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Mycelium: The Building Blocks of Nature and the Nature of Architecture

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Mycelium: The Building Blocks of Nature and the Nature of Architecture

A Thesis Presented

by

CARLY REGALADO

Submitted to the Graduate School of the
University of Massachusetts Amherst
in partial fulfillment of the requirements for the degree of

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Department of Architecture

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Approved as to style and content by:

Ray K. Mann, Chair

Stephen Schreiber
Department of Architecture

DEDICATION

To the individual who is reading this.

ACKNOWLEDGMENTS

I wish to express my appreciation to Ray K. Mann for your guidance throughout this project. Your insight has been inspiring and your belief in this project has helped push it forward even in times of difficulty. I would also like to extend a special thanks to Carey Clouse for her assistance and support during the production of this thesis and throughout my academic career.

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Finally, I would like to thank my parents for their support throughout this project. You listened to my ideas and believed in them, you inspired me, and you gave me hope when prospects looked dim.

ABSTRACT

MYCELIUM: THE BUILDING BLOCKS OF NATURE AND THE NATURE OF ARCHITECTURE

MAY 2022

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In the face of global climate change, all disciplines and backgrounds have a responsibility to the shared future. The world is facing an impending environmental disaster and humanity's current efforts are not enough to slow this change, let alone reverse it. Much more drastic efforts must be undertaken by every person and discipline. Architecture has both aesthetic and structural components that have contributed to this situation. Much like the rest of the world, the current practices of architecture are not responsive or responsible enough. The building sector has a unique role in national and global energy consumption. Not only are the structures that are created by these assorted professions responsible for consuming large amounts of annual energy, but the very materials used in their construction add millions of tons of waste to landfills each year. The building sector should not just be responsible for the long-term effects of a structure during the construction and demolition phases. Architecture's and other design professions' responsibilities should not end with the completion of a project. Rather, all of the choices, designs, and decisions made before, during, and after the project will echo through the ages as the structure lives on, long after the building has been occupied.

There are many possible solutions to this conundrum, ranging from passive techniques to complex technologies. The incorporation of biological design into modern construction is explored in this thesis. This paper investigates the implications of current building materials in comparison to the potential of an organically informed alternative created from mycelium, the root network of fungi, and post-industrial waste. This thesis considers laboratory experiments and case studies in architecture to understand the shortcomings and potentials of organically derived structures and building materials. Original observations are undertaken to understand the effect of a mycelium composite's design on various physical properties. This project seeks to evaluate the building blocks of architecture and reevaluate the building field from the ground up. Small individual components are assessed, and their long-term implications are explored.

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A WORLD IN TURMOIL

1.1. The Pressing Present

In the face of global climate change, all disciplines and backgrounds have a responsibility to our shared future. While the world faces a rapidly approaching environmental disaster, the current efforts of humanity are not enough to slow this change, let alone reverse it. Much more drastic efforts must be undertaken by every person and every discipline. Architecture has both artistic and technical components that have hurt and helped the tumultuous situation we dwell in and the future we will live through. Much like the rest of the world, the current practices of this field are not responsive or responsible enough. The buildings and construction brought about by architecture and the many related building disciplines are responsible for 36% of energy use and 39% of carbon dioxide emissions globally (“Global”). In America alone, buildings are responsible for 40% of national energy consumption (“An Assessment”). Architecture, in its negligence, has contributed to a global problem. But why is this considered negligence? This is because architecture can do better and should do better, but does not do better. Instead of pressing forward with improvement, it lags behind and delivers minimum requirements. Instead of being a part of innovation, research, and experimentation, it loosely follows the developments of other disciplines. Instead of being an active contributor to the environmental reality, it is a passive artistic participant. This is not acceptable anymore. As citizens of this world and members of a discipline that contributes a disproportional quantity to the current environmental situation, it is architecture’s duty to become an active participant if an environmental disaster is to be avoided. But this poses a question of its own. What is the future of sustainability in architecture?

1.2. The Building Sector and the Environment

It is an undeniable fact that the energy production and consumption of the world has exploded in the past seventy years. America alone has gone from consuming over 34 quadrillion BTU of energy in 1950 to a total of almost 93 quadrillion BTU in 2020 (“Monthly Energy Review”). In the most recent study, around 73% of the nation's primary energy is derived from fossil fuels while only around 11.6% comes from renewable energy. While the steps to de-escalating this situation can be found in the simple phrase "reduce, reuse, recycle", the reality of the energy use of the nation makes it clear that these rational words are not being heeded.

The Building Sector has a unique role in national and global energy consumption. The products of their professions are responsible for consuming a large amount of this annual statistic, yet this sizable consumer is often overlooked. The sector is responsible for creating the places where humans spend the majority of their lives: buildings. In this sense, the sector relates to almost every person who dwells in this nation, but ironically, their perceived connection ends upon the completion of their project. Little does the nation address the future consequences of the products they have made. The building sector is not just responsible for consequences on the environment during construction. Their choices, designs, and decisions will echo through the ages as their creations live on, long after the building has been occupied.

1.3. The Responsibility of Architecture

The designers must be held responsible. The environment is at a critical juncture, and the decisions of humanity count now more than ever. Every decision that is made or not made, deeply thought over or carelessly decided, cut or added, will echo through time. Designers tied to the building sector have an essential duty to navigate structures towards a sustainable path. This does not solely occur when designing to meet the immediate demands of their clients and teams, but in every phase of architecture. Design, construction, and performance in terms of sustainability must be considered from the start and the long-term implications of the project must be acknowledged at every phase.

Architecture is a field that is strongly associated with aspects such as designing and planning. The field is responsible for not only the structures they create, but the impact they have on the occupants and furthermore, the world at large. Though not every project built involves an architect, architects should, at least theoretically, bring the vast knowledge of their field with them to any project they contribute to.

How is it then, that they are sometimes “not necessary”? Indeed, there are many projects that do not need an architect, for an architect is not intrinsically useful for what needs to be completed. Are architects useful in general? Could they be more useful? Could architects and their skills be more essential? Architecture is more than an arts degree, and now more than ever, it needs to prove this to the world. Instead of focusing on the aesthetic, it needs to focus on the effective. While bound by the requirements of their clients, architects still possess a unique opportunity to put their design and planning skills to use in creating a better future in every project they are a part of.

1.4. A World of Solutions

Can innovation be brought into the field by bringing the simplicity of nature back into consideration? Does this perchance sound illogical and even contradictory? To achieve innovation through simplicity? While sustainability in architecture can go in countless directions, I seek to research the implications of implementing a natural phenomenon into the built world. In a world filled with complex and hidden innovation, I seek to focus on simple and transparent methods that can revolutionize architecture, building, and our battle against a global climate crisis.

Now what is this subject I seek to investigate? It is a network of strands that while individually small, can make up the largest living organism on the planet. A member of a family that is often disdained by humans as a disgusting and destructive entity, but in reality, can be a savior to the situations created by man. I seek to explore mycelium, the hidden network of fungi, in its potential in the built environment. Mycelium has many uses across the disciplines ranging from bioremediation to medication, but in this study, I seek to investigate it in its use as a waste-deferring and upcycling building component (Stamets 2005). It has many potential applications due to its insulative, fire retardant, and acoustic properties, but also due to its potential benefits in comparison to common building materials. Instead of contributing to waste and emissions, mycelium can be grown on substrates of post-industrial waste. Instead of creating a need for new materials, it repurposes spent materials decreasing demand for new materials. It reuses pre-existing waste items and recycles them into a new usable product. Mycelium is important not only because it stops unsustainable demand and environmental effects, but undoes damage caused by them through a natural process.

CHAPTER 2

MYCELIUM

2.1. What is Mycelium?

It surrounds us. It came before us. It will outlive us. Whether humans realize it or not, the very ground they walk upon is the habitat of a diverse world of networks and connections that only occasionally rise above the surface. Mycelium can be thought of as a root system of fungi, and much like an iceberg, there is much more below than what can be seen on the surface. The world abounds with a plethora of species with different shapes, size, habitats, and methods of survival. The member of the Fungi Kingdom represented throughout this paper is the Oyster Mushroom (*Pleurotus Ostreatus*).

2.2. Mycelium in the Environment

This paper will focus on fungi in architecture and the subsequent possibilities and effects. While much of the world of fungi is a mystery to humanity, the swift extinction of many members of all kingdoms of organisms is hardly a secret. At the base of these organisms' lives is their partnership with each other. Fungi are often one of the most basic and essential members of Earth's biosphere. As Paul Stamets writes in *Mycelium Running,*

> "As caretakers for future generations, mushroom communities surrounding trees govern habitat progression. I believe fungi have evolved to support habitats over the long term, protecting generations hundreds of years into the future. Saprophytic mushrooms gobble up debris fallen from the trees and prevent invasion by parasites. The mycorrhizae channel nutrients, expand root zones, and guard against parasites. Similarly, endophytic fungi, less well understood, chemically repel bacteria, insects, and other fungi. After hundreds of millions of years of evolution, fungal alliances have become part of nature's body politic." (Stamets 61)

This alliance between fungi and other members of the environment can be found far beyond just that of trees. They can be seen to some degree as the building blocks of nature. An "organism" is a living entity that is capable of growth, development, and reproduction. To be capable of these things, organisms require energy. The form of the required energy varies from organism to organism. Some, known as autotrophs, are able to take inorganic compounds. Others, known as heterotrophs, consume organic compounds. Where and how do organisms acquire these necessary resources? Over the millennia, Fungi have played a pivotal role. Fungi have been useful in sequestering components from inorganic sources and helping build the base of soils (Stamets 24). Furthermore, fungi themselves can serve as a food source for other organisms. Fungi have helped create the environment and continues to supply and break down the beings within it. In this way, fungi have helped serve as a building block of nature.

While fungi perform important roles that allow the environment to thrive, the actions of one species of animal has generated extensive damage this complex system of nature: humans. While diversity in habitats has helped encourage evolution, as different organisms evolve to meet the challenges of their ever-changing environment, the action of humankind has rapidly intervened in the system. Humans have caused decreasing diversity by altering the environment quicker than organisms can respond, resulting in death. This usurpation leaves holes in an interdependent system, decreasing its diversity and the possibly of subsequent diversity in the future.

With changes in climate and the forced introduction of foreign and artificial elements into the environment, the network of nature has been strained. Not only is this occurring at an alarming rate, but there is not enough being done to slow it down, let alone stop it. The carbon footprint, though only one way of gauging the negative effect of humanity on their environment, shows the extreme burden. There are many more ways that humanity has affected nature than what can be assessed by emissions. As Paul Stamets writes in *Mycelium Running*,

> “In the 1960s, the concept of “better living through chemistry” became the ideal as plastics, alloys, pesticide, fungicides, and petro-chemicals were born in the laboratory. When these synthetics were released into nature, they often had a dramatic and initially desirable effect on their targets. However, events in the past few decades have shown that many of these inventions were in fact bitter fruits of science, levying a heavy toll on the biosphere” (Stamets 32)

Humanity has played a large role in developing the current environmental reality. Its negligence has caused environmental shifts that have developed faster than the organisms that must overcome them. Humans have introduced foreign elements that organisms have no proper response or diverting strategy to use against their presence. Humanity has made a lasting impact for life on earth, but members of another kingdom pose strategies for overcoming it.

2.3. Mycelium as a Resource

Fungi play a pivotal role in the environment, but what if they played a pivotal role in humanity's interaction with it? What if the building blocks of nature could be used as building blocks of architecture? Mycelium can help revolutionize one of the large sectors of human disturbance by becoming a groundbreaking resource for the building sector.

Though it starts its life as a microscopic spore, the Oyster Mushroom, like so many of its cousins, possesses features that make it an evolutionary marvel, though these adaptive traits that are prominent throughout the kingdom, are perceived as nightmares if found in other species. Oyster Mushrooms are fast growing, able to consume a great variety of substrates from ranging from wood to plastic, but have fruiting bodies that are safe enough for a human to eat. They have been used in bioremediation, commercial kitchens, and art. As a white rot species of fungi, they breakdown lignin, leaving cellulose behind, which gives the remaining material a pale look (Stamets 158). This hardy, non-toxic species and its wood-based diet make it the fungi of choice for experimentation.

