the cardboard as it grows and form a self-supporting 3-dimensional matrix with time. (3) A 3D printed form of the same latticed structure that needed to be made out of cardboard was designed using Craftbot 3D printer present at the University of Oklahoma Innovation Hub facilities. The mock 3D form was printed out of white Polylactic Acid (PLA) filament. (4) Laser cutter present at the Lab was used to cut out the final design of the 3D latticed structure out of cardboard. The software tool used to design the form was Rhinoceros 5.

Type of Mycelium used: One bag of Grow-It-Yourself (GIY) Mycelium material (Hemp) purchased from Ecovative.

Type of Mold used: (1) Cardboard (leftover from other projects at the Lab) of 0.5 inch thickness was used to Laser cut the form (2) The brick growth forms purchased from Ecovative before were proposed to be used to serve as growth containers for the remaining Mycelium mix left after being filling the cardboard structure.

Hemp Mycelium material	Dry bag: $13.00/bag Shipping: $12.00 Total cost: $25.00 One (1) bag was purchased
Dry weight of Hemp Mycelium material	0.9 lbs./bag
Dry volume of Hemp Mycelium material	207 in^3/bag
All-purpose flour	Purchased before
Brick growth form (8" x 4" x 2")	Already purchased before
Sheets of Cardboard	Thickness: 0.5 inch Collected from leftover stock
Notes: It was assumed that amount of Mycelium mix that remains after filling the hollow pockets of the cardboard structure will be used to make extra bricks.	

Table 5. Summary of specifications of materials used for Growth Test V

Total growth time – $2^{1/2}$ weeks approx. for each phase

Stage I: Process of Rehydration: The bag of Mycelium was mixed with 6 tsps. of flour and 5 cups of water (or as specified on the surface of bags). In a separate mixing bowl, the flour and water were added to form a uniform mix. Then the viscous liquid was poured in the bag of Mycelium material. The contents within the bag was mixed well by shaking it. The top was rolled and tied with clips, making sure that the filter patch on bag remains uncovered, for Mycelium to respire while growing. As before, the bag was left untouched for 5-6 days.

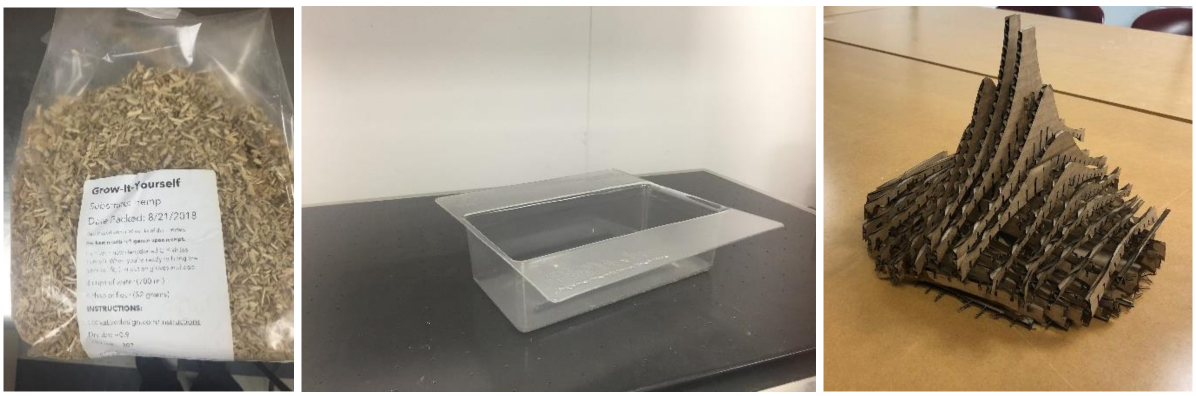

Figure 52: (left to right) Dry GIY Hemp; Brick plastic mold; 3D cardboard mockup of Test

Stage II: Mold preparation: (1) The 3-dimensional latticed structure to be made of cardboard was prepared. The design for the 3D structure was cut out of cardboard sheet using Laser cutter (using Speed-5/ Power-100/PPI-300). The pieces were joined using the notching system. A little superglue was used at some joints to help reinforce a few pieces together. (2) At the end Stage I, the contents inside the bag of Mycelium were taken out as before and mixed with flour (6 tsps.) in a mixing bowl, making sure all the media was sterilized and clean. (3) Then the uniform mixture was packed into (i) the 3D cardboard lattice structure and (ii) Brick plastic molds. (4) Plastic wrap was used to cover the 3D cardboard structure and the top surface of brick molds as before, leaving a few holes for Mycelium to respire. (5) The growth systems were left untouched for 6-7 days.

Figure 53 : (left to right) Rehydrated Mycelium(hemp) grows to cover the GIY bag; Mycelium material packed into the 3D cardboard latticed structure; Remaining Mycelium material used to grow more bricks

Stage III: Baking: (1) It was seen at the end of Stage II that the growth of Mycelium on the 3D cardboard structure was not substantial and it was decided to let it grow for another week more. (2) The Mycelium blocks were taken out of the plastic brick molds. Their weights were measured. Then they were put in the oven at 250 degree Fahrenheit for 2 hours to dry. The weights were checked at the end of 2 hours. The process was repeated until it was ensured that the bricks were completely dry by making sure that the weight of bricks do not change even after further heating.

Figure 54 : (left to right) Rehydrated Mycelium growing in brick molds; 3D cardboard latticed structure packed with Mycelium material, still growing and no visible signs of growth of Mycelium/ both observed 4-5 days after start of Stage II

2.2 Compression Test

The Compressive tests were performed in two phases. In the first phase, (i) Old bricks from Test III having 5% and 10% glass respectively and (ii) One new brick (Hemp blend) from Test IV; were used. In the second phase, only new bricks (having no glass) from Test IV were used.

In both phases samples was tested using Universal Testing Machine (UTM) with a 1 mm/min load speed. Two separate weights were used to facilitate the movement of the machine and for equal distribution of load. The bricks were tested (i) Horizontally: Across surface having area = 8x4 sq.in. (ii) Vertically: Across surface having area = 4x2 sq.in. The results were recorded after the end of each experiment and are discussed later in the next section "Results".

Phase I

Equipment used: Universal Testing Machine (UTM) at Fears Lab, University of Oklahoma

Load distribution: Load was distributed uniformly over the whole surface area of the brick by placing a metal plate on top of it. A metal cylinder was also placed on top of the plate for easy movement of the UTM while compressing the brick. In this phase three (3) bricks were tested:

O1 – Old brick from Test III having glass percentage 5%

O2 – Old brick from Test III having glass percentage 10%

H1 – New brick (Hemp blend) from Test IV having no glass

Load was applied (1) Horizontally across surface area 8x4 inches of O1 (2) Vertically across surface area 4x2 inches of O2 and (3) Horizontally across surface area 8x4 inches of H1. The results were recorded for each of them.

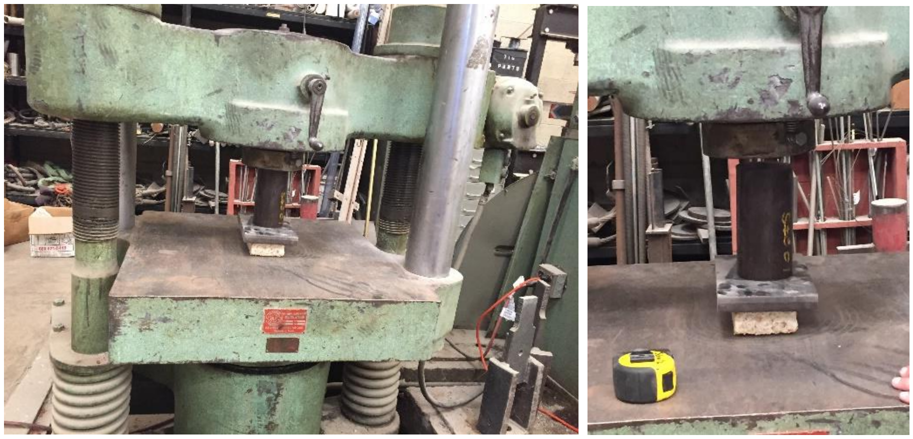

Figure 55: (left to right) Universal Testing Machine (UTM) at Fears Lab, University of Oklahoma, used for testing Mycelium bricks for Compression; Brick under Compression

Figure 56: (left to right) Bricks O1 (5% glass) tested horizontally and O2 (10% glass) tested vertically for Compression

Figure 57: (left to right) Brick H1 (Hemp) tested horizontally for Compression; at a certain load value the brick releases water indicating insufficient drying of brick.

Phase 2

In this phase four (4) bricks were tested (grown during Test IV):

H2, H3: Hemp Blend and A1, A2: Aspen blend

Load was applied (1) Horizontally across surface area 8x4 inches for H2 and A1 (2) Vertically across surface area 4x2 inches for H3 and A2. The results were recorded for each of them. At the end of the Tests, the mechanically transformed bricks were discarded and mixed with the garden soil in the landscaped area outside the Lab.

Figure 58: (left to right) Brick A1 (Aspen) tested for Compression horizontally, a gradual shrinkage in depth of the brick is noticed with increase in load

Figure 59: (left to right) Brick A2 (Aspen) tested for Compression vertically, a gradual shrinkage in depth of the brick is noticed with increase in load

Figure 60: (left to right) Brick H2 (Hemp) tested for Compression horizontally, a gradual shrinkage in depth of the brick is noticed with increase in load without cracking

Figure 61: (left to right) Brick H3 (Hemp) tested for Compression vertically, it bulges out in the middle with increase in load and keeps getting compressed without cracking

2.3 Water Absorption Test

For Water Absorption Test: Two (2) bricks, one of each blend (Hemp and Aspen) were used. Water Absorption test in masonry is performed to check its moisture retention and durability. This test is used to determine the rate of absorption (sorptivity) of water by the Mycelium brick, by measuring the increase in the mass of the specimen resulting from absorption of water as a function of time when induced by a consistent moisture condition. In masonry, it is intended to determine the susceptibility of an unsaturated concrete to the penetration of water[45].

For our research, we soaked two bricks (one Hemp and one Aspen blend) in a plastic pail full of water and used a weight on top of it to prevent the bricks from floating upwards due to buoyancy. The weights of the bricks were recorded before and after soaking into water. At the end of the test, the soaked bricks were discarded and mixed with the garden soil in the landscaped area outside the Lab. We soaked (1) Brick A4, Aspen blend, grown during Test IV and (2) Brick H1, Hemp blend, mechanically deformed after being tested under the UTM for Compression. Another Hemp blend brick could not be used for this test because the rest were used for other tests. Since brick H1 was mechanically altered it was decided to not use the values recorded for it as results for this test. Even though it was was used for the test, recording values for such a brick will give inaccurate results as its properties have already been transformed.

