Mycelium Wall Systems:
Harnessing Adaptive Fabrication with Biocomposites in Buildings

by
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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
I understand that my thesis may be made electronically available to the public.

Abstract

Wall assembly prototyping is a strategy that allows for technical performance analysis of construction materials to investigate the function of a building façade and its integrated components. Departing from the complexity of a given building, façades must constantly mediate evolving human needs for comfort and environmental performance. However, traditional construction strategies to address these complex, changing needs, such as multiple wall layers with fluid-wall and fluid-solid interfaces are practically and environmentally inefficient. Mycelium biocomposites can combine effective performance properties for wall systems with reduced layers while being biodegradable. This thesis introduces a novel mycelium biocomposite assembly integrated in a naturally prefabricated wall panel with reduced material layers compared to a typical system. Construction prototyping is employed through nine digitally modelled iterations, supported by three physical experiments and thermal simulations. The key impact of this research is in the introduction of a new framework for utilizing construction prototyping to efficiently accommodate the growth and performance requirements of mycelium biocomposites within a prefabricated wall assembly while applying hands-on procedures in façade engineering and design.

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Chapter 1 - Introduction

1.1 Background

The building façade is often considered one of its most complex elements, as it is called upon to mediate numerous environmental conditions between the interior and exterior. [1] Over the years, increased demands have been placed on the insulating and weatherproofing performance of façades to improve their energy efficiency and meet net-zero energy targets.[2] To meet these demands, conventional wall envelopes rely on multiple layers of different materials, each performing a specific purpose.[3] Though this strategy is proven in practice, it adds unnecessary complexity and increases the building's total embodied energy. One study catalogued the embodied carbon associated with each material layer of 17 wall assemblies commonly found in Southern Ontario.[4] Each material layer's embodied energy was measured based on quantity and sourcing, implying that fewer layers would correlate to less embodied carbon if given a larger sample size.[5] In another study of six typically constructed residential buildings, the building with added insulation only saved 1% of energy annually instead of the simulated 7%.[6] This lack of correlation can be attributed to the complexity of typical multi-layered construction.

Master builders of the past would gain a holistic understanding of materials through working closely with them. Hylomorphism, a school of thinking popularized by Aristotle, breaks down human knowledge of objects through their matter and form.[7] Matter refers to an object's composition, for example, a house made of bricks. Form describes the essence of the object: a house shelters people from the elements. This connection between the bulk properties of materials and their purpose was crucial to architects' practice. Vitruvius also highlighted the importance of understanding the physical properties of primary construction materials (wood, stone) as fundamental to the building practice.[8] Through physical experimentation, architects ascertained that based on their properties, certain materials were more suited for specific purposes than others. For example, wood's lightweight nature and strong performance under tension made it suitable for applications such as bridges.

1 Jens Böke, *ThinkingSkins. Cyber-Physical Systems as Foundation for Intelligent Adaptive Façades* (Delft: BK Books, 2020).
2 John Straube, "BSD-025: The Passive House (Passivhaus) Standard—A Comparison to Other Cold Climate Low-Energy Houses | Buildingscience.Com," Building Science Corporation, October 15, 2009, https://buildingscience.com/documents/insights/bsi-025-the-passivhaus-passive-house-standard.
3 Florian Nagler, "Building Simply: A Guideline," in *Building Simply* (Birkhäuser, 2021), https://doi.org/10.1515/9783035624663.
4 Anna Beznogova et al., "New Design Resources for Embodied Carbon Targets," 2024.
5 Beznogova et al.
6 "FORSCHUNGSPROJEKT RIEM: WICHTIGE ERKENNTNISSE FÜR ZUKÜNFTIGE BAUVORHABEN," risi.muenchen.de, https://risi.muenchen.de/risi/dokument/v/4001844.
7 Thomas Ainsworth, "Form vs. Matter," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Summer 2020 (Metaphysics Research Lab, Stanford University, 2020), https://plato.stanford.edu/archives/sum2020/entries/form-matter/.
8 John Fernandez, *Material Architecture: Emergent Materials for Innovative Buildings and Ecological Construction* (Oxford Paris: Architectural press, 2006).