2.4. The Properties and Potential of Mycelium in Architecture

The world continues to demand new materials, yet thoughtlessly places spent materials into the waste steam, much of which is construction material. Waste can be diverted from the landfill and used as a substrate for these organisms. Instead of taking up space and slowly decomposing, materials can be upcycled and stored in mycelium building components. The mycelium acts as a binding agent as it penetrates and feeds on the substrate, bonding the material as it feasts on its nutrients. Once cured, it results in a strong, fire retardant, sound absorbing, insulative product that is biodegradable at the end of its life.

CHAPTER 3
CASE STUDIES

3.1. Introduction

Mycelium composites have been not only been studied but put to use on large scale projects. These projects range in size and scope but show that a novel building material can be used in the construction of a structure, even if only temporary.

3.2. The Hy-Fi Tower

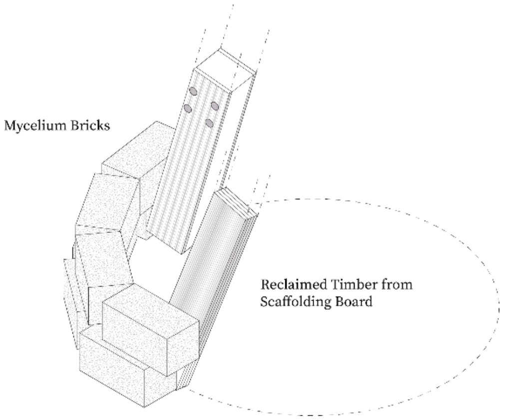


Figure 1: Material and Design.

In 2014, a new chapter of bio-material emerged. While there had been interest in mycelium since the 1970's, David Benjamin of The Living led his team in the creation of a 12-meter tall structure made from mycelium composite bricks. By teaming up with Ecovative, the group was able to create 10,000 bricks were made of agricultural waste. The mycelium was placed in forms and colonized the waste byproduct. The bricks were removed, cured, and set in place with a sustainable mortar. The structure itself was supported by a skeleton of steel and reclaimed timber ("Hy-fi").

The bricks measured 17" x 7" x 4" with strength of 30 psi and a durability that after testing in an accelerating aging chamber, showed no changes in mechanical properties for at least three years. Some of the other notable properties include the material's embodied energy. The mycelium composites embodied energy was estimated to be 0.2 MJ/kg in comparison to 4.5 MJ/kg, 4.7 MJ/kg, and 20.1 MJ/kg in brick, concrete, and steel respectively. The carbon emissions were estimated to be 0.04 kg CO2/kg in comparison to brick at 0.24 kg CO2/kg, concrete at 0.16 kg CO2/kg, and steel at 1.37 kg CO2/kg ("Hy-fi").

The raw material costs of the project were encouraging. It was estimated that the mycelium bricks cost \$1.25/ft^3. This is competitive with the concrete at a slightly higher \$1.89/ft^3, and far below brick at \$11.52/ft^3, steel at \$1.343.04/ft^3, glass at \$272.73/ft^3, and wood at \$10.73/ft^3 ("Hy-fi").

The material is low cost, both financially and environmentally, especially in comparison to many conventional materials. The project only stood outside for several months, but sample bricks were accelerated aged to three years in exterior environment to see how such a material might perform long term. The physical properties did not change, however, the end of the Hy-Fi's stay at MOMA, did not see the structure dismantled and relocated. The bricks had been mortared in place and broke as they were removed from the structure. This however was not a detrimental to the project's mission. The mycelium bricks did not follow the path of many Construction and Demolition materials. Instead of taking up space in the landfill, the mycelium bricks were composted. In a matter of 60 days, the bricks went from being a building component to 40 cubic meters of soil.

This analysis of an early mycelium structure yields interesting information. This is the first large scale structure of this fungal variety. A 40-foot structure was made out of living units created from waste materials. This is impressive and innovative. However, what are the shortcomings and what might be gleaned from the shortcomings and improved upon in other studies?

The bricks are both lightweight and sustainable, however, they are not ideal structural elements. They are lighter than the average brick, but they are also weaker than the average brick. This ambitious project marked the first large-scale use of mycelium as a building component. Though temporary in nature, it posed the possibility of long-term exterior applications. At the same time, this project highlights one of the large shortcomings of mycelium composites in Architecture; its compressive strength. The bricks had a strength of 30 psi, far below the standard properties of most building materials.

3.3. Shell Mycelium Pavilion

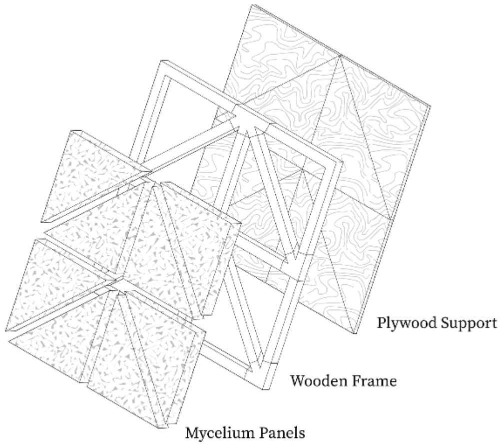


Figure 2: Material Layout.

The next case study is an exterior structure that was meant to fall to pieces. In 2016 BEETLES 3.3 and Yassin Areddin Designs came together to analyze and create. The resulting project, "Shell Mycelium Pavilion" is a response to the wasteful construction trend in the world. Everything from shopping malls to Olympic Villages are built rapidly and then quickly abandoned. These dilapidated shells possess a great amount of embodied energy in the very materials that have been left to succumb to the elements. The two teams came together to create a structure that is intentionally temporary, but instead of contributing to resource mismanagement, creates a structure from nature that can peacefully return to nature.

In this structure, the mycelium was not a weight bearing element. The structure was supported by a wooden system. Coir pith was added on top of this layer and mycelium was introduced into the coir where it began to grow. The mycelium grew and died, forming a protective shell atop the structure that eventually disintegrated with the rest of the structure.

While the mycelium in this study did not perform much of a structural function, it reveals some of the shortcomings of using mycelium in this method. Mycelium is not weatherproof. In this situation it was intentionally left to decomposed, however, in other applications, this characteristic must be taken into consideration. "The Hy-Fi" and "Shell Mycelium Pavillion" both raise questions relative to the hardiness and strength of living culture structural elements.

3.4. MycoTree

In 2017, a new variety of Mycelium structure emerged. Under the guidance of the Block Research Group, a cured mycelium structure was developed. "Mycotree" is a self-supporting structure made from mycelium and bamboo. The innovation in this design is that it seeks to use geometry to put a weak material into compression and allow it to perform optimally as a structural element.

This case study is innovative in its use of cured mycelium, geometric design, and use of compression, however, it poses a few questions. To what extent is the mycelium supporting the structure? Upon examining the structure’s diagrams, it becomes clear that the internal components and the connection plates are the key to making this structure work. These elements however are made from bamboo. In this study, the mycelium is grown like a fungal tissue around a bamboo-based bone. Is it at the very least the mycelium that is holding the system together? Does it serve a purpose, or could the same structure operate without it as a bamboo skeleton? On the other hand, this study also offers ideas for future studies. Instead of just being an fill material, what if the mycelium could be used to hold structural elements together like in the earlier brick example? However instead of being a blended substrate, the mycelium would grow in an optimally oriented wooden base. Instead of having a bamboo core, the mycelium could grow as the adhesive of an engineered lumber unit.

3.5. The Growing Pavilion

In 2019, another ambitious project arose in a temporary outdoor exhibition. Pascal Leboucq, Erik Klarenbeek's Krown Design studio, and Biobased Creations came together to create, “The Growing Pavilion”.

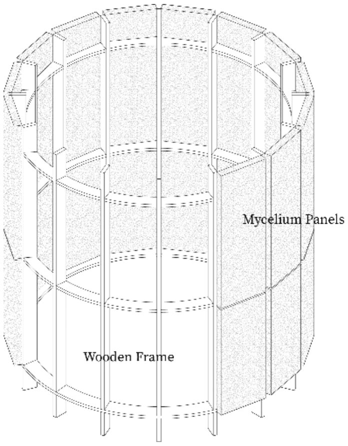


Figure 3: Panels and Frame.

Having been strongly inspired by the current state of the world, the group sought to find new sustainable solutions. This led them to create a structure made from bio-based material. The drum shaped structure stood outside for the duration of Dutch Design week, allowing an opportunity for 75,000 people to explore (Pownall). While it was immediately clear to many onlookers what the structure was composed of, everything from plants to fungi was used in the creation of the pavilion. Of the materials used, the most eye-catching was the mycelium panels. These panels were composed of Ganoderma mycelium and agricultural waste. The mixture is placed into forms and covered. It is then placed in dark room to cultivate until it is removed from the forms and cooked at 80 degrees Celsius for 2 days (“About”). The panels are then placed into the supporting structure of “The Growing Pavilion” where they contribute to the thermal and acoustic properties of the building.

CHAPTER 4

LABORATORY REPORTS

4.1. Introduction

There is a large body of ongoing research into mycelium composites. While these studies vary in size and scope, they help create a background for understanding the potential and the shortcomings of mycelium as a building component. From these experiments, general properties like compressive strength, flexural strength, fire, and thermal properties are examined in accordance with different variables like substrate formula and fungi species used. Years of experimentation are made available to remote parties, and the methodology, results, and conclusions are accessible for the general public. A master's thesis is only one year in duration, a short amount of time in an emerging field that possesses so much potential and tangents of interest. Several studies were especially useful in the development of this thesis. These lab reports helped establish the general properties and limitations of mycelium composites today.

4.2. Mycelium-Based Bio-Composites for Architecture: Assessing the Effects of Cultivation Factors on Compressive Strength

One of the largest focuses of this thesis is compressive strength. Ali Ghazvinian, Paniz Farrokhsiar , Fabricio Vieira, John Pecchia, and Benay Gursoy's 2019 paper, "Mycelium-Based Bio-Composites for Architecture: Assessing the Effects of Cultivation Factors on Compressive Strength", was one of the most pivotal papers in the development of this thesis. The team from Penn State University's Architecture Department tested the compressive strength of different varieties of substrate.

Pleurotus Ostreatus, Gray Oyster Mushroom was used to inoculate several sterilized substrates. They were placed in a growth chamber for two weeks and then placed in sets of plastic forms for three days to allow for greater density. Afterwards, the samples were removed and cured in an oven. The compressive strength of each sample was tested.

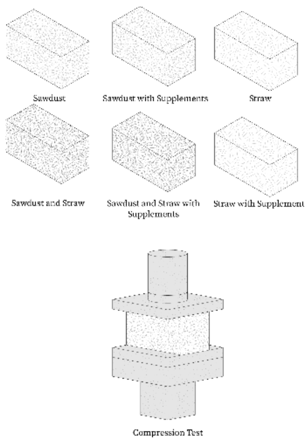


Figure 4: Substrates and Compressive Testing.

The independent variable was the content of the substrate. There were six different mixes. The first was composed of 100% sawdust, the second was composed of 90% sawdust and 10% wheat bran, a third was composed of 100% straw, a fourth was composed of 90%straw and 10% wheat bran, the fifth was composed of 50% sawdust and 50% straw, and the final was composed of 45% sawdust, 45% straw, and 10% wheat bran (Ghazvinian et al. 510).