Figure 62: (left to right) Bricks made ready for 24 hour Absorption Test; Testing pail filled with water to perform the Absorption Test

2.4 Water Retention Test

The dried Mycelium bowl obtained from Test IV was used in this process. Half a cup of water was taken in a beaker and poured into the bowl. The bottom and side surfaces of the Mycelium bowl was checked for any seepage of water. At the end of the Test the Mycelium bowl was discarded and mixed with the garden soil in the landscaped area outside the Lab.

Figure 63: Bowl shaped Mycelium block ready to be tested for Water Retention Test

2.5 Adhesive Test

The 3-dimensional matrix made of cardboard covered with Mycelium material obtained from Test IV was used for this Test. As mentioned before, the Mycelium material was allowed to grow further for this test. The results were observed after 2 more weeks instead of the conventional 5-6 day time period.

Figure 64: Mycelium material allowed to grow on cardboard matrix for Adhesive Test

2.6 Joinery Proposal

In this case smaller cubes of Mycelium obtained at the end of Test IV were used. Hypothesis: It was assumed that in future, 3D printed joinery could be used to develop connection joints with Mycelium blocks. It was proposed that the fabricated Mycelium blocks could be pre-drilled to snap fit the 3D printed joinery systems.

Figure 65 : (left to right) Modular shelf system showing joinery with 3D printed plus connections[18]*; Mock-up Assembly Structures made in lab with Mycelium*

For our project the challenges were (1) To design a joinery system for connecting Mycelium blocks that would allow minimum use of connection material (2) To choose a material that would not react with Mycelium and change its physical properties. The furniture project shown above in the figure was chosen for its (i) Modular design and simplicity (ii) Concept of 3D printing. Such prototyping seemed to be a good option as we already know from previous experiments PLA (plastic) does not react with Mycelium. However we propose to replace PLA with Mycelium matrix (as used by Eric Klarenbeek[13]) for 3D printing joinery members. For the shelf project, 3D-printed plusses were created as connection joints. Each plus connects two boxes diagonally by snapping into holes pre-drilled into the edges of the boxes.[43] It is thus believed that 3D printed joinery system using Mycelium as the 3D print filament for connecting Mycelium blocks will provide a completely biodegradable solution in future.

For our research, considering the time frame, mock-up models were designed using (1) Super-glue to join the Mycelium blocks (2) Metal wire mesh to add basic re-enforcement to the structure (3) Plywood to serve as base for the joinery system (4) Corkboard pins to support the assembly structure temporarily.

2.7 Following the Form Test

A mock-up 3D printed latticed structure was fabricated to check for stability of the design of the structure using Craftbot 3D printer. The design was then Laser cut and fabricated with cardboard sheet. The tab or notching system incorporated in the design helped join one sheet of cardboard with the other to form the 3-dimensional structure. It was then packed with Mycelium material to cover the hollow pockets of the latticed structure and allowed to grow.

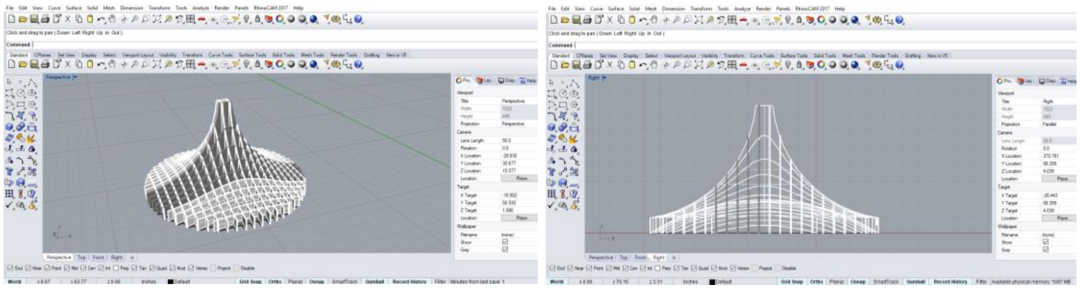

Figure 66: (left to right) 3D model of to-be built cardboard structure in Rhinoceros 5

Figure 67: (left to right) 3D model unfolded in Rhino for Laser Cut; 3D printer Craftbot; 3D printed latticed structure with white PLA filament

Figure 68: (left to right) Laser cutter in operation at Creating_Making Lab; View of final 3D structure made out of laser cut cardboard sheets

Figure 69: (left to right) Cardboard latticed structure packed with Mycelium material

The assembly of cardboard structure with Mycelium was allowed to grow for 3 ½ weeks. However it was proposed that this block after growth of Mycelium cannot be baked because Mycelium will form a monolithic bond with cardboard and it would be hard to separate them.

Chapter 3. Results & Analysis

3.1 Growth Test

Test I

Observation: (1) The blocks were lighter in weight than expected. (2) Some of the blocks also had formation of black mold shoots on the surface which meant there was growth of external bacteria. (3) The compactness of the blocks was poor. With hand-pressure, parts of them started coming out from the whole block material.

Figure 70: Blocks formed with Plastic molds; a few of them grew molds with time

Analysis: (1) Since the blocks were transported in between Stage II and Stage III in this case, that might explain for the less compactness of the blocks. The growth process might have been disturbed because of movement of the bags. Since initially an oven was not available at the place of inoculation of the Mycelium material, they had to be moved to a different place. (2) It was realized that the sterilization process had to be more thorough. The growth of molds pointed out the blocks were exposed to external bacterial growth.

Test II

Observation: A single composite Mycelium-glass brick was formed at the end of this Test. It was noted at this stage that (1) The brick formed after baking was much heavier than the first set of blocks produced after Test I (2) The odor of bricks after baking was not pungent and smelled of moist earth. (3) No formation of black mold was noticed on the surface like before. (3) The glass used was visible on the top and bottom surfaces as well as the edges reflecting light but did not transmit light all the way through (which was the initial hypothesis to let light pass across the length of the brick unit) as (i) The layering of glass was not correct and (ii) The percentage of glass used was not measured. That might explain for the need of a fixed volume ratio of Mycelium to glass that should be used in future. (4) The glass pieces did not bond well with the Mycelium block. That could be explained by (i) The size of glass pieces being too big (ii) Absence of an external adhesive agent help bind the Mycelium particles with glass.

Figure 71: (left to right) A single Composite Mycelium-Glass brick before drying; Blocks being baked in oven

Figure 72: Composite Mycelium-Glass brick after drying and ready to use

Analysis: (1) No black mold shoots were noticed which led to the conclusion that the sterilization process was correct. (2) Blocks were heavier. That refers to the fact that the process of rehydration and baking was completed successfully. (3) Plastic molds work best with Mycelium growth, also they can be re-used. The brick formed was compact in form and shape. (4) It was also decided that a suitable method of layering of glass in the mold needs to be achieved to make the block translucent. In this case the glass pieces settled down at the bottom as there was no framework to hold them in place among the Mycelium materials. (5) The block burnt a little on its surface. This could be prevented by (i) Covering one surface of brick at a time with aluminum foil and then baking or by (ii) Controlling the temperature to prevent over-heating. (6) It is convenient to use a mold release, for example petroleum jelly (Vaseline), for easy removal of Mycelium block from molds. It was noticed that due to lack of smoothness along the sides of mold, it was hard to pull out the Mycelium block without damaging the block.

Test III

Observation: (1) Bricks having glass percentages above 50 failed in structure. It was found the higher the volume of glass, the less is its binding capacity with Mycelium. Bricks having higher percentages of glass remained loose after baking and fell off easily when moved. In some cases the brick broke apart in two halves being unable to bind with glass. In other cases bricks developed a deep crack line across its length and eventually broken into halves. (2) At the end of Stage II when the brick was removed from its mold a large amount of moisture fell off the surfaces of bricks. It was found that small pockets of moisture were formed inside the brick (3) The weight of the successfully bonded composite bricks were higher than the weight of bricks previously made. (4) Some of the blocks grew back molds in them (5) The cardboard sheets used to frame the layering of glass did not get consumed by Mycelium as per the hypothesis. The sheets did not facilitate bonding of the layers and all the components remained as separate entities. (6) Foam used as a mold material was found hard to sterilize because of its porous nature.

Figure 73: (left to right) Bricks with different percentages of glass formed at the end of Test III

Figure 74: Bricks in oven being baked during Stage III of Test III

Figure 75: (left to right) Bricks developing cracks; Bricks with higher percentages of glass breaking off from structure

Figure 76: (left to right) Image showing cardboard sheet peeling off from structure without bonding; Composite Mycelium glass brick with 80% glass having a structural breakdown

Analysis: (1) It was concluded that for Mycelium to bind with glass an external additive agent must be inserted at Stage II to facilitate their binding capacity. At this stage the time frame did not allow to conduct further research into finding the appropriate binding agent or the suitable method of layering of glass with Mycelium. (2) The sterilization of the fabricated foam molds could not be conducted thoroughly because of the porous nature of foam. That led to attack of external bacteria in the blocks resulting in formation of molds. It was concluded that foam is not the best option to be used as containers for growing Mycelium. (3) It was assumed that Mycelium will feed into the cardboard sheet, however in reality that did not happen. Cardboard sheets remained as separate entities and did not facilitate the bonding of Mycelium with glass. It was concluded, that, using cardboard sheets for layering glass is not the best option and further research needs to be performed to find a suitable method of laying glass in the growth containers. (4) Increase in weight of the new batch of bricks was because of measured use of glass for each of them. (6) Mycelium respires while rehydrating and it is natural to form water droplets on the surface of the plastic wrap depicting air exchange. However the number of moisture pockets found in the blocks were more compared to previous tests. It was concluded that low air conditioning of the Lab environment during Stage III and presence of humidity in the air must have led to the increased amount of moisture in the blocks.

Test IV

Observation: It was noted that (1) The bricks formed were compact in shape and form. They did not develop any crack lines while taking apart from the molds. (2) A few of them developed molds on the surface during Stage II, which can indicate attack from external bacteria. However, after being baked and dried the molds were not visible. (3) External fans helped keep circulating the air in the work environment of the lab. This facilitated efficient air exchange of Mycelium material. (4) The plastic brick molds used were observed to work best as growth containers (5) The Aspen blend Mycelium material used to form bricks were heavier than Hemp Mycelium material. (2) The ice cube trays used for Joinery Proposal were convenient to grow Mycelium and easy to sterilize. (3) The shape of the curved bowl shaped Mycelium block formed for Water Retention test helped hold water efficiently to check for water leakage. (4) The Mycelium block formed on the 3-dimensional cardboard structure could not be separated from its substrate (cardboard). The whole assembly had to be discarded at the end of the Test. The Mycelium was mixed with the garden soil outside the lab.