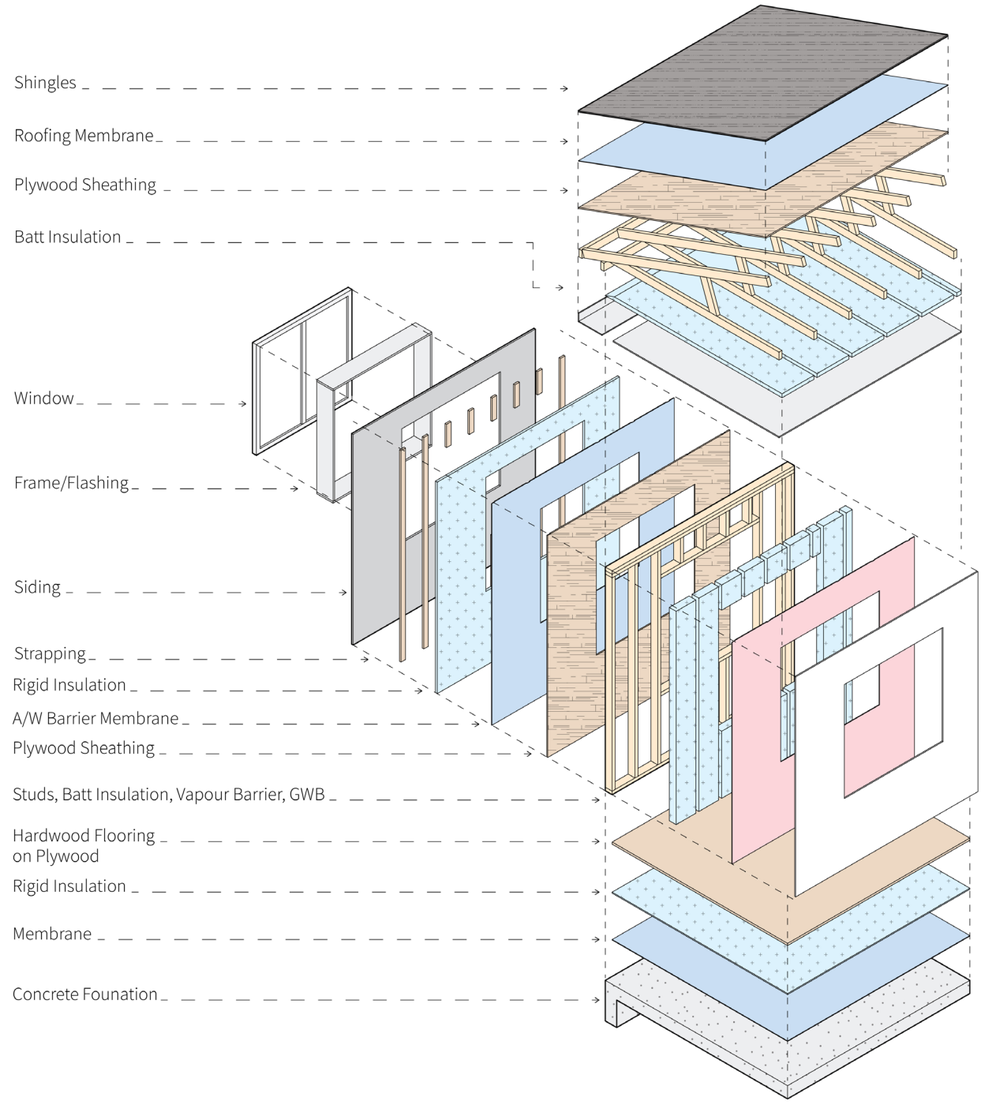


Figure 1.1: Diagram highlighting the numerous layers involved in a typical residential wall system.

Since the Industrial Revolution introduced synthetic materials with specific properties standardized by manufacturers, architects and designers became distanced from materials.[9] Architects today often ascribe materials as secondary during the design process. In *Material Precedent*, Gail Peter Borden argues that materials are currently subservient to issues of form, structure, and sustainability, and not core to conceptual architectural discourse.[10] In her dissertation, Neri Oxman argued that in architectural and industrial design projects, it has become common practice for form to be given the highest priority before materialization.[11] The tendency to increase the number of layers in wall assemblies can be observed as a byproduct of this shift. Materials are often ascribed to serve a single purpose, even though their properties allow them to perform multiple.[12] Wood can provide structural support, insulate against heat flow, and resist fire through charring. Re-introducing a holistic understanding of materials can ensure today's ever-changing building needs are addressed as efficiently as possible.