When the performance of the substrates with and without supplements (wheat bran) are compared, the samples with the addition of supplements had higher compressive strengths with an ultimate strength of 1380.6 kPa, 169.2 kPa, and 116.1 kPa in comparison to the non-supplemented samples at 1018.4 kPa, 72.7 kPa, and 105.9 kPa for sawdust, straw, and sawdust-straw mixed substrate respectively (Ghazvinian et al. 512). The authors suggest that this was apparent early in the preparation of the samples, for the samples with supplements had more homogenous mycelium growth throughout the sample (Ghazvinian et al. 512). Of the substrate compositions tested, the sawdust samples had the greatest compressive strength.

This study inspires a great deal of future ideas. My thesis is based on the concept of using wood waste materials, to divert landfill waste and repurpose it as a new product that decreases the demand for raw materials. The inclusion of sawdust samples and their results after testing suggest that the use of this waste wood product has potential.

This study helped establish physical properties of a material I proposed early in the development of my thesis. The results of the report suggest that sawdust has a higher compressive strength than several other organic composites. From this study, my interest in sawdust as a substrate is supported. One of the other large takeaways from this paper regarding the development of my thesis is the limitations of the mycelium composites as tested in this study. The greatest compressive strength was 1380.6 kPa, or in imperial units, roughly 200.24 psi. This is far below the compressive strength of most building materials.

While supplemented sawdust provided the greatest results in the experiment, it is still far below the properties required for it to be used in many applications.

4.3. Mechanical Physical and Chemical Characterization of Mycelium Based Composites with Different Types of Lignocellulosic Substrates

This 2019 study by Elise Elsacker, Simon Vandelook, Joost Brancart, Eveline Peeters, and Lars De Laet provides valuable insight into other properties of mycelium composites. One of the variables studied in the was thermal conductivity. It was measured according to ASTM D 5334-00. The thermal conductivity of the mycelium composite ranged between 0.0404 – 0.0578 W/m.K. The thermal properties of mycelium composites are in the same scope of performance as other common insulating materials in use today. For example, mineral wool has a thermal conductivity of around 0.047 W/m.K, sheep wool plates perform at between 0.038 – 0.054 W/m.K and extruded polystyrene has a conductivity between 0.025 – 0.035 W/m.K (Elsacker et al. 15).

Another property tested in the study was the mycelium composites' water absorption rate. The study suggests that a denser exterior mycelium layer's hydrophobic properties can result in lower water absorption rates (Elsacker et al. 15).

4.4. Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium – Biomass Composite Materials

This study by Mitchell Jones, Tanmay Bhat, Everson Kandare, Ananya Thomas, Paul Joseph, Chaitali Dekiwadia, Richard Yuen, Sabu John, Jun Ma, and Chun-Hui Wang was published in 2018 and explores the fire replated properties of mycelium composites.

In this setting of experiments, *T. versicolor* was used to inoculate a substrate of sterilized wheat grain. The components were mixed together and placed into petri molds where they grew for 6, 12, and 18 days in a controlled environment. The samples were then cured for 48 hours at 50 degrees Celsius.

The study found that growth period does not hve an effect on the “thermal degradation characteristics of mycelium” (Jones et al. 8) The authors also write,

> “The fibrous structure of mycelium is retained following pyrolysis, albeit with a reduction in its diameter. The fire reaction properties of mycelium have found to be superior to other competing thermoplastic polymers (PMMA and PLA) due to its tendency to form relatively higher char yields. The presence of mycelium is responsible for an improvement in the fire reaction properties of wheat grains. However, beyond 6 d, the growth time has been found to have no significant effect on the fire reaction properties of mycelium-wheat grain composites. Mycelium has been found to possess certain flame-retardant properties (e.g. high char residue and release of water vapour) and could be used as an economical, sustainable and fire-safer alternative to synthetic polymers for binding matrices.” (Jones et al. 9)

4.5. Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites

This 2018 study by Freek V.W. Appels, Serena Camere, Maurizio Montalti, Elvin Karana, Kaspar M.B. Jansen, Jan Dijksterhuis, Pauline Krijgsheld, and Han A.B.Wösten, investigates mycelium composites through several sets of tests.

Samples of various substrate mixes fungi species, and fabrication methods are tested. The two varieties of fungi used were *Trametes multicolor* and *Pleurotus ostreatus*, the substrate consisted of Rapeseed Straw, Beech Sawdust, and Cotton, and the treatments involved no pressing, cold pressing, and hot pressing.

When placed on top of water, they found no relation between the absorption rate in the samples and fungi species, substrate composition, or fabrication method. This is contributed to mycelium’s water repellant properties. When the samples were exposed to different relative humidities, their masses and measurements varied over time. They concluded that this expansion would need to be considered if mycelium composites were to be used in a building. One of the other takeaways from this study regarding this thesis was the need for more uniform colonization of the substrate. The authors found that for both *Trametes multicolor* and *Pleurotus ostreatus*, the substrate was more densely colonized near and on exterior surfaces (Appels et al. 70).

4.6. Growing living and multifunctional mycelium composites for large-scale formwork applications using robotic abrasive wire-cutting

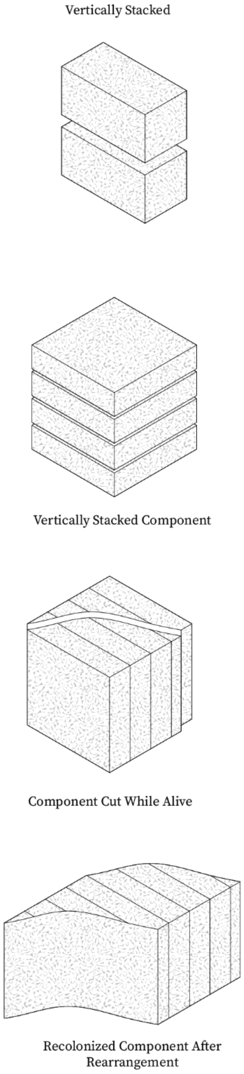


Figure 5: Development.

This 2021 study by Elise Elsacker, Asbjørn Søndergaard, Aurélie Van Wylick, Eveline Peeters, and Lars De Laet consisted of a Belgian-Danish team of researchers seeking to investigate and model fabrication processes for mycelium material. Their work resulted in a method for growing large amounts of material blocks, a method for cutting the colonized blocks, use of mycelium as a framework, and the self-healing properties of the fungi in the composite.

The study investigates creating biohybrid components, units that are made from a combination of biological and non-biological materials. It also investigates the use of technology in the creation of components through the use of robotic wire cutting.

In regard to my thesis, this study was helpful in its investigation of component connection method and its potential to replace popular unsustainable construction materials. Insulation like Expanded Polystyrene is used throughout built structures on exteriors and interiors but are not biodegradable and often end up in a landfill. Like many mycelium studies before it, it proposes the reuse of organic waste into a new material.

One of the unique takeaways of this study were the results from the "Understanding the Impact of Mixing and Densifying the Substrate" (Elsacker et al. 7). Blocks were placed in three variations. In the first variation blocks were placed next to each other. In the second variation, the blocks were compressed and stacked vertically. In the third variation, blocks made of uncompressed, pre-colonized, and remixed substrate were stacked vertically. Of these three trials, the final offered the greatest insights to future design. Compressing component damages the fungal skin, causing blocks to perform better when not compressed. On a related note, allowing the substrate to be fully colonized and then remixed allows for a more thoroughly myceliated structure. As the authors write,

> “Moreover, mycelium responds to local damage by reinforcing, re-growing and reconnecting neighboring branches; the strengthening of the branches improves their robustness to damage [13]. When the hyphae are continuously trimmed, more local branching is stimulated, thus resulting in improved hyphal connections and a more robust and denser network [14]. Consequently, damaging or cracking the mycelial network during growth stimulates the formation of a more robust and denser network” (Elsacker et al. 3)

In the final fabrication method, living mycelium block was cut. This was decided due to the interior of the substrate being less colonized than the areas on the exterior. By keeping the mycelium alive after cutting, the newly exposed areas could be colonized more densely, resulting in a stronger surface and component. By keeping the block alive after cutting allowed the mycelium to compete with other fungi, and despite the risks of an uncontrolled environment that it faced in transport between locations, the block won out against contamination.

CHAPTER 5

MYCELIUM COMPOSITE DESIGN AND TESTING

5.1. Structural Component

I seek to ultimately make composite materials; materials made of more than one material and possessing a bonding material. In the case of this study, the bonding material is mycelium and the other materials are the substrate whose properties and direction can be manipulated. This project will use a variety of post-industrial wastes ranging from wood, plastic, drywall, and cardboard with Oyster Mushrooms. When the mycelium has reached the desired level of growth, the unit is cured by heating. Depending on how it is treated (cured, pressurized, substrate manipulation such as firmness, density, material, dimensions), the product will vary.

5.2. Background on Earlier Observations:

The initial trial commenced January 16, 2021 to explore the possibility of growing Oyster Mushroom mycelium through propagation. Oyster Mushrooms (*Pleurotus Ostreatus*) were selected from a local market for experimentation. The work area was sterilized with 70 % alcohol and 91% alcohol. The tools and materials were sterilized. Gloves and masks were worn while handling materials during experiment. The substrate was boiled for one hour to reduce the risk of bacterial intervention and the containers were sterilized with heat and then thoroughly cleansed with 70% and 91% alcohol which was then allowed to evaporate before substrate was added to containers. Holes were punched through the top of the containers to allow ventilation and the containers were then sealed and left to cultivate in the dark of a 68 F room. All containers produced mycelium growth and no contamination was found.

Secondary trials started on Saturday, March 6, 2021 and focused on substrate variety. The three substrates used were composed of sawdust, rice hulls, and a mix of sawdust and rice hulls. The sawdust was from Sanford & Hawley, Inc., a building material supplier, and the rice hulls were sourced from *Rice Hull Organic,* an online supplier. The same handling and sterilizing procedure as listed above was performed save for the exception of boiling the containers. The containers were instead cleansed with alcohol. There were 12 samples total that were divided into 3 testing categories. Four containers were filled with wood shavings, four were filled with rice hulls and four were filled with a mixture of shavings and rice hulls. A ¼" hole was drilled into the top of the lids which were then sterilized and a poly-fil filter was added to it. The containers were left to cultivate in a dark room at 68 F. Only one container (100% wood shavings) showed signs of contamination and was subsequently removed from the area.


Figure 6: Mycelium Samples.

These trials showed that mycelium could be propagated from other mushrooms, but also showed a need for greater accuracy and measurement in the future. This inspired the next round of observations.

5.2.1. Tier One Observations:

Previous trials showed that mycelium could be grown, but now the question shifted. What are the best conditions to grow mycelium? This set of experiments explores three variables: temperature, substrate composition, and ventilation area. Two types of substrates were used; saw dust and shavings from Sanford & Hawley, Inc. and wood chips from the local landfill. It was decided from this point forward, only waste materials would be examined, additives could be considered later but the focus of the experiment would revolve around reusing waste as a building material. The Sanford & Hawley sawdust/shavings (SHSS) was ideal for its small particle size, but also the imperfections of its contents. The objective of this study is to use *waste* as a material. As such, it is bound to be imperfect. Unlike other studies which may seek to investigate the effect of species after species of tree sawdust on mycelium growth, this study embraces the fluidity and variation of wood and wood waste that actually exists in our waste stream. This sawdust is likely a mixture of coniferous and deciduous wood along with plastic and other small additives that industrial lumber and materials include. It is a realistic slice of the variety of waste wood products that are manufactured, used, and disposed of. This is a unique opportunity to investigate how actual waste can be used as a building resource. The wood chips (WC) are much larger in size. They were sourced from the Avon Landfill and are predominantly coniferous. Every year, the town of Avon offers Christmas tree collection services in the times after the holiday. Perfectly good trees are cut down early in their life so their corpses can be decorated, only to be deposited on the curbside in less than a month after their death. These trees are then gathered across town, ground up and left for the public to use as mulch at the local dump. Oyster Mushrooms are generally grown on beds of deciduous substrate, but what of conifers? Softwoods continue to represent an increasing percent of American lumber, but what of the lumber that has outlived its initial structural service? In many previous studies, hardwoods are used because the white-rot fungi take to them quickly. However, that is not to say that *Pleurotus Ostreatus* could not take to softwood. The strongest strain of fungi from the first trial was collected and used as the mycelium source for this trial.