Figure 77: (left to right) Solid Mycelium bricks/ Smaller cubes/ Bowl shaped block of Mycelium formed after Test IV

Analysis: (1) Bricks formed were compact in nature and able to hold their shape (2) Mold development was still found in a few bricks which means the sterilization process was not sufficient. It was concluded from next time, more care should be taken for sterilizing the work table and the containers. (3) Use of external fans was a good choice in keeping the moisture content in room low. (4) It has been established the fact that Mycelium does not react with plastic (5) Time is a very important factor while growing Mycelium. Every step needs to be performed at their specific times for stable formation of bricks.

Test V

Observation: (1) The notching system of the cardboard structure made as a mock-up model to test for self-supporting properties of Mycelium was not completely efficient. External tabs were not used at joints to make connections. It was assumed the design of the notching system would hold the structure together. However, in reality, superglue had to be used at various places to hold two cardboard pieces together. (2) Even at the end of Stage III, growth of Mycelium material on cardboard was not noticeable. This was observed contrary to the adhesive test done with cardboard and Mycelium before where Mycelium grew completely to cover the cardboard. (3) The remaining Mycelium material packed in brick plastic molds grew naturally like before and were baked and dried at the end of Stage III. The bricks formed were compact and the particles were held together in shape and form.

Figure 78: (left to right) A single solid Mycelium brick; Mycelium still growing on cardboard 3D matrix

Analysis: (1) The bricks formed at the end of this stage were compact and dry without formation of molds. This indicates that if the process of sterilization is thorough, external growth of bacteria can be prevented completely. (2) Since in this case no visible growth of Mycelium was observed on cardboard structure this could indicate the following: (i) The amount of Mycelium material allowed to grow on cardboard might be a determining factor for growth. Previously, for Adhesive Test, the amount of Mycelium material was twice as much as the amount of cardboard sheets it was allowed to grow on. In this case, Mycelium was only inserted in the hollow pockets of the structure and the ratio of cardboard to Mycelium could be roughly assumed to be 2:1. That might be a reason for the significant slow growth of Mycelium. (ii) The design of the structure matters. Previously since cardboard sheets only ran along the perimeters with a bulk of Mycelium material grown in the middle, the surface area covered by Mycelium was more. In this case, the cardboard formed the main structural vein. An optimal ratio of substrate material to be used with Mycelium should be determined for future experiments.

3.2 Compression Test

Phase I

Equipment used: UTM (Universal Testing Machine)

Load distribution – Load was distributed over the whole surface area of the bricks by placing a metal plate on top of it. A metal cylinder was also placed on top of the plate for easy movement of the UTM while compressing the brick.

Brick O1: (Aspen blend; old stock brick; with 5% glass; direction: horizontal)

Brick dimensions: 7.5 x 3.2 x 2.5 inches

Figure 79: Brick O1 tested for Compression using UTM

Load (in lbs.)	Thickness (in inches)	Notes
Start Load	2.5	UTM starts operating
600	2.0	The brick starts to shrink in height
800	1.5	--
900	0.9	Brick starts cracking. Sound heard.
9400	0.75	Maximum load given. The brick does not crack but keeps getting compressed. It is to be noted that more load can be applied on brick above this point but that would only deform it by compressing and it will not crack at a single distinct point like conventional brick masonry. The elastic nature of Mycelium brick can be accounted for such behavior. At this point, it starts acting like a sponge which instead of breaking with increase of load, shrinks in depth.

Table 6. Summary of results recorded for Brick O1 under UTM in Compression

Brick O2: (Aspen blend; old stock brick; with 10% glass; direction: vertical)

Brick dimensions: 7.8 x 3.5 x 2.3 inches

Figure 80: Brick O2 tested for Compression using UTM

Load (in lbs.)	Thickness (in inches)	Notes
Start Load	3.5	UTM starts operating
350	3.25	The brick starts to shrink in breadth
470	3	Brick does not crack, keeps getting compressed
2500	2	--
5500	1.25	Maximum load given. The brick does not crack but gets compressed to minimum. It is to be noted that more load can be applied on brick above this point but that would only deform it by compressing and it will not crack at a single distinct point like conventional brick masonry.

Table 7. Summary of results recorded for Brick O2 under UTM in Compression

Brick H1: (Hemp blend; new stock brick; no glass; direction: horizontal)

Brick dimensions: 8.05 x 3.97 x 2.15 inches

Figure 81: Brick H1 tested for Compression using UTM, releases water under pressure

Load (in lbs.)	Thickness (in inches)	Notes
Start Load	2.15	UTM starts operating
1000	1.2	The brick starts to shrink in height
1800	1.0	Brick starts cracking, releases water. Conclusion: The brick is not dried sufficiently. Baking stage needs to be revisited.
4500	0.75	Brick keeps shrinking. Releases more water.
6000	0.5	Maximum load given. The brick gets compressed to minimum and gives out large amounts of water. This indicates insufficient drying of bricks.

Table 8. Summary of results recorded for Brick H1 under UTM in Compression

Analysis: (1) The bricks sustained a load heavier than expected. (2) The release of water from brick H1 on being compressed indicated (i) Insufficient drying of the brick. It was taken back to C_M Lab and dried in successive phases. The weight was recorded until there was no change in weight of the brick. It was then further used for Absorption Test. However its values were not counted for Absorption Test as it was already mechanically deformed. (ii) There was a time gap of 3-4 days between the day the bricks were dried and the actual day the Compression test was conducted. The humidity in the Lab being high could have resulted in increase in the weight of brick by absorption of atmospheric moisture by Mycelium. Growth of black molds was also noticed in the time gap. Such results can be accounted for the humidity in air and improper drying of bricks as discussed before. It was concluded that in future it must be ensured the bricks are dry before using them for other tests. (3) Weighing bricks was concluded to be an essential part of the process. (5) Labelling each brick was also found to be of significance importance at this stage. Since the bricks were not labeled it was found difficult to associate them with the values of their weights recorded before the start of Compression Test. It was decided in future labeling should be given priority. (6) It was assumed for each Compression Test that the term "maximum load applied" corresponds to a load value, which does not necessarily mean the maximum load that could be applied by the machine. It however refers to the end load applied on it. Increase in load beyond that value will keep compressing the brick without cracking it. The brick was assumed to structurally fail at this load value. It was concluded that Mycelium bricks will not break like conventional masonry bricks at a sharp distinct load value. Such behavior can be accounted for its elasticity like a sponge.

Phase II

At this Phase, before conducting the Compression test on two blends of each of Hemp and Aspen blend of Mycelium, a two week gap period was taken to ensure that the bricks to be used for the test were completely dry. This step was followed after observing the results from Phase I of Compression test where water was released by brick H1 that belongs to the same category of these bricks. So the Compression test for Phase II will be preceded by the Weight test.

Weight test

Materials used: Six (6) bricks obtained from Test IV: H2, H3 (Hemp); A1, A2, A3, A4 (Aspen). Brick H1 could not be used in this case as it was physically deformed under Compression test, performed before.

Equipment used: Digital scale present at the C_M Lab (scale unit: ounces)

	H1	H2	H3	A1	A2	A3	A4
Date/Time	09/19; 9:20 am						
Weight(oz)	--	13.85	10.95	13.45	14.55	15.2	8.75
Notes	Weights were taken before putting bricks in the oven. After weights were recorded the bricks were put inside the oven for drying them further. The temperature was set at 250 degree Fahrenheit and they were baked for 2 hours. Time when oven started – 9:45 am.						
Date/Time	09/ 19; 11:30 am						
Weight(oz)	--	11.7	9.3	11.95	12.8	13.6	7.6
Notes	Weights were recorded and the bricks were put inside the oven for drying them further. The temperature was set at 200 degree Fahrenheit and they were baked for 2 more hours. Time when oven started again – 11:40 am.						
Date/Time	09/ 19; 2:06 pm						
Weight(oz)	--	10.3	8.2	10.95	11.6	12.35	7
Notes	Weights were recorded and the bricks were put inside the oven for drying them further. The temperature was set at 200 degree Fahrenheit and they were baked for 2 more hours. Time when oven started again – 2:13 pm.						
Date/Time	09/ 19; 4:00 pm						
Weight(oz)	--	9.45	7.55	10.35	10.9	11.65	6.7
Notes	Weights were recorded and the bricks were put inside the oven for drying them further. The temperature was set at 200 degree Fahrenheit and they were baked for 2 more hours. Time when oven started again – 4:15 pm.						
Date/Time	09/19; 5:35 pm (The C_M Lab closes at 6:00 pm)						
Weight(oz)	--	8.8	7.1	9.9	10.35	11.1	6.55

Notes	Weights were recorded and the bricks were not further dried as it was C_M Lab closing time.						
Date/Time	09/ 20; 9:46 am						
Weight(oz)	--	8.4	6.8	9.85	10.2	10.95	6.85
Notes	Weights were taken before putting bricks in the oven. After weights were recorded the bricks were put inside the oven for drying them further. The temperature was set at 200/250 degree Fahrenheit and they were baked for 2 hours. Time when oven started – 9:54 am.						
Date/Time	09/ 20; 12:00 pm						
Weight(oz)	--	7.4	6	9.1	9.35	10	6.45
Notes	Weights were recorded and the bricks were not further dried today.						
Date/Time	09/ 24; 1:04 pm						
Weight(oz)	--	6.65	5.7	9.15	9.25	9.95	7.05
Notes	Simply weights were recorded. Further drying was not felt necessary as there was less significant change in weight of bricks.						
Date/Time	09/ 26; 12:22 pm						
Weight(oz)	--	6.3	5.65	9.1	9.15	9.85	7.05
Notes	Weights were recorded before taking to Fears Lab for compression test.						
Date/Time	09/26; 2:30 pm						
Weight(oz)	--	6.3	5.6	9.1	9.15	--	--
Notes	Weights recorded of four bricks (H2, H3, A1, A2) after compression test on same day as above.						