Understanding a material's bulk properties and capabilities allows designers to optimize its form and function within a building system. The advent of additive manufacturing allowed designers to fine-tune the infill geometry of a component for the greatest efficiency and select the filament with their desired properties.

Novel biocomposites such as mycelium introduce a new element into this narrative, as their material composition can be naturally altered. Biocomposites are fibre-reinforced materials whose ingredients are derived from biological sources such as plants and fungi.[13] These materials typically consist of a natural fibre and a binding component.[14] In the case of mycelium composites, living mycelium, the root system of fungi, serves as the binding component for natural substrates such as sawdust or agricultural wastes. The composite is formed as the mycelium grows into a filamentous network and bonds with its substrate. These lightweight composites have been found to exhibit numerous properties favourable to wall systems, such as insulation and fire resistance. Mycelium composites can be formed into various geometries, and their properties can be altered by selecting different fungal species and substrate types. Applied in wall systems, mycelium composites can be a biodegradable option for combining multiple material properties without adding additional layers.

9 D. Michelle Addington and Daniel L. Schodek, *Smart Materials and New Technologies: For the Architecture and Design Professions* (Amsterdam ; Boston: Architectural Press, 2005).
10 Gail Peter Borden, *Material Precedent: The Typology of Modern Tectonics* (Hoboken, N.J: John Wiley & Sons, 2010).
11 Neri Oxman and Jesse L. Rosenberg, "Material Based Design Computation" (CAADRIA 2007: Digitization and Globalization, Nanjing, China, 2007), https://doi.org/10.52842/conf.caadria.2007.x.d2j.
12 "Building Simply: a Guideline," in *Building Simply* (Birkhäuser, 2021), https://doi.org/10.1515/9783035624663.
13 Centre of Expertise Biobased Economy, "Biocomposites," MaterialDistrict, February 26, 2020, https://materialdistrict.com/material/biocomposites/.
14 Centre of Expertise Biobased Economy.

Case Study: Three Research Buildings in Bad Aibling

A research initiative at the Technical University of Munich sought to develop a material- and climate-conscious building design which required minimal heating loads in the winter and did not overheat in the summer.[15] Three three-storey residential buildings were built in Bad Aibling, Germany, each with a conceptually monolithic wall assembly. One building was made of cross-laminated timber (CLT), one with insulated masonry, and another with lightweight concrete (Figure 1.2). [16] A key aspect of their strategy was: *"Using single-layer building components made from renewable or mineral raw materials where possible and taking their material properties into account to design robust and durable structures."* [17] Though this case study investigated monolithic wall systems, all three were composite assemblies of similar components (i.e. bricks and mortar) with reduced layers. [18] Hence, these strategies and objectives can also be applied to the design of any composite wall system.



Figure 1.2: Sample sections of three research buildings, each constructed from one material. Left: Brick Masonry. Middle: Wood. Right: Concrete.

In each building, the material's properties were carefully considered to inform the design of its exterior wall assembly. [19] Figure 1.3 illustrates a typical wall section of the residential building

15 "Three Research Buildings Want to Show How to Build Simply," Stylepark, accessed January 16, 2023, https://www.stylepark.com/en/news/building-simply-dam-nagler-stylepark.
16 "Building Simply: a Guideline," in *Building Simply* (Birkhäuser, 2021), https://doi.org/10.1515/9783035624663.
17 Nagler.
18 Nagler.
19 "Three Research Buildings Want to Show How to Build Simply."

constructed from CLT. The cross-section of CLT was oversized to account for its gradual charring and shrinkage when exposed to fire.[20] The thickness in cross-section similarly provided greater thermal inertia; an ability to retain and gradually release heat gained throughout the day, helping to regulate temperature overnight.[21] The capillary structure of interior-exposed wood also proved beneficial in controlling moisture. Consideration of a material's properties allowed for a "monolithic" CLT wall assembly to satisfy residents' thermal and spatial comfort needs. The construction process was also reported as simpler, more durable, and easier to repair with fewer specialized tradespeople required. [22] The success of this project called on architects to apply iterative processes of holistic building, centred on materials. Understanding material properties becomes especially relevant with emerging mycelium biocomposites, to ensure their application within a composite wall system is practical, efficient and sustainable.