One of the improvements of this trial is its commitment to greater accuracy and measurements. 24 samples were created to test the effect of three variables: temperature, substrate size, and ventilation area. Twelve samples were be left to grow at room temperature and twelve others were left to cultivate at 80 F. Half of the samples are composed of the small SHSS substrate and half consist of the larger WC substrate. Finally, half of the samples possess lids with one ¼” diameter hole with a poly-fil filter and half possess lids with two ¼” diameter holes with poly-fil filters.

The work area, materials and utensils were sterilized, and gloves were worn to prevent contamination in the experiment. The substrate was boiled for an hour to decrease the risk of bacterial infection and the containers were sterilized with 91% alcohol. Thirty-five grams of substrate were added to each container and 2 grams of the mycelium sample were added to each container of cooled substrate. For this experiment, quality of mycelium growth was judged based upon uniformity, spread, density, and inoculation time.

The mycelium consistently spread more quickly throughout the wood chip substrate. It was able to spread from the top of the substrate surface, down the center and sides. Meanwhile the SHSS samples stayed mainly on the surface and occasionally featured a small amount of growth on the sides.

There were, however, some setbacks. Over the course of this experiment, the WC substrate became contaminated, and the temperature control component could not be achieved due to equipment failure. This observation continued as the SHSS continued to be digested. Ideally, a second trial of Tier One observations would be repeated with a different method of substrate preparation, the inclusion of the temperature variable, and the introduction of new substrate: dry wall, cardboard, and several kinds of plastic.

5.2.2. Tier Two Observations

The second tier built upon the former by exploring the effect of various proportions of different substrate types on growth uniformity and density, growth time, and material strength. The tier explored the incorporation of other materials into substrate. Figure 7 illustrate testing the effect of waste gypsum on substrate growth. In the tests 0, 1, 2, and 3 grams of drywall were added to a substrate composed sawdust from Sanford and Hawley, cardboard, and waste wood from warped pine studs. The mycelium showed a preference for the cardboard across all the samples, leaving it pale in color, as can be seen in the figures below

Figure 7: Gypsum samples left to right: zero grams, one gram, three grams, and two grams of gypsum.

One of the other materials considered was plastic. Poly-fil fiber was mixed with the waste wood substrate to see if the mycelium would attempt to colonize it. This was inspired by an earlier observation. In the first round of experiments, fruiting bodies grew from the substrate. They grew towards the source of oxygen coming though a hole in the lid. As they grew vertically, they grew *through* the poly-fil filter.

There have been papers, such as “Degradation of Green Polyethylene by Pleurotus Ostreatus”, that suggest that Oyster Mushrooms have the ability to break gown certain types of plastic (Da Luz, José Maria, et al.). Could these attributes be used to allow another type of waste to be diverted from the landfill and part of a new product? Figure 8 displays the samples and the inspiration for the trials. The substrate was composed of equal amounts of waste sawdust and rice husk with poly-fil mixed throughout.

Figure 8: Poly-fil substrate viewed from side, viewed from the top, mycelium growing through filter, fruiting body emerging from the filter.

5.2.3. Tier Three Structural Observations

Building upon the findings of the former studies, this tier begins to examine layering. This study seeks to create a compound product loosely inspired by engineered lumber. The direction and the dimensions of the layers of substrate can be manipulated, but first, the way that these layers are constructed needs to be explored.

There are many wood-based products used throughout an individual’s day. Products made from wood pulp are a common example. While such materials are recyclable, not all will end up being reprocessed. The Environmental Protection Agency estimates that paper and paperboard products make up 23.1 percent of the total Municipal Solid Waste generated in 2018 (“Paper and Paperboard”). However, paper and paperboard products have the greatest recycling rate of MSW products, with a recycling rate of 68.2 percent (“Paper and Paperboard”). Cardboard from a pizza box was selected to act as the substrate for this round of experiment. Equally sized disks were cut from the box and piled four layers high, moistened, and sterilized in oven. Once cool, a liquid culture of Oyster Mushroom was introduced to the substrate.

The control consisted of three unaltered samples stacked three layers high. The next group consisted of three samples with four holes drilled vertically through the stacked layers. In the third group, each layer was cut into thin strips. The strips were then reassembled into the shape of the disks and set in alternating direction, with each layer running perpendicular to the next. The fourth group consisted of two samples of abstract shaped chunks of cardboard and the fifth group consisted of vertically assembled pieces of cardboard. The question was how the mycelium could grow through these layers and layouts. The mycelium was able to grow through each of the samples. Once removed from their respective containers, it became apparent that not only was the mycelium able to find ways through the material, but it was holding the substrate together. The samples were cured in the oven and examined. It could grow through and around materials, taking advantage of the vertical channels like in the second group. It could grow between cracks like in group three, and it could grow around and into pieces of substrate, as modeled in each of the groups. This connection the mycelium formed through the substrate fused individual layers into one product. Figure 9 illustrates the sample designs and how the mycelium spread through them.

Figure 9: Cardboard samples starting at the left with the control, the vertical holes, the alternating direction strips, the abstract chunk, and the vertical assembled substrates.

One of the pressing questions of this tier involved how layers of traditional bulk substrate should be joined. Should layer upon layer of live cultures be added one on top of the other with varying properties and then cured?

I attempted to test this idea by taking a unit of substrate colonized with Pink Oyster Mushroom and cutting it into layers 0.5 inches thick. I layered pieces of wood between the layers and left them to grow. In the end, this method was ill advised. The mycelium did reach out to the wood but could barely anchor it in place. Would a rough surface have been easier for the mycelium to grow through? Another issue was likely the lack of contact between the substrate layers. The densely colonized layers were not in contact with each other and only a few weak connections were made. The 2021 study, “Growing living and multifunctional mycelium composites for large-scale formwork applications using robotic abrasive wire-cutting” had valuable findings for joining mycelium components that inspired a change in direction of thinking. Connecting colonized substrate with colonized substrate is more rational than trying to encourage mycelium to spread across a foreign material. Figure 10 shows the shortcomings of this trial.

Figure 10: Stacked substrate samples.

5.2.4. Tier Four: From Observations to Experimentations

This tier of experiments builds upon the findings of the former experiments. In this tier, the direction of the layers is manipulated along with the layers’ depth, and the size of members in each layer. Density, substrate proportion and size, and layering technique will be very important in this level of experiments. I seek to combine these components to create compound products. I am inspired by engineered lumber that is made out of weaker materials but is layered and adhered together to create a stronger final product. Can I make structural products out of this? Can I replicate this on a large scale to create stronger bricks, structural members, or stronger decorative elements? I seek to look into the previously mentioned insulative, fire retardant, and acoustic properties, to understand the shortcomings of mycelium composites and overcome them.

5.3. Water Absorption

One of the questions of mycelium composites is their durability. While studies like Houette et al.'s paper, " Growing Myceliated Facades: Manufacturing and Exposing Experimental Panels in a Façade Setting" and projects like The Living Embodied Computaion Lab's project, "The Growing Pavillion" seek to investigate the effect of environmental exposure on the strength of mycelium, I also sought to investigate the effect of one element of the environment on mycelium; moisture.

If mycelium were to be used in an outdoor environment for a long duration, how would it perform after being exposed to moisture over the course of time? Would it be advisable to use a water repellant sealant to decrease water absorption? Should water repellents be used like in many conventional exterior products? To what extent could they help repel water and subsequent long-term damage. How effective would a sealant be at allowing absorbed water to dry? I decided to examine this in two sets of observations.

5.3.1. Round One

Mycelium composites were layered with wood and left to regrow. Once the fungal skin reached its maximum growth on the exterior surface area, the composites were air dried and cured in the oven at 250 degrees. After cooling, the composites were cut perpendicular to the wood grain. The first sample was used as the control and was unaltered. The second sample was covered with one layer of "Vermont Natural Coatings PolyWhey". The third sample was covered with two layers and the third sample was covered in three layers of the coating. The samples were left to dry completely. Upon the coats being dry, 500g of distilled water was added to 4 glass containers. The room temperature was around 72 degrees and the relative humidity in the room was 40. The samples placed on a scale and measured. Finally, the samples were placed cut surface up with the fungal skin sides left exposed to the water.

Before exposure to water, the control sample had a soft, velvety texture while the other samples had a hard lacquered surface. After spend time in the water, the samples would experience color change and texture change.

The samples were removed during hours 1, 2, 3, 4, 6. 8, 12, 16, 20, 24, and 48. Samples were removed from the distilled water, placed on filter paper to remove unabsorbed moisture on the surfaces, and placed on the scale and measured within a minute of their removal from the water.

Table 1: Round One Absorption Over Time

Time (hr)	1	2	3	4	6	8	12	16	20	24	48	Dry Wieght Mass (g)	Water (g)
Control (g)	2.5	2.5	3	3	3.5	4	4	4.5	5	5	5	2.5	120
Layer 1 (g)	3	4	4	4	4.5	5	5	5.5	5.5	5.5	6.5	3	120
Layer 2 (g)	3.5	3.5	4	4	4	4	4.5	5	5.5	6	6.5	2.5	120
Layer 3 (g)	3	2.5	3	3	3	3	3.5	4	4	4	5.5	2	120

Some observations occurred at hour 8 where the wood at the center of the control and one-coat sample was visibly darkened due absorption of the water by the members.

At the end of the observation at 48 hours, all of the samples were still floating in the water but had absorbed various amounts of water. The best performers based on water absorbed in comparison to the original dry mass was the control sample. This sample had doubled in mass, while the other samples absorbed even more. The one-coat sample was 116% more mass than its original dry weight while the two-coat and three-coat samples had an increase of 160% and 170% respectively.

The samples were then measured as they dried at hours 49, 51, 53, 60, 64, 68, 72, 73, 74, 75, 76, 80, and 89. The control and one-coat sample reached their original dry mass first at hour 72 while the two-coat and three-coat samples reached their original dry mass before hours 80 and 89 respectively.

Table 2: Round One Drying Time

Time (hr)	49	51	53	60	64	68	72	73	74	75	76	80	89
Control (g)	5	4.5	4	3	3.5	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Layer 1 (g)	6.5	6	6	4.5	4.5	3.5	3	3	3	3	3	3	3
Layer 2 (g)	6.5	6	6	5	5	4	3.5	3.5	3.5	3	3	2.5	2.5
Layer 3 (g)	4.5	4.5	4.5	4	4.5	3.5	3	3	3	3	3	2.5	2

This set of observations offered more questions into the water repellant properties of the fungal skin. When treated with a coating of sealant, was the fungal skin damaged and disturbed, allowing moisture to enter the sample when it would have been repelled before? More samples and more accurate testing are required in the future.

One of the large issues with this observation is that not all sides were equally exposed to the water. Each sample has sides that are coated in fungal skin and sides that have no uniform fungal skin. The sides without fungal skin never came in contact with the water. In a mycelium composite, there are bound to be instances in the surface where the fungal skin is not completely uniform. An exterior panel can be cut or chipped and these exposed areas can come in contact with water. When this occurs, the water-repellant properties of the fungal skin no longer protect the interior of the component. Having a sealant could prevent excess amount of moisture from getting into the component. Another test needs to be done that better tests the effect of sealants on water absorption. Instead of floating above the liquid, all sides would be forced below the water.

5.3.2. Round Two

I prepared samples in the same fashion in the first round of observations but placed them in the water where both surface situations (fungal skin and non-fungal skin surfaces) were put in contact with the distilled water. Once again samples with no coats, one-coat, two-coats, and three-coats of “Vermont Natural Coating PolyWhey” were placed in water and periodically removed and measured. The same rapid measurement procedure was followed and occurred at hours 1, 2, 3, 4, 8. 12, 16, 20, and 24.