Table 9. Summary of change in weight of bricks recorded on successive drying

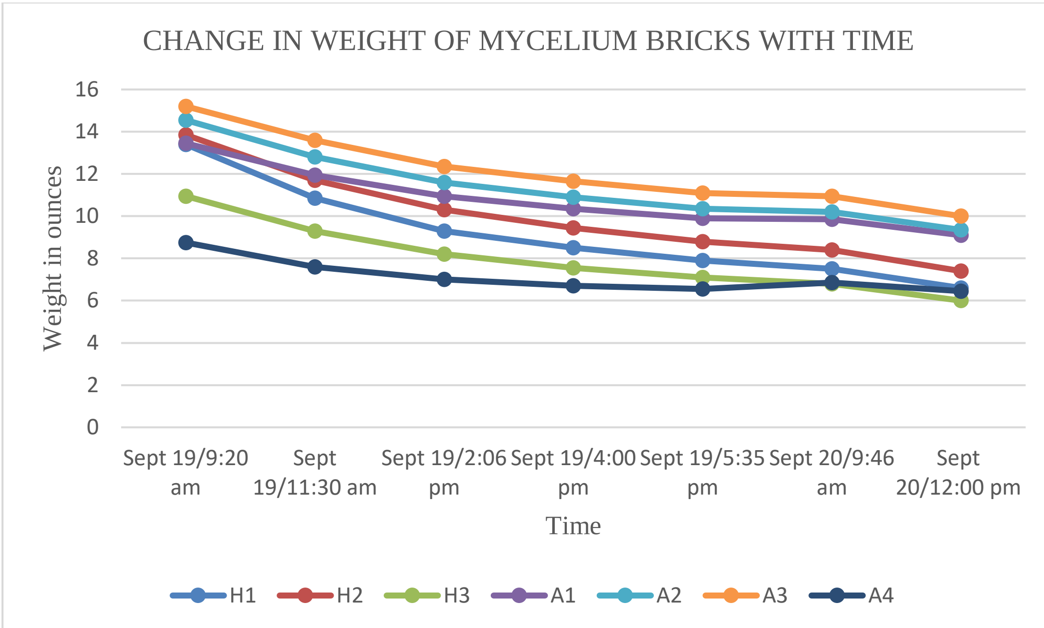

Figure 82: Graph showing Change in weight of bricks with Time

Analysis: It was concluded from the above graph that with successive drying over time the weight of the bricks decrease substantially. This could be explained from the shrinkage of air gaps present in the Mycelium-based material. Decrease in air gap leads to the decrease in weight of bricks as it gets compressed along with the release of excess water.

The Compression Tests were performed as follows after ensuring the bricks to be used were completely dry.

Compression Test

Materials used: Four (4) bricks: H2, H3 (Hemp); A1, A2 (Aspen).

Equipment used: UTM (Universal Testing Machine)

Load distribution – Load was distributed over the whole surface area of the bricks by placing a metal plate on top of it. A metal cylinder was also placed on top of the plate for easy movement of the UTM while compressing the brick.

Brick A1: (Aspen blend; brick made at Test IV; no glass; direction: horizontal)

Brick dimensions: 7.65 x 3.6 x 2.3 inches

Brick No.	Dimension (in inch)	Load Direction	Thickness of side/ Deflection (in inch)	Load (P,in lbs)	Area of surface where load is applied (A, in square inch)	Compressive Strength [S=P/A] (in psi)	Notes
A1	7.65"/3.6/2.3 (LxBxH)	Horizontal (H)	2.3	0	LxB=7.65x3.6=27.54(A)	0	Compression test starts
			2.2	800		29.0	Brick starts compressing
			2	1300		47.2	
			1.95	1500		54.5	
			1.8	2500		90.8	
			1.7	3000		108.9	Starts cracking (sound heard)
			1.5	3800		138.0	
			1.45	4000		145.2	
			1.35	4400		159.8	
			1.3	5000		181.6	
			1.2	6000		217.9	
			1.1	7000		254.2	
			1.05	7500		272.3	
			1	8000		290.5	
			0	10000		0.0	Maximum load given to the brick (please note that load more than this could be given but that would only make the brick compress more without breaking/cracking)

Figure 83: Calculations in Excel showing data recorded for brick A1 under Compression

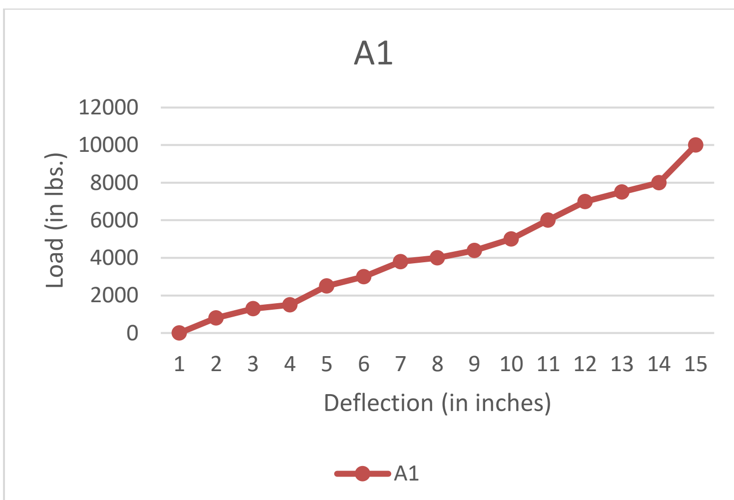

Figure 84: Graph showing Deflection of brick A1 with increase in load using UTM

Brick A2: (Aspen blend; brick made at Test IV; no glass; direction: vertically)

Brick dimensions: 7.65 x 3.9 x 2.1 inches

Brick No.	Dimension (in inch)	Load Direction	Thickness of side/ Deflection (in inch)	Load (P,in lbs)	Area of surface where load is applied (A, in square inch)	Compressive Strength [S=P/A] (in psi)	Notes
A2	7.65/3.9/ 2.1 (LxBxH)	Vertical (V)	3.9	0	LxH=7.65x2.1= 16.065(A)	0	Compression test starts
			3.8	200		12.4	Brick starts compressing
			3.3	1100		68.5	
			3.2	1150		71.6	
			3.15	1130		70.3	Starts cracking (sound heard)
			3.1	1125		70.0	Brick rebounds like elastic and load decreases. Hypothesis – air gaps decreasing, material pushes up as it gets compressed.
			3	1100		68.5	Load decreases.
			2.9	1060		66.0	
			2.7	1040		64.7	
			2.6	1020		63.5	Load still decreases.
			2.5	1060		66.0	Load starts increasing again.
			2.4	1070		66.6	
			2.25	1200		74.7	
			2.2	1220		75.9	Maximum load applied. Brick bulges out in the middle and fairly cracks.
			0	10000		0.0	

H2 | H3 | A1 | A2 | Comparisons

Figure 85: Calculations in Excel showing data recorded for brick A2 under Compression

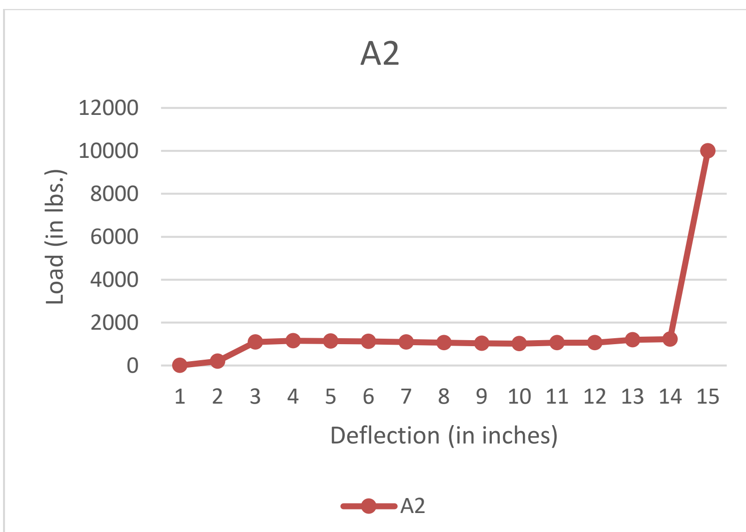

Figure 86: Graph showing Deflection of brick A2 with increase in load using UTM

Brick H2: (Hemp blend; brick made at Test IV; no glass; direction: horizontally)

Brick dimensions: 7.65 x 3.6 x 2.5 inches

Brick No.	Dimension (in inch)	Load Direction	Thickness of side/ Deflection (in inch)	Load (P,in lbs)	Area of surface where load is applied (A, in square inch)	Compressive Strength [S=P/A] (in psi)	Notes
H2	7.65/3.6/2.5 (LxBxH)	Horizontal (H)	2.5	0	LxB=7.65x3.6=27.54 (A)	0	Compression test starts
			2.3	300		10.9	Brick starts compressing
			2.1	700		25.4	
			2	1100		39.9	Starts cracking (sound heard)
			1.8	1500		54.5	
			1.75	1690		61.4	
			1.5	1850		67.2	
			1.3	1900		69.0	
			1.28	1925		69.9	
			1.25	1950		70.8	
			1.2	2000		72.6	
			1.1	3000		108.9	
			1.05	4000		145.2	
			1	4380		159.0	Maximum load given to the brick (please note that load more than this could be given but that would only make the brick compress more without breaking/cracking)
			0	10000		0.0	

Figure 87: Calculations in Excel showing data recorded for brick H2 under Compression

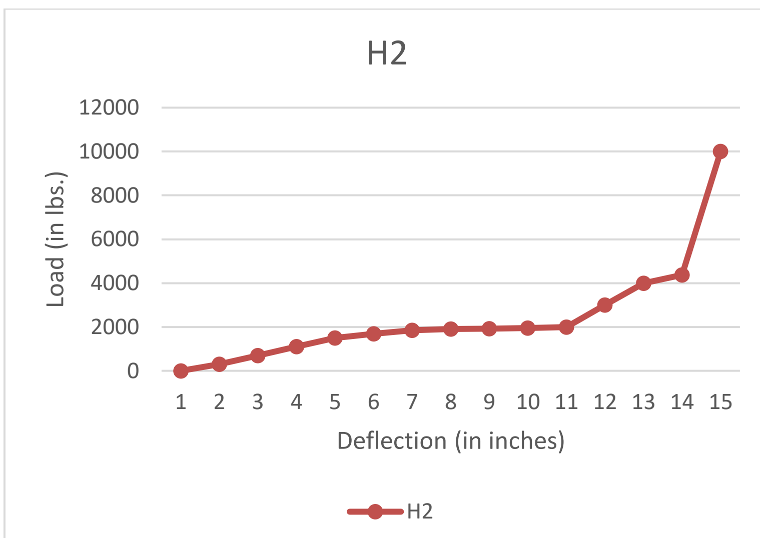

Figure 88: Graph showing Deflection of brick H2 with increase in load using UTM

Brick H3: (Hemp blend; brick made at Test IV; no glass; direction: vertically)