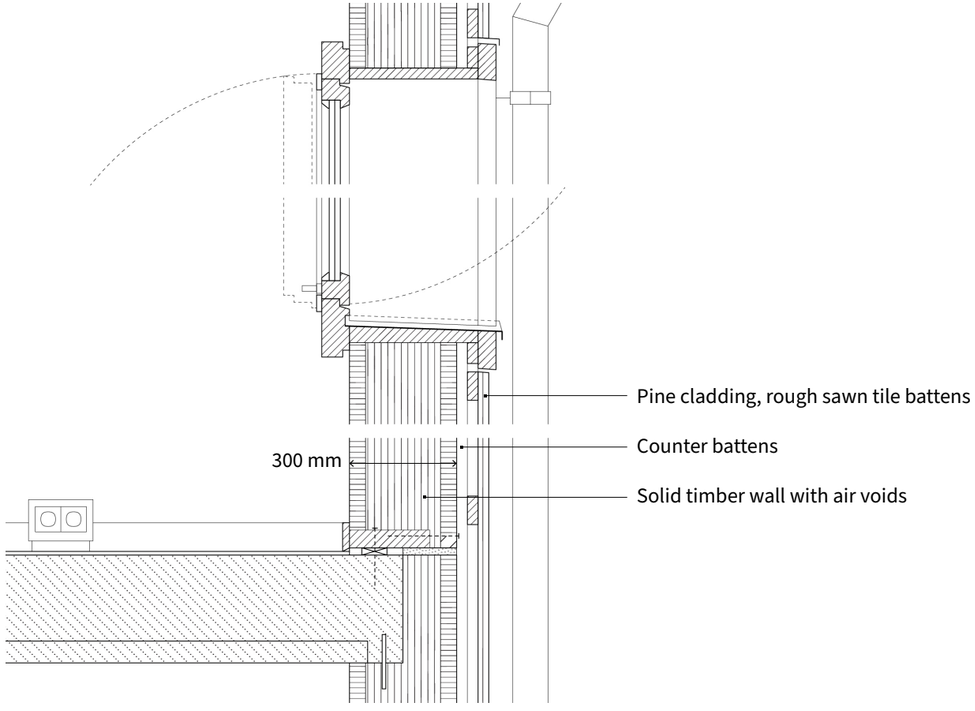


Figure 1.3: Section of robust building wall comprised of CLT and wood. Adapted from "Building Simply", by Florian Nagler.

20 Nagler, "Building Simply."
21 Nagler.
22 "Building Simply: a Guideline," in *Building Simply* (Birkhäuser, 2021), https://doi.org/10.1515/9783035624663.

1.2 Research Goals and Objectives

Through a compiled literature review and experimentation, this research will investigate the application of mycelium composites within a natural prefabricated wall system. The literature review will capture a comprehensive scope of mycelium's architectural applications along with comparable and applicable building construction technologies. The methodology will provide a framework for testing its application through experimentation, design and prototyping of a mycelium wall system based on the literature review.

To achieve these primary goals, specific objectives will be addressed, as follows:

- Catalogue the existing literature on mycelium as a biomaterial, its growth patterns, architectural applications, and performance properties.
- Conduct a literature review of contemporary prefabricated wall systems and new manufacturing technologies.
- Test mycelium's growth patterns through a physical experiment.
- Test mycelium's dimensional adhesive properties through a physical experiment.
- Utilize design prototyping to integrate mycelium's growth and performance considerations within a natural prefabricated wall system.
- Construct and evaluate the thermal resistance of a full-scale prototype mycelium wall, to compare to similar products on the market.

1.3 Scope and Limitations

This thesis research and the application of the developed product will be positioned within the context of Ontario, Canada. Literature Review and testing of mycelium growth patterns and performance properties will focus on criteria relevant to a wall system application. For example, experiments will test for dimensional considerations of homogenous mycelium growth, its preferred environmental conditions, and optimal substrate mixture. Mycelium is also being applied in various other fields, including food security, bioremediation, decomposition, clothing, and furniture, however, these applications are not within the scope of this research.