Table 3: Round Two Water Absorption Over Time

Time (hr)		1	2	3	4	8	12	16	20	24
Control (g)	2.5	4.5	5	5.5	5.5	6	6.5	6.5	6.5	6.5
Layer 1 (g)	3	5.5	6.5	7	7	7.5	7.5	7.5	7.5	7.5
Layer 2 (g)	3	5.5	6	6.5	6.5	7	7.5	7.5	7.5	7.5
Layer 3 (g)	3	4	4.5	5	5	5.5	5.5	6	6	6

In this observation, the samples with more layers performed better. The best performing sample was the three-coated sample that doubled its original dry mass at the end of 24 hours. The double and single coated samples weighed 150% more than their original dry mass and the control sample weighed 160% more than its original dry mass.

Drying time was once again observed. Like in the first round of observations, the samples with the least amount of coating returned to their original dry mass first. Do sealant coatings trap moisture inside of sample and prevent them from drying to the exterior? If so, this could cause complications for mycelium composites, creating a moist organic interior that could be a welcoming environment for mold while creating the possibility of long-term moisture damage.

Table 4: Round Two Drying Time

Time (hr)		1	2	14	16	18	20	22	24
Control (g)	6.5	6	6	3.5	3	2.5	2.5	2.5	2.5
Layer 1 (g)	7.5	7.5	7.5	5	4	3.5	3	3	3
Layer 2 (g)	7.5	7.5	7.5	5	4	3.5	3.5	3	3
Layer 3 (g)	6	6	6	4.5	4	3.5	3.5	3.5	3

5.4. Structured Mycelium

While there have been many projects and studies that have explored mycelium as a material, they have focused on the composition of the substrate. Inspiration for idealized growing conditions, substrate ingredients and fungi species can be drawn from these studies, however, mycelium still has limitations as a building material. One of the main issues can be found in its compressive strength. According to Merriam-Webster Dictionary, compressive strength is “the maximum compressive stress that under gradually applied load a given solid material will sustain without fracture” (”Compressive strength”). This is an inherently important quality in a building material. What loads can a component sustain, what roles can it perform, where should it be located in the building? All of these questions rely on the compressive strength.

While there have been several studies into mycelium as a building material, one of the great shortcomings is its low compressive strength. Studies such as Ghazvinian et al.’s 2019 paper, “Mycelium-Based Bio-Composites for Architecture: Assessing the Effects of Cultivation Factors on Compressive Strength” suggest mycelium composites having a compressive strength between 10psi to 148 psi depending on the substrate in use, while the bricks used in The Living’s 2014 project “HY-FI” was constructed from mycelium bricks with a compressive strength of 30 psi (“Hy-fi”). Comparatively, the compressive strength of severe weathering (Grade SW), moderate weathering (Grade MW), negligible weathering (Grade NW) brick are 3000 psi, 2500 psi, and 1,500 psi respectively (Mehta et al. 558) . For lumber, the compressive strength is around 1600 psi when measure parallel to the grain (Mehta et al. 213). Concrete has a compressive strength ranging between 2500 psi and 4000 psi. Conventional building materials tend to have much higher compressive strengths than mycelium composites.

The objective of my thesis is to divert wood waste from the landfill and turn it into a new product that decreases the demand for new resources and the use of toxic ingredients that are common in building products today. To do this, I propose adding oriented wood into substrate. I seek to investigate the effect of internal support on the compressive strength of a myceliated component. While other studies focus on the ingredients and proportions of a bulk substrate, I seek to add structural element *inside* of it. The choice of substrate material and fungi species can be based off of the findings of pre-exisiting studies, but these variables are not the focus of the investigation. I seek to learn how the addition of vertically altered wood affects the compression strength of a cured unit

5.4.1. Process

In this observation, Blue Oyster Fungi in a rye substrate was utilized. While there are better performing substrates and varieties of fungi, these variables can be altered in later tests based off the findings of earlier studies. In this case, Blue Oyster Fungus was chosen, for like many other members of the *Pleurotus* genus, this white-rot fungus digests wood. In this study, the substrate was composed of grain due to substrate's speed of colonization. In future trials, I would like to use sawdust, another common wood waste product, as the substrate. Experiments have suggested that sawdust-based substrates have higher compressive strength than several agricultural waste products (Ghazvinian et al).

The inoculated substrate was placed in a container and allowed to grow. Once the blue Oyster Fungi completely colonized the rye base, the substrate was removed from the form. The wooden components were sterilized for two hours at 300 degrees in an oven. They were removed and cooled before being added to the substrate. For standardization of size, popsicle sticks were used in the samples due to their uniform size. The popsicle sticks were inserted vertically into the substrate away from the edges of the block. Once the wood was inserted, the substrate block was trimmed of the surrounding fungal skin. This thickened layer of mycelium would have had an effect on the properties of the samples, requiring it to be removed. Once the fungal skin was removed, the samples were cut from the main substrate body and left to recolonize for one week. All of the samples came from the interior of the rye block, meaning they were less colonized than the trimmed away areas that had been closer to air exposure. This incubation period allowed the mycelium to grow denser, binding the substrate and the wood together. After seven days had passed, the samples were removed from their container and left to air dry for several hours. Afterwards, they were placed in the oven to cure at 220 degrees over the course of several hours. When they were forty percent of their original weight, they were removed from oven. To prepare the samples for the compression test, their surfaces were cut. Any outlying wooden members or uneven surface was trimmed away by a band saw. The samples were then measured at the center with calipers. These dimensions would be used to find the cross-sectional area for their respective compressive strength. Each of the samples were photographed before being put in the compressor (Appendix). After the machine had found the peak load, the samples were crushed to see where the buckling had occurred (Appendix). The results can be found below in Table 9.

Table 5: Compressive Strength

	Sample Name	l (in)	w (in)	Cross Sectional Area (in^2)	Peak Load (lb)	Speed (in/m)	Compressive Strength (f=load/area)	% of Area that is Popsicle Stick
Control 1	C1	0.851	0.65	0.55315	20.76	0.03	37.5305071	0
Control 2	C2	1.06	0.786	0.83316	24.511	0.02	29.41931922	0
Control 3	C3	0.845	0.841	0.710645	15.666	0.018	22.04476215	0
1 Popsicle Stick	P1	1.104	0.972	1.073088	286	0.03	266.5205463	2.058316187
2 Popsicle Sticks	P2	0.651	0.96	0.62496	455.177	0.01	728.3298131	7.068466462
4 Popsicle Sticks	P3	1.067	0.925	0.986975	419.114	0.01	424.6450011	8.951612351
6 Popsicle Sticks	P4	1.102	1.03	1.13506	833.287	0.01	734.1347594	11.6756175
Random Chunk 1	CH1	0.999	1.025	1.023975	25.75	0.01	25.14709832	N/A
Random Chunk 2	CH2	0.97	1.138	1.10386	105.452	0.01	95.53023028	N/A
Random Chunk 3	CH3	1.135	1.269	1.440315	421.514	0.01	292.6540375	N/A

In the end three control samples (unaltered substrate) were tested along with samples that included 1, 2, 4, and 6 popsicle sticks respectively, and three non-uniform chunk samples that had 1, 2, and 3 wood chips in turn.

The average compressive strength was calculated by dividing the peak load by the cross-sectional area. The average compressive strength of the control samples was 29.66 psi. When uniform wood was added to the sample, the compressive strength increased greatly, ranging between 266.52 psi and 734.13 psi. This suggests that adding vertical structural components, could help increase the compressive strength of mycelium materials.

This investigation was not a laboratory study. Due to time and funding, there were few samples and subsequent test results. I would like to replicate this study on a larger scale in a more controlled study and to examine the bonding characteristics of the mycelium in the substrate on a microscopic level.

Another important item to take note of is the percent of the cross-sectional area that was wood. While some samples included more wooden members than others, the actual size of the cross-sectional area varied. I propose in the future that the wood to area ratio be the focus instead of the *number* of wooden members in any given area.

Another suggestion for future improvement would be the number of samples. This thesis was conceived and developed in the course of one year. It started with understanding the basics of *what* mycelium is, to trying my hand at growing it, to developing samples that could be tested in the lab. So much has happened in a short amount of time, and there is so much more that can be done if given more time. By examining the table, it is easy to see that the testing results suggest that adding vertical wood support can increase compressive strength, but more testing needs to be done. With only one sample of each available for testing, small issues and inconsistencies in any of the samples can have a large effect on their results. Each of the tests need to have multiple samples. I propose in the future that the effect of wood percentage of the cross-sectional area on compressive strength be tested. The percentage of wood would increase incrementally in the study with multiple samples of each percentage. Regardless, the initial tests results suggest that compressive strength can be increased substantially by manipulating the structural characteristics of the substrate. The compressive strength went from being around 30 psi in the control samples to over 734 psi with the implementation of directional members. This design can create a high performing product by manipulating the substrate's suitability as a host for mycelium bonding, and the substrate's performance as a structural component.

CHAPTER 5

MICRO-SCALE ARCHITECTURE

5.1. Multiple Levels of Architecture

What is architecture? According to Merriam Webster Dictionary, it is the art or science of building, especially in regard to structures that are habitable (“Architecture”). For the most part, the main focus of architecture has been on one organism: the human. However, humanity, is just one small part of a great system, and so is the architecture.

This thesis focuses on architecture across different scopes; starting at the microscopic level of the threadlike network that makes up mycelium, to the macro-level application of using mycelium composites as building components.

This project investigates the implications of current building materials in comparison to the potential of an organically formed alternative created from mycelium. It will evaluate the building blocks of architecture and reevaluate the building field from the ground up. Small individual components are reassessed, and their long-term implications are explored in comparison to the growing field of bio-design. I propose a multi-step system. What if harmful waste could not only be remediated, but turned into a useful product through the use of mycelium, the fungal root network?

5.2. Waste as a Resource

I propose to look into an often-overlooked contributor to landfills; Construction and Demolition (C&D) Materials. According to the United States Environmental Protection Agency, these are materials that are produced when new structures are built or when pre-existing structures are “renovated or demolished” (“Construction”). The Environmental Protection Agency also found that in 2018, 600 million tons of C&D debris were generated and while 455 million tons were directed to the next use market, around 143 million tons ended up in landfills (“Construction”). This can be viewed product by product. Concrete is the largest variety of C&D debris. It was estimated that 66,535,034 tons were sent to landfills, however, 315,222,966 tons were sent to next-use markets. In comparison, 11,491,724 tons of Asphalt shingles are thrown out every year while only 2,033,276 tons get recycled ("Construction"). 10,803,717 tons of Gypsum Drywall are thrown out every year and only 2,238,283 are put towards reuse. Finally, and most important to this study, 27,053,922 tons of wood are thrown out while only 11,896,078 tons are put towards the next-use market ("Construction"). While some products like concrete see a majority of waste get recycled, only a minority of wood, gypsum, and asphalt shingles "waste" avoid the landfill. These materials, however, do not need to be considered "waste". Each could be used as a component to feed mycelium. By using these castoff materials in mycelium composites, waste is diverted from the landfill, a high performance and waste negative material can be created, and demand for new resources can be decreased. Waste can be a resource to revolutionize the building sector.

5.3. Mycelium as the Client

Who is the client and what do they want? The design of structures starts at a very small scale with the entity that holds the entire project together. The client is the mycelium itself. The client has specific temperature and ventilation requirements, and the structure must accommodate the client's transportation needs, lighting suggestions, and material choices. The client desires a wood-based structure to best accommodate its lifestyle and consumption needs. This project seeks to address both the environmental conditions and the comfort of the client. The transportation and nutritional needs of the client can be met while the ventilation and light exposure can be controlled to satisfy the client and allow them to prosper in their structure.