Brick dimensions: 7.65 x 3.9 x 2.3 inches

Brick No.	Dimension (in inch)	Load Direction	Thickness of side/ Deflection (in inch)	Load (P,in lbs)	Area of surface where load is applied (A, in square inch)	Compressive Strength [S=P/A] (in psi)	Notes
H3	7.65/3.9/ 2.3 (LxBxH)	Vertical (V)	3.9	0	LxH=7.65x2.3=17.595(A)	0	Compression test starts
			3.8	200		11.4	Brick starts compressing
			3.75	300		17.1	
			3.6	400		22.7	
			3.5	500		28.4	
			3.2	700		39.8	Starts cracking (sound heard)
			3.15	710		40.4	
			3.1	700		39.8	Brick rebounds like elastic and load decreases. Hypothesis – air gaps decreasing, material pushes up as it gets compressed.
			3	690		39.2	Load decreases.
			2.8	650		36.9	Load still decreases.
			2.6	700		39.8	Load starts increasing again
			2.5	800		45.5	
			2.2	900		51.2	
			2	1100		62.5	Maximum load applied. Brick bulges out in the middle. (please note that load more than this could be given but that would only make the brick compress further without breaking/cracking)
			0	10000		0.0	

H2 | H3 | A1 | A2 | Comparisons

Figure 89: Calculations in Excel showing data recorded for brick H3 under Compression

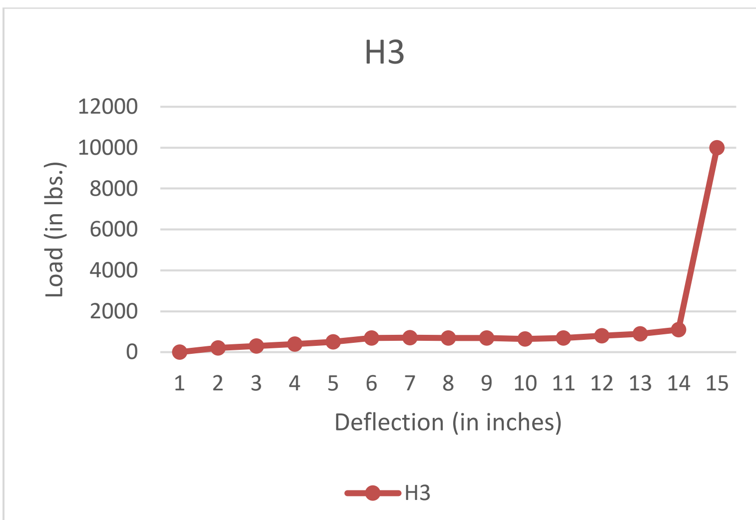

Figure 90: Graph showing Deflection of brick H3 with increase in load using UTM

Analysis: (1) It was noticed when bricks were tested in horizontal (8x4) orientation the load increased successively along with compressing the brick. (2) However when they were tested in vertical (8x2) direction the load rebounded at a certain value and started decreasing indicating the elastic property of Mycelium. They again started increasing after a certain load point. The bricks kept getting compressed throughout. (3) The weight tests done before Phase II of

Compression helped to ensure complete drying of Mycelium bricks. It was realized the process of recording weights of brick, forms an essential part of growing bricks out of Mycelium (4) An almost distinct crack point could be observed in case of bricks loaded vertically compared to the ones loaded horizontally. The load value at that point was recorded. (5) Bricks loaded vertically bulged out in the middle instead of uniformly getting compressed as compared to bricks loaded horizontally. (6) A metric scale placed along lines of application of load aligned to the bricks helped track the exact change in deformation with change in load.

	A	B	C
1			
2	Deflection	H2	A1
3	2.5	0	0
4	2.3	300	0
5	2.1	700	1200
6	2	1100	1300
7	1.8	1500	2500
8	1.75	1690	3000
9	1.5	1850	3800
10	1.3	1900	4400
11	1.28	1925	4000
12	1.25	1950	5000
13	1.2	2000	6000
14	1.1	3000	7000
15	1.05	4000	7500
16	1	4380	8000
17	0	10000	10000

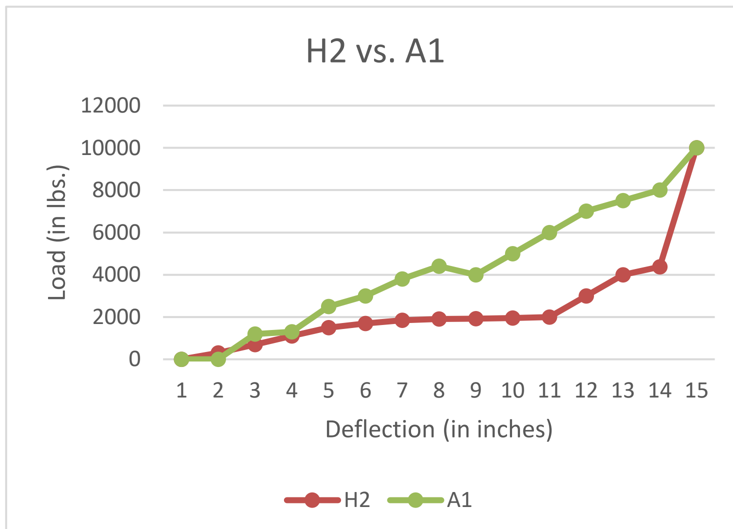

Figure 91: (left to right) Table showing change in deflection values for bricks H2 and A1 both loaded horizontally under Compression; Graph comparing deflection values of H2 and A1 with change in load

E	F	G
Deflection	H3	A2
3.9	0	0
3.8	200	200
3.75	300	800
3.6	400	900
3.5	500	1000
3.2	700	1500
3.15	710	1130
3.1	700	1125
3	690	1100
2.8	650	1060
2.6	700	1020
2.5	800	1060
2.2	900	1220
2	1100	1300
0	10000	10000

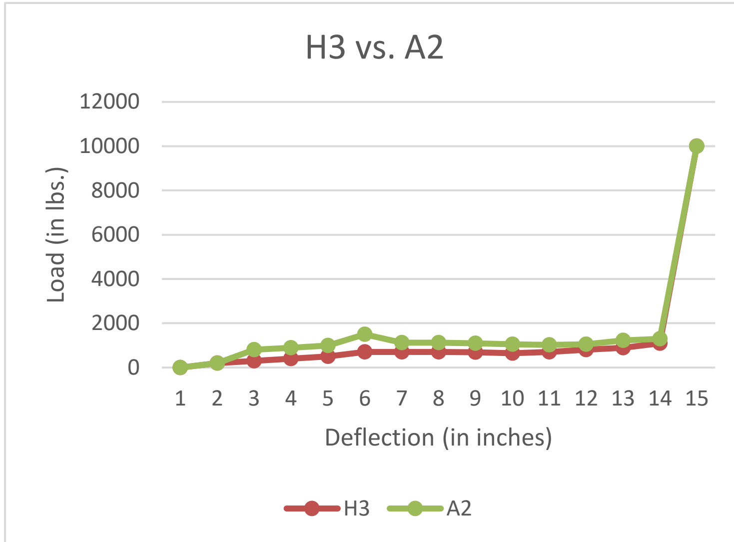

Figure 92: (left to right) Table showing change in deflection values for bricks H3 and A2 both loaded vertically under Compression; Graph comparing deflection values of H3 and A2 with change in load

The combined graphs draw a final comparison in Compression strength of bricks in two different direction of application of load. The behavior of the first group (loaded horizontally) differs substantially from the second group (loaded vertically). The reason for the difference could be explained by the (i) Change in orientation and (ii) The area of application of load

Mycelium proposed to be a good insulation material: It was observed and concluded that Mycelium-based samples are porous and contain large pockets of air in between. While in compression, this air is released leaving a material which is much more compact. If the remaining material is then loaded again a much greater resistance can be build up.

For our research, an important hypothesis was drawn from the load changes observed for bricks loaded vertically at this stage. A distinct pattern in change in behavior of the Mycelium-based material is noticeable in this case. Half the deformation of the first load cycle of the brick loaded vertically was plastic until the point it started rebounding. It is to be noted that the phase through which the load increased at first and then decreased is considered its “Elastic” phase. Nearly all deformation after that point when the load started increasing again was plastic. This is because once the air is pushed out, a compact material is created, however the air cannot return once the load is removed. If the unexpected elastic to plastic nature of Mycelium could be explained due to presence of air content in Mycelium-based materials, this could imply that such materials can act as good insulators. The high air content signifies a low thermal conductivity.

3.3 Water Absorption Test

Material used: Brick A4 (aspen)

Equipment used: Digital weight scale

	H1	**H2**	**H3**	**A1**	**A2**	**A3**	**A4**
Date/Time	09/ 26; 2:30 pm						
Weight(oz/gm)	--	--	--	--	--	--	7.05/199.86
Notes	Weight of brick A4 was recorded before soaking it in water.						
Date/Time	09/27; 3:00 pm						
Weight(oz/gm)	--	--	--	--	--	--	13.9/394.05
Notes	Weight of brick was recorded after 24 hours time interval.						

Table 10. Summary of results of Water Absorption Test

Figure 93: (left to right) Mycelium blocks after being soaked for 24 hours: Brick H1 (Hemp, right) was tested for Absorption test after being mechanically transformed underload by the UTM, and brick A1 (Aspen, left) grown during Test IV; Bricks weighed on digital scale

Analysis: (1) The weight of Mycelium brick recorded after Absorption test shows an increase in weight. This indicates that the Mycelium absorbs water. Hence from results it is recommended to abstain from using Mycelium as an external structural material. (2) Mechanically deformed bricks should not be used for further tests as they do not produce correct results.

3.4 Water Retention Test

Figure 94: (left to right) Bowl shaped Mycelium block tested for Water Retention Test

Analysis: As discussed before, water was poured to half-fill the bowl shaped Mycelium block. The block did not allow water to pass through instantly. This proves that Mycelium blocks can help retain water for a certain time period. In our case, the Mycelium bowl of thickness 1.5 inches was observed to retain water for 8 hours. At the end of 8 hour time period it started growing molds again and turned black eventually.

3.5 Adhesive Test

Figure 95: Stages of growth of Mycelium on a cardboard structure demonstrating its adhesive property

In this case, Mycelium material was allowed to grow on a 3-dimensional cardboard structure for 3 weeks.