1.4 Approach and Organization

This thesis will investigate the potential of mycelium composites applied within façades through design prototyping and 3 phases of physical experimentation. Each experiment will aim to build craft-based material knowledge while maintaining independent and dependent variables for generating relevant findings. The methodology anticipates moments for feedback from each experiment to be incorporated into the design of a wall system. The first experiment will explore mycelium growth patterns by growing several specimens with varying substrate supplementation in a controlled environment. The second experiment will investigate the adhesion of mycelium composites with different adjacent materials. Lessons learned from these experiments will be applied through the design prototyping of a mycelium wall panel. Afterwards, the third experiment will involve constructing a full-scale prototype sample wall system. Once assembled, its thermal resistance will be tested and compared with similar building products and systems.

This thesis contains 5 chapters. The first chapter is an introduction to the research, to be concluded by this paragraph. The second chapter features a literature review of mycelium composite biomaterials, and contemporary prefabricated wall systems and technologies. The third chapter will outline the methodology of this research. The fourth chapter will highlight and discuss all results from the physical experiments and the design development. The fifth chapter will discuss the key findings and limitations of this research. The final sixth chapter will provide a conclusion and highlight the key contributions and future research potentials stemming from this body of work.

Chapter 2 - Literature Review

This section will catalogue the existing knowledge base on mycelium, relevant applications of mycelium biocomposites, contemporary wall panel systems, and fabrication technologies within construction. This knowledge will provide a basis for designing a mycelium wall assembly that is simple, adaptable, and sustainable.

2.1 Mycelium

Mycelium is the vegetative body of fungi consisting of tube-like cells called hyphae that penetrate and decompose surrounding organic matter to absorb their nutrients.[23] Fungi are a kingdom of organisms separate from plants and animals, as they are multicellular, require food from external sources, and digest nutrients externally.[24] Fungi reproduce through spores formed by sections of specialized hyphae.[25] Through a continual reproductive process, mycelium spreads throughout its organic substrate to form a root-like filamentous structure.[26] Visible forms of mycelium include mycelial fans which spread radially as mats throughout natural substrates like wood in high-humidity environments, or thread-like rhizomorphs which transport water to moisten and invade their substrates.[27]

Fungi perform three major roles within ecosystems. Pathogens cause diseases among plants or animals, saprobes decay plant debris to release CO_2 for other plants to perform photosynthesis, and mutualistic symbionts develop symbiotic relationships with other organisms.[28] Examples of mutualistic symbionts are fungi called mycorrhizae, which form relationships with the roots of trees and establish vast networks allowing them to transfer nutrients with one another.[29] Among these, saprophytic fungi have been noted to carry the most potential for mycelium bio-composite applications.[30] Notable saprophytic fungi are wood-decay Basidiomycetes capable of spawning fruiting bodies such as mushrooms.[31]

The life cycle of basidiomycetes begins with basidiospores landing on a suitable substrate and germinating under favourable conditions to form hyphae.[32] Each of these hyphae is haploid, containing one-half of a fungus' genetic material and reproduces asexually in this state as

23 Robert A. Zabel and Jeffrey J. Morrell, *Wood Microbiology: Decay and Its Prevention*, 2nd ed (London: Academic Press, 2020).
24 Zabel and Morrell.
25 Zabel and Morrell.
26 Zabel and Morrell.
27 Zabel and Morrell.
28 Zabel and Morrell.
29 S. Simard, *Finding the Mother Tree: Discovering the Wisdom of the Forest*, First edition (New York: Alfred A. Knopf, 2021).
30 Ali Ghazvinian and Benay Gursoy, "Basics of Building With Mycelium-Based Bio-composites," *Journal of Green Building* 17 (March 25, 2022): 37–69, https://doi.org/10.3992/jgb.17.1.37.
31 Rebekka Volk et al., "Life Cycle Assessment of Mycelium-Based Composite Materials," *Resources, Conservation and Recycling* 205 (June 1, 2024): 107579, https://doi.org/10.1016/j.resconrec.2024.107579.
32 Zabel and Morrell, *Wood Microbiology*.