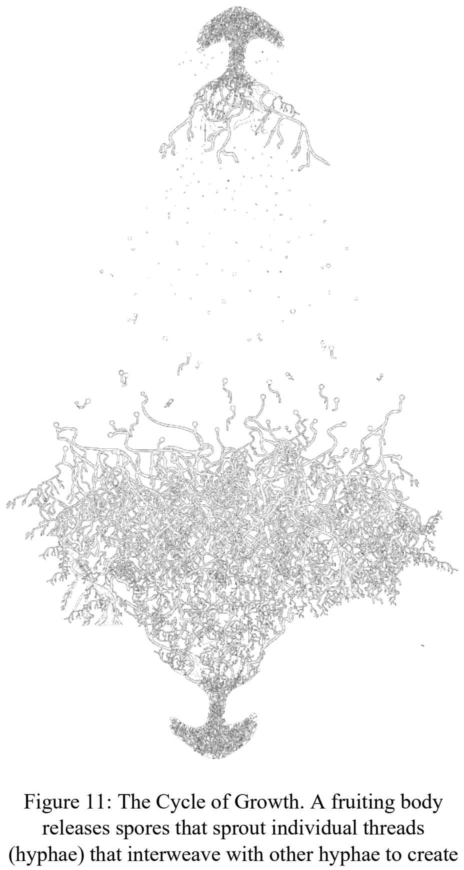


Figure 11: The Cycle of Growth. A fruiting body releases spores that sprout individual threads (hyphae) that interweave with other hyphae to create mycelium.

5.4. Site and Structure

Where does the project take place? Why there? How will it be altered? The site of the project is manipulated, added to, and shaped to create a structure. The substrate is the site which the mycelium colonizes, a mix of waste wood dust and shavings.

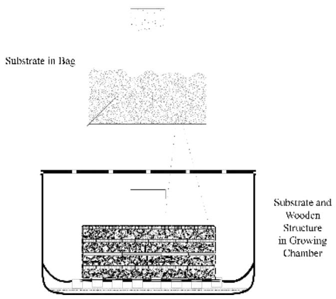


Figure 12: Substrate being colonized in bag (above) and in a growth chamber (below).

Other waste wood components are built into the site to create a structure. The structure that the client inhabits is made of levels of various design, size, and shape. Wood is a common feature of construction and demolition waste as around 43 percent of it ends up in the landfill. The client is making a friendly decision when choosing to use waste wood as the building material for the project.

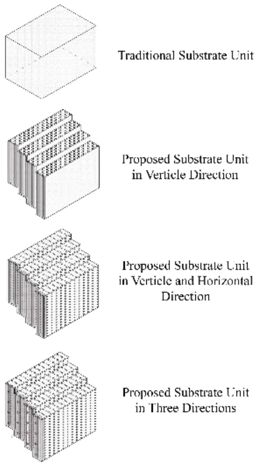


Figure 13: Traditional Mycelium Composite (top) and Proposed Variations (below).

While many designers have used substrate, finely ground up or small in size material that the mycelium grows through and colonizes, to make structures, this project is not using bulk substrate in molds. The structure is made of layers altering in direction, size and depth of the material.

The client receives a structure that accommodates its needs during its lifetime, and occupies a structure that will serve a purpose, even after the complete colonization by the client. The structure becomes part of architecture on a different scale.

5.5. Architecture Beyond Humanity

While architecture has been focused on one organism, humanity, is just one small part of a great system. Architecture must go beyond humanity. It must address the complex and interdependent relationships of nature: the biosphere.

What is it like to build for a non-human client? While it can neither say nor write down what it wants, it is quite clear on its requirements. The client needs a wood-based structure, ventilation, temperatures around 70 degrees, and space for movement and circulation within the structure. If not satisfied with the design, the client will visibly display its discontent. Instead of designing for a human client, the designer must listen and watch. The client is very small, but its program is still a technical undertaking. This is the micro-scale of architecture, and much like the scope of this project, the commissioned structure must jump between scales. The structure that the client inhabits can be used on a larger scale of architecture after the client has fully taken over and the structure no longer accommodates its growing needs.

The waste wood structure becomes a mycelium composite that can be used on the macro-scale of architecture as a building component. It can be used for improving the performance of new and existing buildings, creating flexible interior design with its light weight, acoustic, thermal, and fire-retardant properties along with its ability to transform the exterior of a building with the components' uniform, customizable, waste negative design.

5.6. The Relation of Design and Waste

Where exactly does architecture fall into this situation? As noted earlier, the current practices of this field are not responsive or responsible enough. The buildings and construction brought about by architecture and the many related building disciplines are responsible for 36% of energy use and 39% of carbon dioxide emissions globally ("Global"). In America alone, buildings are responsible for 40% of national energy consumption ("An Assessment").

In this sense, the sector relates to almost every person who dwells in this nation, but ironically, their perceived connection ends upon the completion of their project. Little does the nation address the future consequences of the products they have made. The Building Sector is not just responsible for consequences on the environment during construction, but their choices, designs, and decisions will echo through the ages as their creations live on long after the building has been occupied.

The designers must be responsible. The environment is at a critical juncture, and the decisions of humanity count now more than ever. Every decision that is made or not made, deeply thought over or carelessly decided, cut or added, will echo through time. Designers tied to the building sector have an essential duty to navigate building to a sustainable path, not just in their duty during the designing of the immediate demands of their clients and teams, but in regard to the future implications of their project.

CHAPTER 7

MYCELIUM AT THE MACRO-SCALE: APPLICATION

7.1. Skin Design

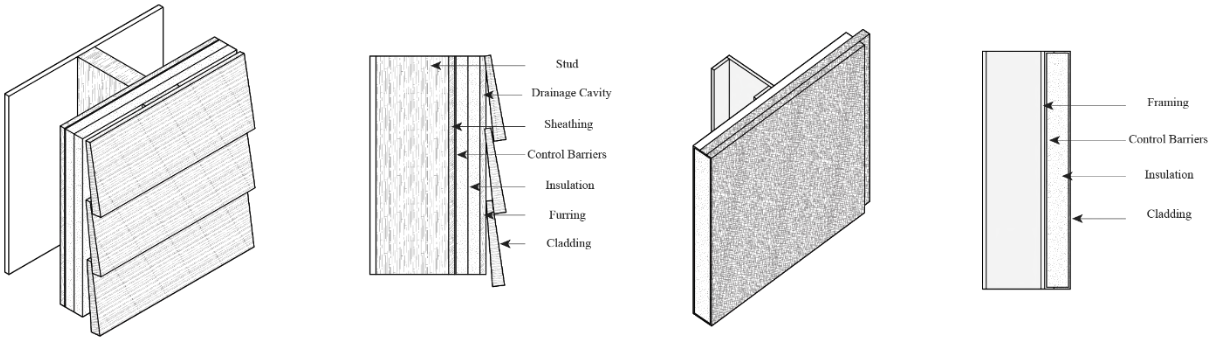


Figure 14: The “Perfect Wall” (left) and Insulated Paneling (right).

The building envelope design is an essential part of creating a high performing building. In the picture above, traditional cladding methods are portrayed in the context of “The Perfect Wall”. The “Perfect Wall” is insulated on the exterior of the structure to create the most efficient building envelope. The building envelope must be unbroken throughout the building to separate the controlled interior environment from the uncontrollable exterior environment. These surfaces mast have uninterrupted rain control, air control, and thermal control layers (Lstiburek). It has several components including cladding on the exterior that resists ultraviolet radiation, a drainage cavity that channels water out, insulation to decrease thermal conductivity and any consequential heat loss or gain in the building, control barriers, and the building structure itself (Lstiburek). These layers work together to create a high-performance structure. The insulated paneling on the right is an interesting take on how to renovate existing or create new walls. This product is able to combine the layers of the perfect wall into one system. It can be added to the exterior of a pre-existing structure to improve its performance, or it can be used as the skin of a new building.

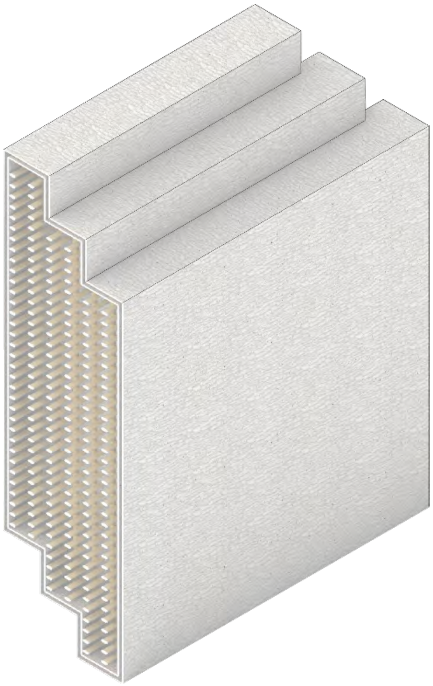


Figure 15: Mycelium Composite.

With the traditional cladding system each layer performs a distinct function, while the mycelium paneling system shown in Figure 15 illustrates the possibilities of combining the layers into one component. Both the traditional and proposed systems are based on layering, especially in regard to moisture control. Rather than a waterproof building skin that is neither realistic, nor advisable, since it is important that moisture be able to move from the building, both of these systems offer ways of moving moisture, whether it be control barriers or drainage cavities. The mycelium composite panel has internal support, due to the alternating layers of waste wood, along with insulative properties of the mycelium throughout the panel. The fungal skin provides water repellant properties, that may be treated with sealants to increase its durability. Finally, the stepped shape of the mycelium composite allows water to drain to the exterior while preventing thermal bridging by avoiding direct gaps between the components. They furthermore connect with each other and the structure.

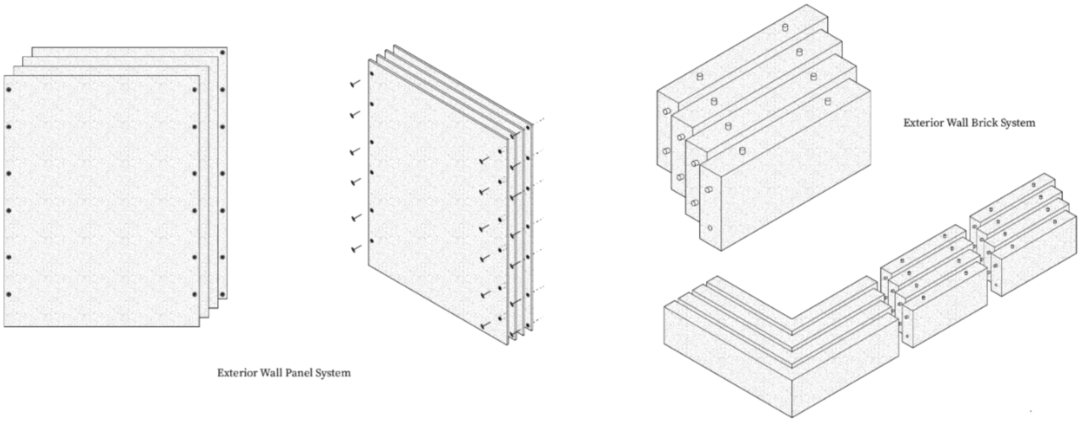


Figure 16: Exterior Components.

There are several benefits and shortcomings of using mycelium as a building component.

Advantages of mycelium composites:

- Waste negative
- Creates a recycled product that decreases demand for new materials
- Has desirable thermal, acoustic and fire-repellant properties
- Can help with myco-remediation
- Can be used in compost and the generation of heat

On the other hand, there are several weaknesses:

- There have been many studies on it, but it is less understood than conventional materials
- It is a natural material that will eventually breakdown (but this can be anticipated and paired with compost and Compost Heat Recovery Systems).
- This cycle may not be for everyone, for it means that the structure owner would have to partake in the upkeep of the structure.
- As an exterior material, use of mycelium components might pose requirements on the design of other parts of the structure such as protective roof overhangs.