Analysis: (1) The test proves that Mycelium acts as a living glue and consumes cardboard as it grows. At the end of 3 week period Mycelium could not be separated from the cardboard sheets as they formed a monolithic structure. This indicates Mycelium binds with cardboard.

3.6 Joinery Proposal

The bricks as discussed before were tested with (1) Metal wire mesh and corkboard pins as supports to make an arched structure. Wooden ice-cream sticks were used to hold down the edges of the wire mesh and tape was used to pin down the sticks temporarily (2) Plywood bases were collected from scrap material in the C_M Lab. Two types of layering of Mycelium blocks were performed (i) A straight wall and (ii) A curved wall. Superglue was used to join each block together.

Figure 96: Mycelium block assemblies with straight and curved walls

Analysis: (1) The straight wall structure showed a sequence of layering Mycelium blocks, adding one layer after the other, to form a three step hollow wall assembly. It was observed that the assembly could stand straight and did not break with movement. (2) The curved wall structure reflected the fact that Mycelium blocks can be fabricated in various custom shapes and are strong enough to withstand gravitational forces to keep in shape. (3) Superglue does not react with Mycelium after it is baked as a block.

Figure 97: Comparison of curved wall assembly made in the lab with Bruce Goff architecture: Bavinger House[46]

3.7 Following the Form Test

For this Test, Mycelium was allowed to grow longer than its usual growth time. The assembly was uncovered after 3 ½ weeks to provide Mycelium enough time to grow on cardboard structure. However it was observed that Mycelium did not bind with cardboard at the end of the testing period.

Analysis: The failure of Mycelium to bind with cardboard is contrary to what observed for the Adhesive Test. It was seen before for the same growth time period, Mycelium grew completely over the cardboard substrate and turned white. This can lead to one noticeable conclusion. The ratio of Mycelium to substrate used should be optimal. In this case, the quantity of cardboard used with Mycelium was much more than that used for Adhesive test. Since the laser cut cardboard structure was designed to grow Mycelium, the number of members of cardboard used was more. For the Adhesive Test cardboard sheets only formed the periphery of the structure and Mycelium was allowed to grow as a bulk in the middle of the structure. In this case, Mycelium covered only the hollow pockets of the cardboard latticed structure. That could explain its long growth time and ultimate failure to bind with substrate particles.

Figure 98: Mycelium material failing to grow on 3-dimensional cardboard structure

3.8 Infection Rate

Sterilization of Mycelium based materials is of utmost importance. At every stage of the process it is to be ensured that the work surface and growth containers are clean and completely sterilized. Even though care was taken, it was found at the end of every test, about 5%-20% of the Mycelium-based materials were infected by external bacterial growth. This could be prevented by adapting a more careful approach while working with Mycelium-based materials.

3.9 Density Gradient

It was observed from the Mycelium blocks grown that there was a steady density gradient change across the length of the material. Stronger concentration of Mycelium was found at the interfaces. This can be explained by the following. (1) Penetration of air occurs in between the plastic wrap while it is growing in molds. The top part receives the highest exposure to air. Thus Mycelium grows more on the top surfaces than at the bottom where air takes longer to travel. Hence more heavy growth of Mycelium is seen at the top than at the bottom where it is observed to be more porous. (2) The mold grows hot while growing which confirms a chemical reaction occurring among Mycelium, substrate particles and air. It could be felt on touching the brick forms during Growth Tests. The heat at the center is able to less successfully transfer to external environment than heat generated at the interfaces and top surface. The oxygen being the important component facilitating air exchange justifies the denser growth of Mycelium at the top surfaces.

From the above experiments it is concluded that if we keep increasing the thickness of the material there will be a point at which the center becomes too hot or too anaerobic (devoid of oxygen) to allow any growth at all. Thus an optimal thickness of the Mycelium material which would allow (1) all its surfaces to breathe uniformly and (2) keep the internal and external thermal exchange consistent, should be taken into consideration while designing growth containers.

Figure 99: (left to right) Top and bottom surfaces of Mycelium bricks; top surface shows denser material growth, bottom surface shows more porosity because of air pockets

3.10 Aesthetic Performance Test

Mycelium blocks were tested for light reflectance using a Hodson Light Box and Optical Set. The experiment was conducted using two bricks: one having glass percentage 20 and the other with no glass. The test was conducted in a dark room and allowing one single ray of light to pass through the Light Box to reflect on the face of each brick. The following results were observed: (1) The Mycelium brick having 20 percent glass reflected light and a spectacular reflection of blue cut glass was seen to form on the white base paper. (2) The Mycelium brick having no glass did not reflect at all.

Analysis: From the test it was proven that if glass is made to bind with Mycelium and the composite block can retain its structure, with glass pieces being present on the surfaces of the block, the composite block can reflect light.

Figure 100: Set-up of Aesthetic Performance Test with Light Box extruding a ray of light which reflects on the surface of Mycelium-glass brick

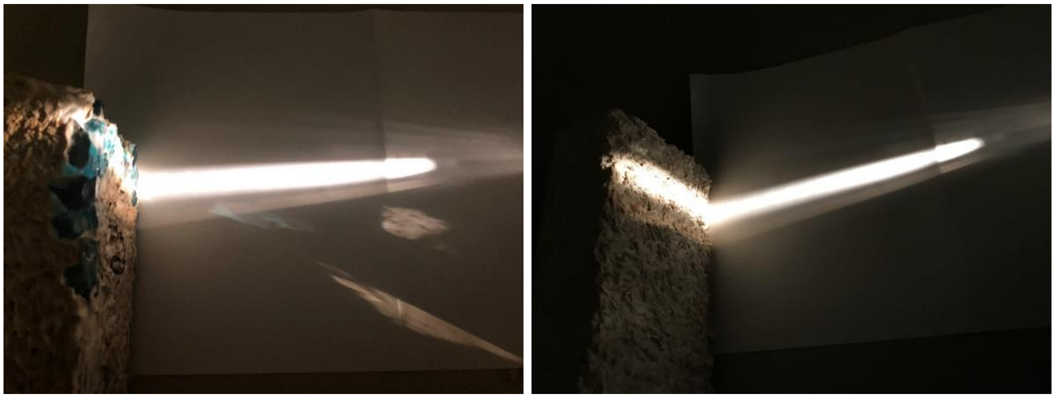

Figure 101: (left to right) Composite Mycelium-glass brick reflecting light; Solid Mycelium brick not reflecting light

Figure 102: Composite Mycelium-glass brick reflecting light; Blue color of the "culled" recycled glass can be observed on the white base paper where the ray of light reflects

Chapter 4. Conclusion

Mycelium is a growing material and it could be one of the most promising future industries in the world. Considering the building industry alone, Mycelium could bring a massive change in the world of construction and revolutionize the industry because of its sustainable design practices. For our research we used glass to combine with Mycelium. It gave unexpected results. However the results provide more insight about using glass as an aggregate and suggests a different approach of experimentation that could be adapted in future. The challenge lies in (1) Identifying the most sustainable methodology, thus asking us to look into nature for solutions, and (2) Develop our understanding of Biomimicry.

We reflect on a few significant advantages of using Mycelium. (1) To make a brick using Mycelium no extra energy is needed (in this case oven was used for baking the bricks because of restricted climatic conditions. However the temperatures at which Mycelium material grow successfully are far lesser compared to those used to fire bricks in conventional masonry construction.) (2) Mycelium follows a cradle to cradle approach where all the materials used for its manufacturing process could be recycled or taken back to Mother Nature following a circular life cycle. Conventional bricks use non-renewable resources like fossil fuel and at the end of their cycle release hazardous pollutants in environment. (3) The cost of production of a single Mycelium brick is lesser than the conventional masonry brick. This is essentially because the materials needed for growth of Mycelium are locally available like fungus, agricultural wastes, flour and water. (4) No special equipment is necessary to manufacture them. Thus Mycelium units can have a significant contribution in future towards low cost sustainable housing options.

Further research is necessary to help find (1) A suitable binding agent with Mycelium and glass at room temperatures. (2) An optimized process of mixing the Mycelium with glass thus helping the bonding of Mycelium through its hyphae structures. (3) Optimal work-room conditions to successfully grow Mycelium-based materials. It is believed with suitable working conditions the Mycelium blocks could achieve their desired strength and rigidity making it more efficient for use in the construction industry. It is also suggested that further research can be conducted on: (1) Determining thermal conductivity of Mycelium (2) Acoustic properties (4) Insulation properties (3) Fire resistance (4) Study of Mycelium materials loaded in shear (5) Life Cycle cost analysis of Mycelium.

In conclusion, currently Mycelium-based materials should not be compared with high strength materials such as composites, wood, bamboo or concrete. They are believed to belong to the category of insulation materials like foam, polystyrene. Thus instead of studying its structural properties viz. strength and stiffness, it is important to gain more insight about its thermal and dynamic properties viz. thermal insulation, air exchange, acoustic insulation, stress amplitude, among others.

From the experiments performed some suggested applications of Mycelium-based materials are: (1) Insulation boards (2) Sandwich panels (3) Acoustic board panels. Presently EPS (Expanded Polystyrene) foam dominates the construction industry because of its inexpensive price and easy availability. However the health and environmental factors associated with foam is immense and detrimental to our surroundings. Mycelium-based materials can offer a sustainable and cheap alternative. The performance of composite materials is important to be observed in shear. Thus it is recommended to perform a thorough investigation of Mycelium based materials loaded in shear in future.

The world needs better materials for our industries and our livelihoods. We should strive to use less energy in manufacturing materials around us. As pointed by Janine Benyus we should be making materials to fit into nature's recycling system. Biologists confirm, that, in nature the mushrooms are the recycling systems. Mycelium are incredible self-assembling materials that feed into materials we would think are wastes such as seed-husks or woody bio-masks and transform it into a chitinous polymer having a variety of services. Because it is made from natural products it is a hundred percent compostable in our own backyards. The use of agricultural wastes gives it the flexibility to be sourced locally for use as substrate for feeding on Mycelium. The organism operates on self-assembly and does most of the work itself in the manufacturing of the bricks and thus a small set-up is sufficient for growing these bricks. The use of mycelium could entirely revolutionize the industries which we are living in right now. All we need is the power to see it and use it consciously. It is time we start making the right choices.