haploid mycelium.[33] Once two haploid mycelia with opposite genetic halves meet, they fuse through plasmogamy and spread within the surrounding substrate as dikaryotic (two nuclei) mycelium.[34] As it spreads, the mycelium will consume nutrients such as cellulose from its substrate through pressure and the secretion of enzymes.[35] Common natural substrates include wood, soil, and agricultural wastes.[36] After the mycelium spreads, favourable energy reserves and environmental conditions will cause it to aggregate into a basidiocarp, the fruiting body.[37] Here, the hyphae undergo nuclear fusion, becoming diploid, before splitting into four haploid nuclei through meiosis and becoming new basidiospores, repeating the cycle.[38] This reproductive cycle highlights the function of genetic diversity among basidiomycetes, allowing them to adapt to changing environments.[39]

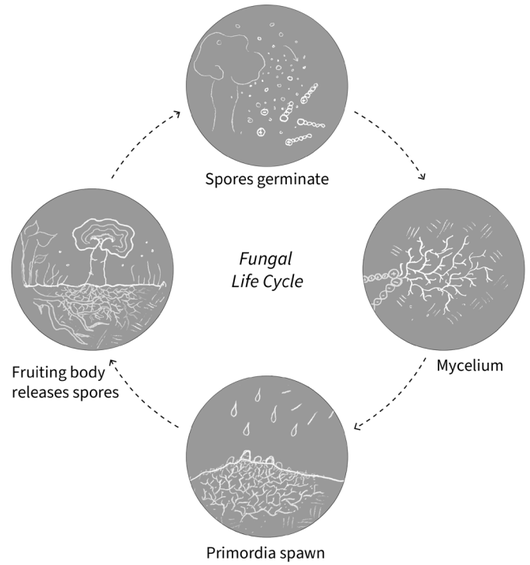


Figure 2.1.1: The natural life cycle of mycelium.

In material science, mycelium is described as a naturally polymeric composite fibrous material, possessing chitin, cellulose, and proteins.[40] Most notable among these is chitin, a

33 Zabel and Morrell.
34 Zabel and Morrell.
35 Muhammad Haneef et al., "Advanced Materials From Fungal Mycelium."*Scientific Reports* 7 (January 24, 2017): 41292. https://doi.org/10.1038/srep41292.
36 Merlin Sheldrake, *Entangled Life: How Fungi Make Our Worlds, Change Our Minds & Shape Our Futures*, Random House Trade Paperback Edition (New York: Random House, 2021).
37 Austin Booth, "Populations and Individuals in Heterokaryotic Fungi: A Multilevel Perspective," *Philosophy of Science* 81, no. 4 (October 2014): 612–32, https://doi.org/10.1086/677953.
38 Zabel and Morrell, *Wood Microbiology*.
39 Zabel and Morrell.
40 Haneef et al., "Advanced Materials From Fungal Mycelium."

chemical compound found in the exoskeletons of animals such as lobsters which exhibits tremendous rigidity and stability.[41] For this reason, researchers are investigating the cultivation of specific mycelial species to create new organic materials with properties that are favourable to applications such as architecture.[42] This process is not limited to a laboratory environment, as many mycologists have also compiled their recipes for cultivating mycelium from within their homes.[43]

The first step to cultivating mycelium is to acquire a sample. This is commonly initiated by harvesting a mushroom sample from nature, placing it within a petri dish with sterilized agar solution, and allowing mycelium to grow.[44] Mycelium may be acquired from mycological herbaria, or through local commercially sold mushroom grow kits containing live mycelium.[45] Next, one must acquire and sterilize a substrate. Viable substrates include, but are not limited to wood products, coffee grounds, soil, and agricultural wastes.[46] One of the most common sterilization methods is pasteurization, where the substrate is heated to approximately 80°C for 30-60 minutes to kill most competing microorganisms.[47] Common pasteurization methods include immersion in hot water and autoclaving in steam.[48] The live mycelium and the pasteurized substrate are then mixed into a sterilized bag or container with air filtration, and stored in a dark, temperature-controlled space.[49] After approximately one month, the mycelium spreads and binds to the substrate forming a composite, which may then be post-processed to halt mycelial growth depending on its application.[50] This process is circular, as mycelium-based materials return to the earth at the end of their life cycle.[51] The service lifespan of mycelium biocomposites was estimated to be 30 years, similar to that of other bio-based insulation materials.[52] However, there is uncertainty about this lifespan as mycelium-based materials have currently only been tested in short-term demonstrations.[53]