Water absorption trials suggests the possibilities of using an organic based building component on the exterior of a building, and studies have been done to test the durability of mycelium panels in an exterior environment. In the 2020 paper, "Growing Myceliated Facades", a group of researchers grew mycelium panels from several substrates and processing methods. The panels exposed to the elements for 7.5 month and performances were assessed (Houette et al.). For both new and pre-existing buildings with poor insulation, insulated cladding on the exterior of the structure can help create a high performing facade. This is important not only for the design of new buildings, but improving existing ones. As Carl Elefante writes, "the greenest building is the one that is already built" (Elefante 26). This thesis poses ways of transforming already standing buildings with poor performances.

Interest in using mycelium in design has been around for a few decades, with each generation learning more about the wonders of fungi. I am exploring design in mycelium through its use as a panel, board, surface, and brick as components that can be used to make structures. Instead of contributing to waste, mycelium can be grown on substrates of post-industrial waste so that instead of creating a need for new materials, it repurposes spent materials while further decreasing demand for new materials.

Instead of the typical use of bulk substrate in molds. I seek to add substrate that can serve as a support element by itself and to alter the direction, size, and depth of the substrate to create a new and stronger product.

Engineered lumber provided a conceptual model (where thin layers of cross grain are placed to increase strength). However instead of a toxic adhesive, the wood is bonded by the mycelium. Unlike earlier studies, instead of stuffing uniform, ground substrate into forms, what if the layers were purposefully designed? These can be used as individual components or put together to make surfaces and structures.

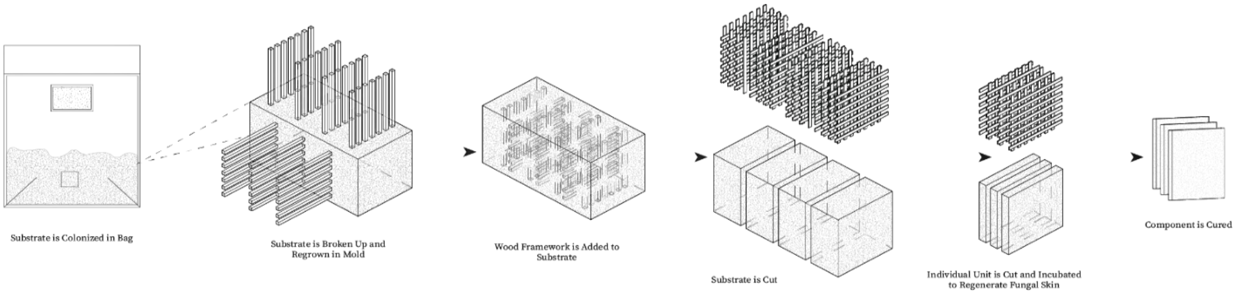


Figure 17: Design Process.

7.2. Design

Figure 17 illustrates the design process I have developed. Bulk substrate is colonized in a bag, broken apart, and allowed to recolonize in a new form. Waste wood is inserted in specific orientations within a block of substrate and the mycelium is allowed to grow into and bond with the support structures. After bonding, the block is cut into the desired design and left to grow a fungal skin on the exterior surface. The component is then cured at 250 degrees Fahrenheit in an oven and intermittently weighed until the components no longer decreases in mass. Below are tables of properties of mycelium according to different papers. In respect to thermal and fire-retardant properties, mycelium has much to offer, but it falls short in regard to compressive strength. It is this property that I seek to improve with my design, thereby opening the door to a new world of mycelium design.

Table 6: Compressive Strength

Compressive Strength		
	Mpa	Author
100% Sawdust Substrate	1.018	Ghazvinian et al.
90% Sawdust 10% Wheat Bran Substrate	1.38	Ghazvinian et al.
100% Straw Substrate	0.072	Ghazvinian et al.
90% Straw 10% Wheat Bran Substrate	0.169	Ghazvinian et al.
50% Sawdust 50% Straw Substrate	0.106	Ghazvinian et al.
45% Sawdust 45 % Straw 10% Wheat Bran Substrate	0.116	Ghazvinian et al.
America Grade NW (Normal Weathering)	10.34	ASTM C62
America Grade MW (Moderate Weathering)	17.24	ASTM C62
America Grade SW (Severe Weathering).	20.68	ASTM C62

Table 7: Thermal Conductivity

	Average Thermal Conductivity (W/(m*K))	Density (Kg/m3)	Moisture Content (%)	Author
Chopped Flax Substrate	0.0578	134.71	9.5466	Elsacker et al.
Hemp Substrate	0.0404	98.92	7.3795	Elsacker et al.
Straw Substrate	0.0419	94.39	12.9625	Elsacker et al.
Mycelium Based Composite	0.0578 – 0.0404	94 – 135		Elsacker et al.
Rock Wool	0.044	470-2250		Elsacker et al.
Glass Wool	0.033-0.045	13-100		Elsacker et al.
Extruded Polystyrene	0.025-0.035	18-50		Elsacker et al.
Kenaf	0.034-0.043	30-180		Elsacker et al.
Sheep Wool Plates	0.038-0.054	25-Oct		Elsacker et al.

Table 8: Fire Reaction Properties

Fire Reaction Properties						
	Temp to PHRR (°C)	pHRR (W/g)	THR (kl/g) 16	Heat Release Capacity (J/gk)	Char Yield (wt%)	Author
Mycelium	300+/1 1	67 +/- 2	6.8 +/- 0.1	70 +/- 1	23 +/- 1	Jones et al.
Poly(methyl-methacrylate) PMMA	399 +/- 2	446 +/- 6	24.6 +/- 0.2	439 +/- 6	0	Jones et al.
Poly(lactic acid) PLA	385	375	17.8	489	0.6	Jones et al.

Table 9: Flexural Strength

Flexural Strength			
	Average Maximum Midpoint Displacement (mm)	Average of (Mpa)	Author
Rice Bran	0.967	1.013	Ongpeng et al.
Rice Bran-Mycelium	1.977	0.916	Ongpeng et al.
Sawdust	2.937	0.472	Ongpeng et al.
Sawdust-Mycelium	2.764	0.962	Ongpeng et al.
Clay	0.87	0.629	Ongpeng et al.
Clay-Mycelium	1.202	0.878	Ongpeng et al.

7.3. Applications

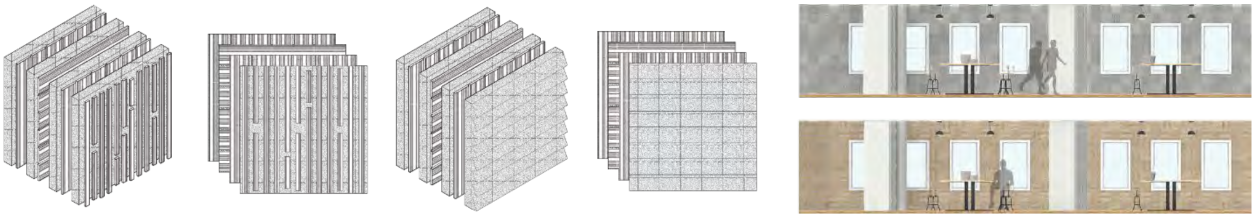


Figure 18: Interior Panels.

What could mycelium-based panel systems look like? In the images above, its properties as an interior material are brought to life. Mycelium units can be very useful to pre-existing structures. While many buildings perform poorly, the excellent thermal, acoustic, and fire repellant properties can create more efficient, comfortable, and safe buildings.

As a panel, mycelium can perform different functions. By having an interior system of support, the panels can possess greater strength and serve more functions. While mycelium design today focuses on placing bulk substrate into forms, by manipulating the layers, this material can perform more functions than substrate alone is able to. It can serve as a self-supporting panel. With its lightweight and internal support, it can serve as a partition that can quickly, safely, and cheaply transform a room.

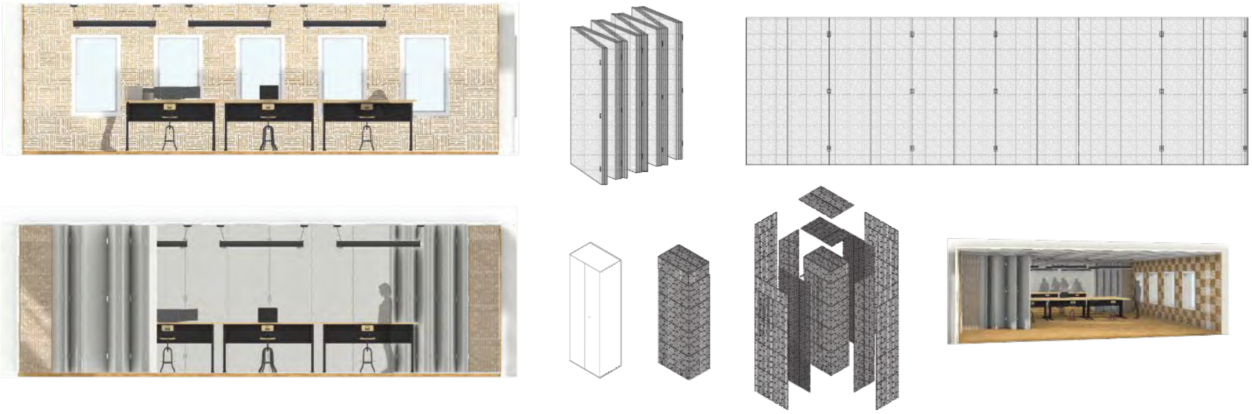


Figure 19: Walls and Furniture.

The images above investigate some of the aesthetic and abstract potential of myceliated components. Walls do not have to be flat. But simply creating a mold for the intended design, a great variety of ideas can be transformed into a reality. Capable of creating shapes, privacy, and instances that would be difficult to replicate in other conventional materials while maintaining the aforementioned properties of mycelium.

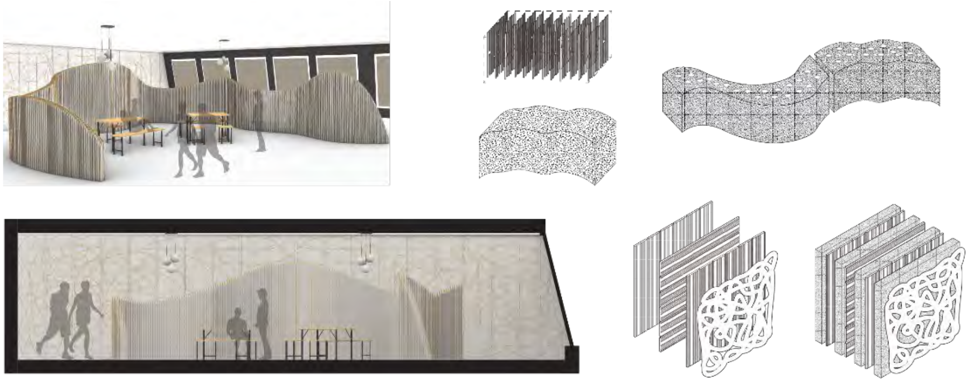


Figure 20: Abstract Panel Design.

What if the interior structure of a building could be dynamic, not just before construction, but if it was able to evolve with the needs of its occupants? While it is possible to achieve this goal with extensive renovation and waste, what if reinvention and redesign was planned for from the start through the use of low cost, low waste, and low risk material?

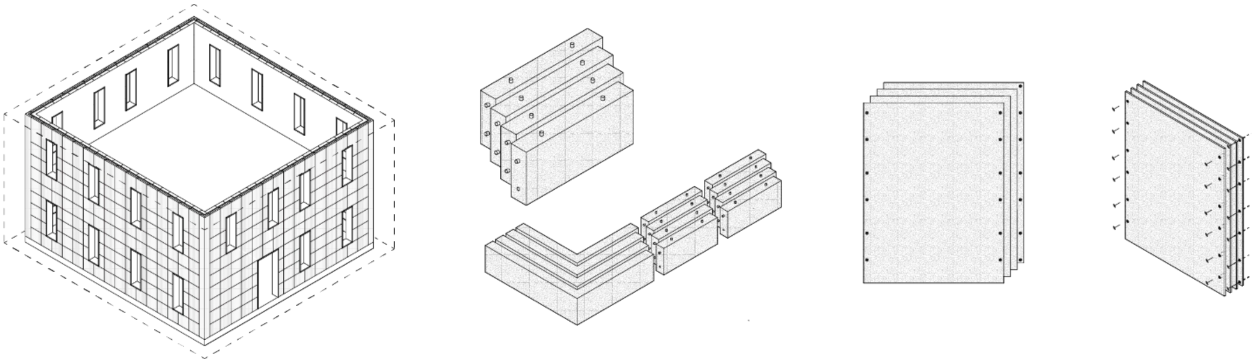


Figure 21: Exterior Components.