References

[1] “Mycelium,” *Wikipedia*. 31-Mar-2018.
[2] “How to Grow Objects With Mushroom Mycelium,” *Core77*. [Online]. Available: https://www.core77.com//posts/55675/How-to-Grow-Objects-With-Mushroom-Mycelium. [Accessed: 29-Sep-2018].
[3] P. O. Akadiri, E. A. Chinyio, and P. O. Olomolaiye, “Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector,” *Buildings*, vol. 2, no. 2, pp. 126–152, May 2012.
[4] M. Haneef, L. Ceseracciu, C. Canale, I. S. Bayer, J. A. Heredia-Guerrero, and A. Athanassiou, “Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties,” *Sci. Rep.*, vol. 7, p. 41292, Jan. 2017.
[5] M. J. Carlile, S. C. Watkinson, and G. W. Gooday, *The fungi*, 2nd ed. San Diego, Calif. ; London : Academic, 2001.
[6] R. J. J. Lelivelt, “The mechanical possibilities of mycelium materials,” p. 83.
[7] “Bread Mold Diagram,” *(Simple Electronic Circuits)* •. [Online]. Available: http://wiringdiagramone.today/bread-mold-diagram.html. [Accessed: 25-Oct-2018].
[8] jurisdiction:Commonwealth of A. corporateName:Australian N. B. Gardens;, “Mycelium.” [Online]. Available: https://www.anbg.gov.au/fungi/mycelium.html. [Accessed: 25-Oct-2018].
[9] “Materials Research — STUDIO MURMUR.” [Online]. Available: http://www.studiomurmur.net/new-project/. [Accessed: 11-May-2018].
[10] “Mycotecture - growing into form,” *IAAC Blog*. .
[11] “Cradle-to-cradle design,” *Wikipedia*. 12-Jun-2018.
[12] “INTERVIEW: Architect David Benjamin on Building The World’s First Mushroom Tower at PS1.” .
[13] “3D-Printed Mycelium Chair Sprouts Living Mushrooms! | Inhabitat - Green Design, Innovation, Architecture, Green Building.” [Online]. Available: https://inhabitat.com/3d-printed-mycelium-chair-sprouts-living-mushrooms/. [Accessed: 11-May-2018].
[14] “Fast Facts About Plastic Pollution,” *National Geographic News*, 16-May-2018. [Online]. Available: https://news.nationalgeographic.com/2018/05/plastics-facts-infographics-ocean-pollution/. [Accessed: 25-Jul-2018].
[15] “Dezeen reports on the opening of MycoTree at Seoul Biennale,” *Fachgebiet Nachhaltiges Bauen / Sustainable Construction*, 04-Sep-2017. .
[16] shaneboland.com, “Grow | Material.” [Online]. Available: https://shop.ecovativedesign.com/products/grow-it-yourself-material. [Accessed: 11-May-2018].
[17] “Aspen & Mycelium Blend,” *GROW.bio*. [Online]. Available: https://grow.bio/products/aspen-mycelium-material. [Accessed: 11-May-2018].
[18] shurlyFollow, “+ Shelf,” *Instructables.com*. [Online]. Available: https://www.instructables.com/id/-Shelf/. [Accessed: 18-Nov-2018].
[19] “CASKIA,” *Officina Corpuscoli*. [Online]. Available: http://www.corpuscoli.com/projects/caskia/. [Accessed: 11-Nov-2018].
[20] “Ecovative Shop.” [Online]. Available: https://shop.ecovativedesign.com/?ref=ecovativedesign-headerlink. [Accessed: 11-Nov-2018].

[21] hugohek, “Shop,” *Krown Design*. .
[22] “Mycelium - The Future is Fungi,” *The Green Temple*. [Online]. Available: https://thegreentemple.net/articles/mycelium-the-future-is-fungi. [Accessed: 29-Sep-2018].
[23] “Chitin,” *Wikipedia*. 24-Sep-2018.
[24] “Glucan,” *Wikipedia*. 24-Sep-2018.
[25] “What Do Fungi Contribute to the Ecosystem?,” *Sciencing*. [Online]. Available: https://sciencing.com/fungi-contribute-ecosystem-21989.html. [Accessed: 29-Sep-2018].
[26] “Symbiotic Relationship: Definition & Examples - Video & Lesson Transcript,” *Study.com*. [Online]. Available: http://study.com/academy/lesson/symbiotic-relationship-definition-examples-quiz.html. [Accessed: 29-Sep-2018].
[27] “Grow-It-Yourself-Instruction-Manual-v1.0.pdf.” .
[28] “Cradle to Cradle Islands (C2CI) - What is Cradle to Cradle®.” [Online]. Available: http://c2cislands.org/sjablonen/1/infotype/webpage/view.asp?objectID=1233. [Accessed: 13-Nov-2018].
[29] R. Abhijith, A. Ashok, and C. R. Rejeesh, “Sustainable packaging applications from mycelium to substitute polystyrene: a review,” *Mater. Today Proc.*, vol. 5, no. 1, pp. 2139–2145, 2018.
[30] “Brick - an overview | ScienceDirect Topics.” [Online]. Available: https://www.sciencedirect.com/topics/materials-science/brick. [Accessed: 28-Jul-2018].
[31] World Bank, *Pollution prevention and abatement handbook, 1998: Toward cleaner production*. The World Bank, 1999.
[32] D. Consulting, “Home | Ecovative.” [Online]. Available: https://ecovativedesign.com. [Accessed: 28-Oct-2018].
[33] “Mycoworks Homepage,” *MycoWorks*. [Online]. Available: http://www.mycoworks.com/. [Accessed: 28-Dec-2017].
[34] “Construction News and Trends | Construction Dive.” [Online]. Available: https://www.constructiondive.com/. [Accessed: 25-Jul-2018].
[35] “Report: Global construction waste will almost double by 2025,” *Construction Dive*. [Online]. Available: https://www.constructiondive.com/news/report-global-construction-waste-will-almost-double-by-2025/518874/. [Accessed: 25-Jul-2018].
[36] “Biomimicry Explained: A Conversation with Janine Benyus,” *Biomimicry 3.8*. .
[37] “First Chapter of Biomimicry: Innovation Inspired by Nature,” *Biomimicry Institute*. [Online]. Available: https://biomimicry.org/janine-benyus/first-chapter-biomimicry-innovation-inspired-nature/. [Accessed: 28-Jul-2018].
[38] P. Gruber and B. Imhof, “Patterns of Growth—Biomimetics and Architectural Design,” *Buildings*, vol. 7, 2017.
[39] “NEWS - Klarenbeek & Dros - Designers of the Unusual.” [Online]. Available: http://www.ericklarenbeek.com/. [Accessed: 18-Jul-2018].
[40] “The Growing Lab / Mycelia,” *Officina Corpuscoli*. [Online]. Available: http://www.corpuscoli.com/projects/the-growing-lab/. [Accessed: 02-Dec-2018].
[41] K. De Vis, P. Jacobs, J. Caen, and K. Janssens, “The use of glass bricks in architecture in the 19th and 20th centuries: a case study,” 2010.
[42] “Bruce Goff, Architect- Thanksgiving In Bartlesville, OK,” *KC Modern*. [Online]. Available: http://www.kcmodern.com/kcmodern/2009/12/bruce-goff-architect-thanksgiving-in.html. [Accessed: 03-Dec-2018].

[43] R. Kamthan and I. Tiwari, "Agricultural Wastes- Potential Substrates For Mushroom Cultivation," *Eur. J. Exp. Biol.*, vol. 7, no. 5, 2017.
[44] "Grain-Field And Forest Products, Inc." [Online]. Available: https://www.fieldforest.net/Grain/products/28/. [Accessed: 29-Jul-2018].
[45] C09 Committee, "Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes," ASTM International.
[46] "Bruce Goff's spiralling Bavinger House in Oklahoma demolished - Archpaper.com." [Online]. Available: https://archpaper.com/2016/05/bavinger-house-demolition/. [Accessed: 07-Dec-2018].

Appendix A: Brick Compression Test Comparison Results

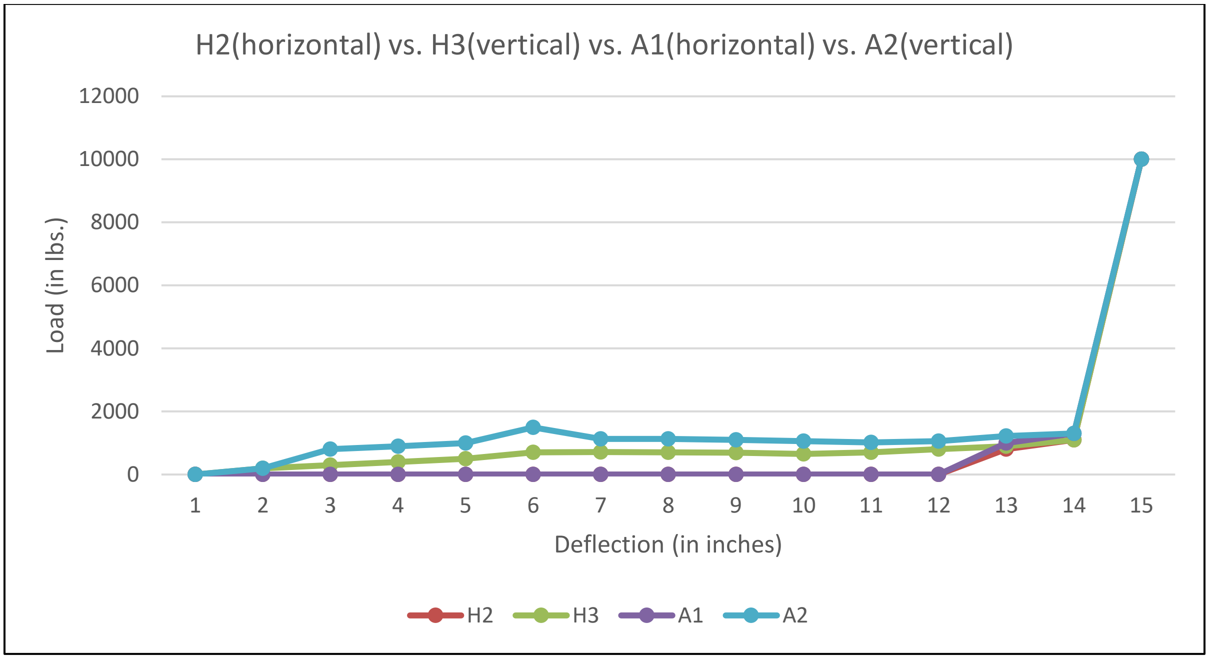

Figure 103: Graph comparing deflection values of bricks H2, H3, A1 and A2 with change in load under Compression