41 Mitchell Jones et al., "Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium - Biomass Composite Materials," *Scientific Reports* 8, no. 1 (December 4, 2018): 17583.
42 Ali Ghazvinian and Benay Gursoy, "Basics of Building With Mycelium-Based Bio-composites," *Journal of Green Building* 17 (March 25, 2022): 37–69, https://doi.org/10.3992/jgb.17.1.37.
43 Marantos, "How to (Deliberately) Grow Your Own Mushrooms at Home."
44 Zabel and Morrell, *Wood Microbiology*.
45 "Canadian National Mycological Herbarium (DAOM)," https://agriculture.canada.ca/en/science/collections/canadian-national-mycological-herbarium-daom.
46 Maria Saxton, "Mycelium Fungi as a Building Material," Rise, February 13, 2020.
47 Armando Antonio Macias Gonzalez et al., "Pasteurization of Agricultural Substrates for Edible Mushroom Production," *Journal of Microbiology, Biotechnology and Food Sciences* 12, no. 1 (August 1, 2022): e5729–e5729, https://doi.org/10.55251/jmbfs.5729.
48 Paul Stamets and J. S. Chilton, *The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home* (Olympia, Wash.: Seattle, Wa: Agarikon Press ; Western distribution by Homestead Book Co, 1983).
49 Sean Campbell et al., *Modular Mycelia: Scaling Fungal Growth for Architectural Assembly*, 2017.
50 Ghazvinian and Gursoy.
51 Verge Science, "This Mushroom Brick Could Replace Concrete," Youtube, February 2, 2021.
52 Nicolas Alaux et al., "Environmental Potential of Fungal Insulation: A Prospective Life Cycle Assessment of Mycelium-Based Composites," *The International Journal of Life Cycle Assessment* 29, no. 2 (February 1, 2024): 255–72, https://doi.org/10.1007/s11367-023-02243-0.
53 Alaux et al.

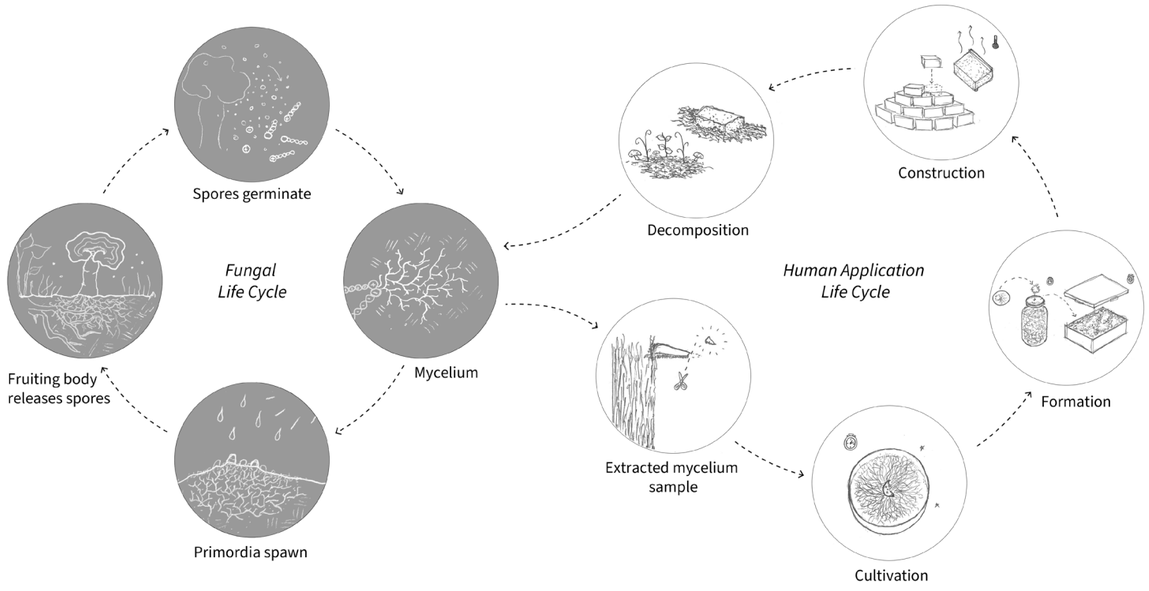


Figure 2.1.2: The combined natural and human-extracted life cycle of mycelium.