These images investigate the potential of exterior mycelium components. Displayed are a brick and a panel design that can be found throughout the thesis. This design allows for interlocking layers, that prevents direct bridging between thermal and acoustical environments. Whether it be sound or moisture, there are no direct cracks that allow leakage into the envelope. While the fungal skin provides water repellant properties, the stepped design encourages water to drain to the exterior of the wall while the layers lock each other into place. The components are identical making the design easy to install and furthermore making mass production and replacement simple.

Being an organic based material means that this component will eventually degrade. However, this is expected and anticipated for it will become part of another cycle in the building: heating.

7.4. Compost Heating

At the end of its use as a part of the building envelope, the waste-based mycelium panel once again becomes part of another system: energy. At this point, the spent building components and the everyday waste generated by the occupants of the structure becomes a resource. Much of the daily waste generated by Americans is sent to landfills, despite being compostable. Not only would the implementation of this alternative method generate rich soil, but heat, a resource for building operation.

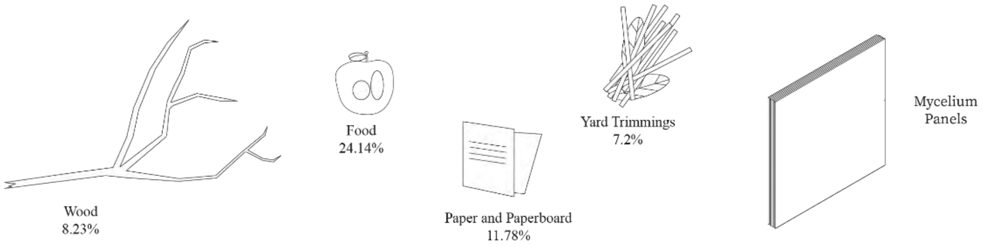


Figure 22: Compostable Landfill Contributors.

The image above suggests that a large amount of material is put in landfills that could have been diverted. Paper products, yard trimmings, food, and wood make up over 57% of landfilled waste, and for the most part, did not need to end up there. A typical American generates 4.9 pounds of waste a day (“Construction”). How much of this goes to the landfill? By the occupants composting the panels along with the other applicable waste, waste is diverted from landfill, and a sequence of benefits unrolls.

Compost Heat Recovery Systems make their debut in the 1972 from the work of Jean Pain. It consists of a large mound of wood-based compost on a large network of tubes. His study found that he could heat a 100 m^2 farmhouse and provide it with domestic hot water for 6 months. He estimated that it was able to extract 50,115 kJ/hr or 4330 kJ/kg DM during the course of his trial (Smith et al).

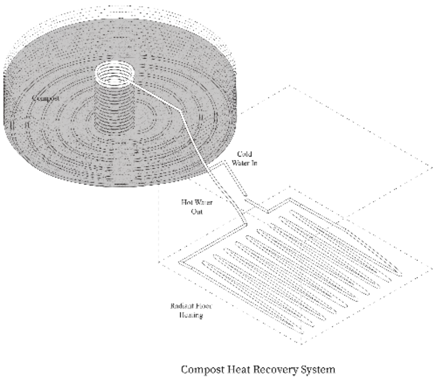


Figure 13: Jean Pain Mound.

The image to the left shows a Jean Pain mound, however, many innovations in design have occurred in the past fifty years. Some improved systems may aerate the compost, use systems that use direct vapor and extract heat from compost vapor using condenser-type heat exchangers, or force ventilate the compost. Using a biofilter in particular was found to decrease NH3 emissions by 90% and VOCs by 70% (Smith and Aber).

CONCLUSIONS

Growing conditions, water absorption, and compressive strength were assessed across a series of trials. By creating a substrate with internal directional wood supports, the compressive strength reached a maximum of 738 psi in comparison to the average compressive strength of bulk substrate at around 30 psi. These experiments suggest an effective way of consuming waste and turning it into a new well performing material. Many waste products like wood and sawdust can be diverted from the landfill and combined with mycelium to create a building component.

The world has reached a critical moment. Decades of negligence by humans across many disciplines has led to an uncertain environmental future. However, where there is a problem, there is potential to solve it. Every person has the ability to help change the projected future, and every discipline has the power to help in their own way. While the building sector is responsible for a disproportionate amount of the emissions, pollution, and waste that is generated every year, it also has a great ability to change for the better. It is time to build smarter with a long-term picture in mind. This can be accomplished in many ways ranging from the implementation of renewable energy to the inclusion of local materials to decrease waste generated from transportation and manufacturing. One particular method explored in this thesis is the implementation of a waste-negative material that can be created locally. Using mycelium composites in architecture can divert waste from the landfill, reduce the demand for new materials, and help create high-performing buildings that decrease energy use and emissions.

This thesis is an accumulation of over a year’s worth of exploration. One winter ago, a person, whose only connection with mushrooms came from the depths of can, took a deep dive into a world of literature and experimentation revolving around an organism they had once avoided. Their preconceptions of this misunderstood kingdom were overturned. A hidden realm that offered potential solutions to many of the issues the world faces unraveled before them.

I did a fair amount of hands-on work with mycelium, from inoculating my own substrate with tissue samples gleaned from supermarket specimens to the creation of a product that I was able to test in the Fabrication Lab. I have learned a great deal and continue to be inspired. These samples and observations were just a start. There is much that can be done with testing, and many directions internally supported mycelium composites can take. I seek to continue my exploration of structured mycelium composites.

APPENDIX A
CONTROL SAMPLES

Three control samples were tested to find their compressive strength. The pictures below illustrate the process and results. The results of the sample were compressive strengths of 37.53 psi, 29.42 psi, and 22.04 psi resulting in an average psi of 29.66 psi.

APPENDIX A
ONE POPSICLE STICK, TWO POPSICLE STICK, AND FOUR POPSICLE STICK SAMPLES

The sample on the top of the left column shows the one popsicle stick sample after being crushed. It shows clearly where the popsicle stick broke.

Below on the left is a picture of the two popsicle stick sample. The image shows where the members snapped.

The right column consists of pictures of the four popsicle stick sample. The members broke in a similar fashion to the samples on the left. The image on the bottom right shows mycelium on the exposed popsicle stick, demonstrating how the mycelium had bonded with the material and adhered it to the substrate.

The one popsicle sample had a compressive strength of around 266 psi. The two popsicle stick sample had a compressive strength of about 728 psi and the four popsicle stick sample had a psi of around 424 psi.

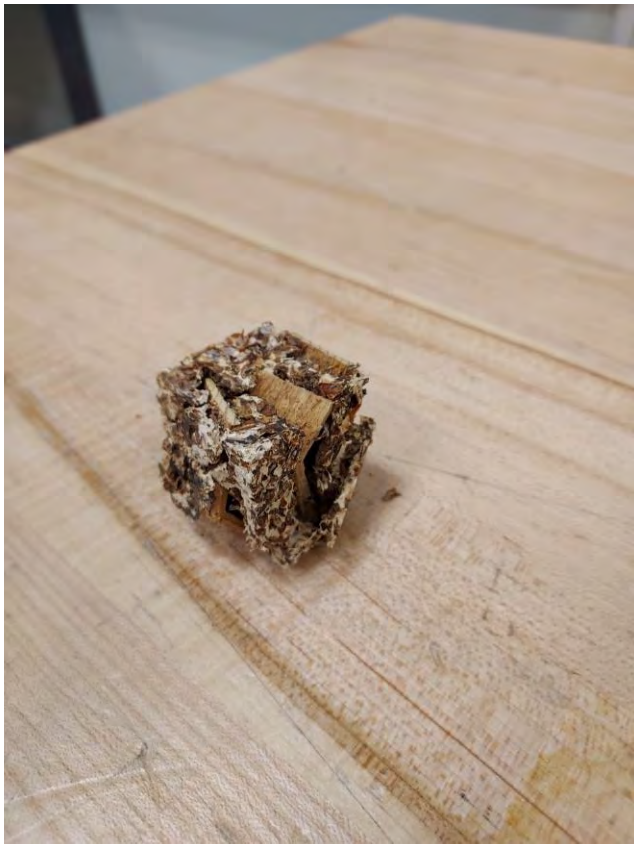
APPENDIX A
SIX POPSICLE STICK SAMPLE




The images above illustrate the results of the six popsicle stick sample. The wooden members bucked under the increasing load of the machine, however, the sample's compressive strength was determined to be around 734 psi earlier in testing. This sample had the greatest number of wooden members, the greatest proportion of cross-sectional area made from popsicle stick, and the greatest compressive strength of the samples tested.

APPENDIX A

TWO AND THREE-CHUNK SAMPLES



The images above show the three-chunk sample and how it broke under the load. The image to the right shows the two-chunk sample and how the substrate split.

APPENDIX B

CONTROL SAMPLE

APPENDIX B
CONTROL SAMPLE

APPENDIX B
CONTROL SAMPLE

APPENDIX B
ONE POPSICLE STICK SAMPLE

The cross-sectional area made up of wooden members is around 2.05% and the compressive strength was determined to be about 266 psi. The images show the surface condition of the sample.

APPENDIX B
TWO POPSICLE STICK SAMPLE

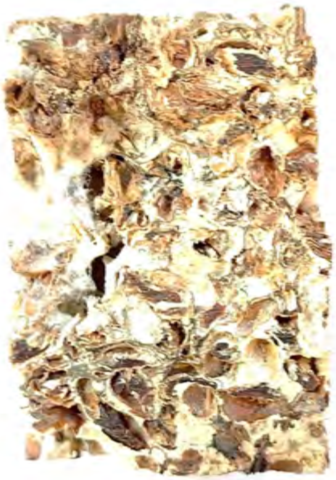
The cross-sectional area made up of wooden members is around 7.06% and the compressive strength was determined to be about 728 psi. The images show the surface condition of the sample.

APPENDIX B
FOUR POPSICLE STICK SAMPLE

The cross-sectional area made up of wooden members is around 8.95% and the compressive strength was determined to be about 424 psi. One notable observation was that this sample had a large crack at the bottom. During the time that the sample was left to recolonize before curing, this fissure was partially fused by mycelium. If left for longer, the connection could have been stronger or maybe even healed itself. However, there is a chance that this crack, though partially fixed, could have caused this sample to have a lower compressive strength. The images show the surface condition of the sample.

APPENDIX B
SIX POPSICLE STICK SAMPLE

The cross-sectional area made up of wooden members is around 11.67% and the compressive strength was determined to be about 738 psi. One observation of note during testing was the slow start. The trial took a longer amount of time due to the unlevel top surface of the sample. The images show the surface condition of the sample.



APPENDIX B
ONE-CHUNK SAMPLE

While the percent of the cross-sectional area made up of wooden members is unknown, the compressive strength was determined to be around 25 psi. This is similar to the control samples. One possible explanation is that this is due to the short wooden member. The sample was never compressed far enough for the member to show its properties. The images show the surface condition of the sample.

APPENDIX B
TWO-CHUNK SAMPLE

While the percent of the cross-sectional area made up of wooden members is unknown, the compressive strength was determined to be around 95 psi. The images show the surface condition of the sample.

APPENDIX B
THREE-CHUNK SAMPLE

While the percent of the cross-sectional area made up of wooden members is unknown, the compressive strength was determined to be around 292 psi. The images show the surface condition of the sample.

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