Deflection	H2	H3	A1	A2
3.9	0	0	0	0
3.8	0	200	0	200
3.75	0	300	0	800
3.6	0	400	0	900
3.5	0	500	0	1000
3.2	0	700	0	1500
3.15	0	710	0	1130
3.1	0	700	0	1125
3	0	690	0	1100
2.8	0	650	0	1060
2.6	0	700	0	1020
2.5	0	800	0	1060
2.2	800	900	1000	1220
2	1100	1100	1300	1300
0	10000	10000	10000	10000

Figure 104: Table showing set of values chosen to compare change in deflection of bricks H2, H3, A1 and A2 loaded under Compression

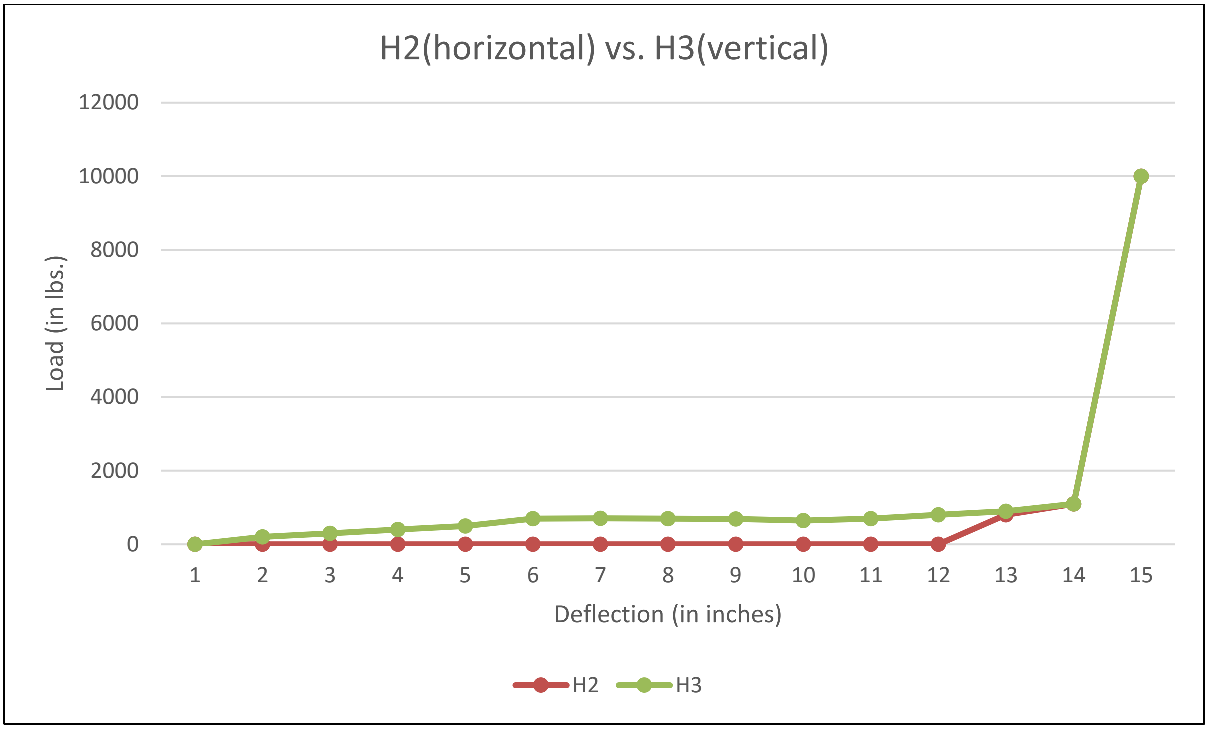

Figure 105: Graph comparing deflection values of bricks H2 and H3 with change in load under Compression

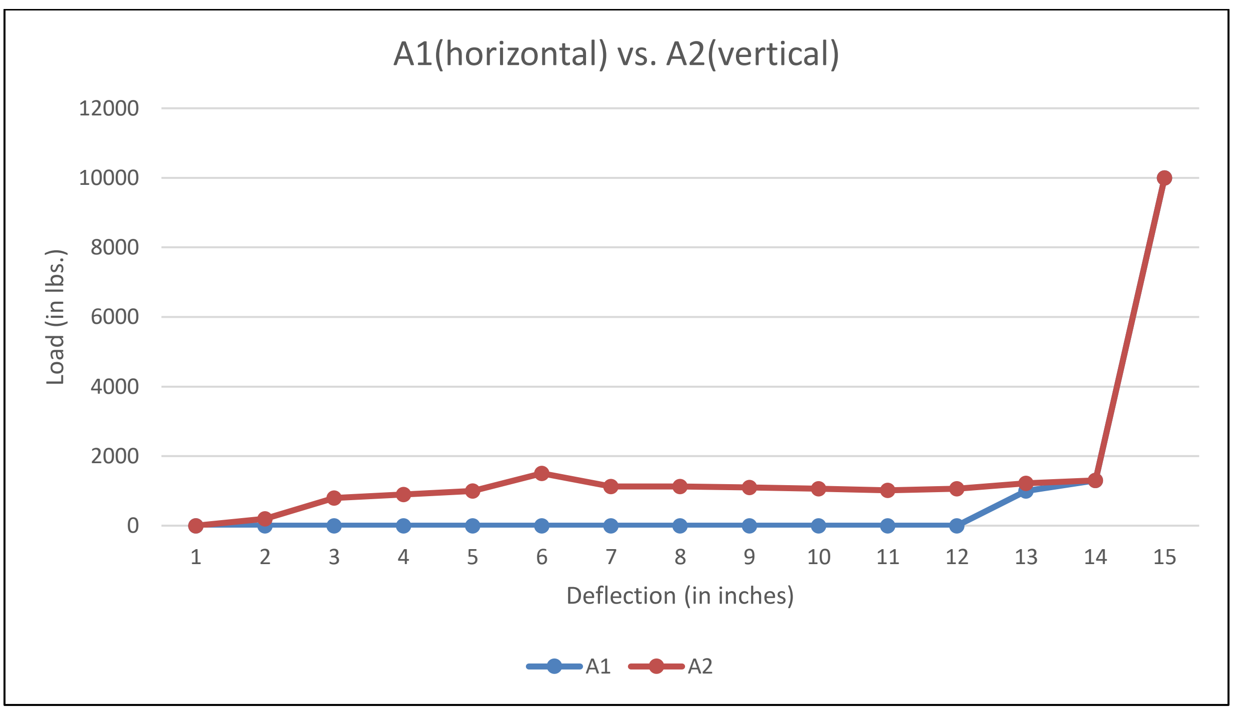

Figure 106: Graph comparing deflection values of bricks A1 and A2 with change in load under Compression

Appendix B: Aesthetic Performance Results

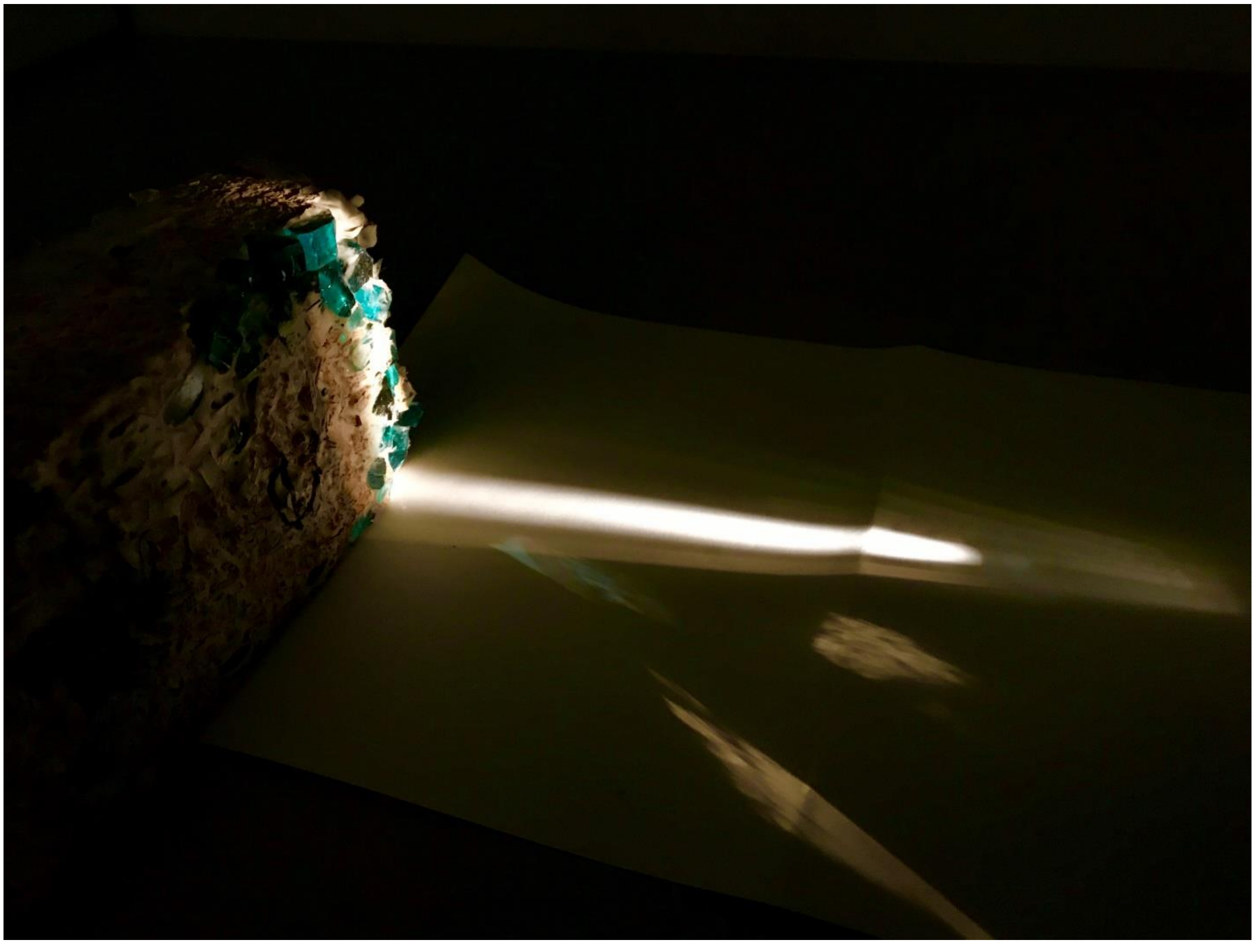

Figure 107: Reflection of light on composite Mycelium-glass brick highlighting the blue "culled" recycled glass