Pleurotus ostreatus, the basidiomycete used in this research, is classified as a BSL-1 organism, indicating that it typically does not cause disease in healthy humans or other living organisms.[54] [55] Although this fungal species is not pathogenic, their spores may pose health risks to immunocompromised persons.[56] As part of their reproductive cycle, fungi release (a)sexual spores in large quantities, with 1000-10 000 fungal spores observed in every cubic meter of air on average.[57] Certain spores such as chlamydospores can also resist environmental stress and remain dormant for many years.[58] Exposure to high quantities of *P. ostreatus* basidiospores was noted to cause respiratory problems in some mushroom growers.[59] Killing or desiccating the fungi by exposing it to high temperatures can help mitigate the release of spores from mycelium biocomposite products. [60] Care must also be taken with the design of mycelium wall systems so that any resting spores remain inactive throughout their service life.

54 "Pleurotus Ostreatus (Jacquin : Fries) Kummer - 56761 | ATCC." https://www.atcc.org/products/56761.
55 "Biosafety," Ohio Wesleyan University. https://www.owu.edu/about/offices-services-directory/office-of-environmental-health-safety/biological-safety/biosafety/.
56 Samuel B. Lehrer et al., "Basidiomycete Mycelia and Spore-Allergen Extracts: Skin Test Reactivity in Adults with Symptoms of Respiratory Allergy," *Journal of Allergy and Clinical Immunology*, Forty-third Annual Meeting, 78, no. 3, Part 1 (September 1, 1986): 478–85, https://doi.org/10.1016/0091-6749(86)90036-9.
57 Jeroen G. van den Brandhof and Han A. B. Wösten, "Risk Assessment of Fungal Materials," *Fungal Biology and Biotechnology* 9 (February 24, 2022): 3, https://doi.org/10.1186/s40694-022-00134-x.
58 Zabel and Morrell, *Wood Microbiology*.
59 Brian Lavrijssen et al., "Interruption of an MSH4 Homolog Blocks Meiosis in Metaphase I and Eliminates Spore Formation in Pleurotus Ostreatus," *PLoS ONE* 15, no. 11 (November 4, 2020): e0241749, https://doi.org/10.1371/journal.pone.0241749.
60 Zabel and Morrell.

2.1.1 Mycelium Growth Patterns

Understanding mycelium's growth patterns in different environments is crucial to applying it efficiently within a building assembly. The six general requirements for fungal growth are nutrients, water, oxygen, pH, temperature and light.[61] Current research is investigating the impacts of these environmental factors on mycelium growth amount and spawn run time.[62] Key topics of investigation include species, substrates, environment, and growth container types.

Mycelium's species influences its growth patterns, as different fungal species exhibit preferences for specific growth conditions and substrates. Understanding the growth preferences of a mycelium species will allow the designer to tune its growth conditions and substrate composition for optimal growth. *Reishi* mycelium (*Ganoderma Lucidum*) and Oyster mycelium (*Pleurotus Ostreatus*) are the most prominent species in current material research.[63] *Reishi*, a wood-degrading mycelium traditionally cultivated on wood logs, uses lignin as its primary carbon source in nature alongside cellulose, and can thrive on various organic substrates.[64] [65] *Reishi* can be cultivated within a specific range of environmental conditions and demonstrates moderate susceptibility to contamination.[66] *Oyster* mycelium is a species recognized for its low-cost production technology and high biological efficiency.[67] An efficient degrader of lignin and cellulose, *Oyster* mycelium can grow on diverse agricultural wastes and within a broad spectrum of microclimates, making it accessible for amateur cultivation.[68] While both species have shown positive growth in straw substrates, *oyster* were uniquely compatible with fibres and bagasse, while *reishi* showed greater growth in sawdust substrate.[69] This highlights the importance of catering substrates to fungal species. Like *reishi*, *oyster* mycelium exhibited some susceptibility to contamination from competing organisms.[70] A study noted that while the optimum growth temperature for *oyster* and *reishi* mycelium was 22°C, *oyster* demonstrated growth within a larger range of temperatures, from 22-30°C.[71]

Successful mycelium growth depends on environmental factors including temperature, humidity, and light. One study found that from a range of 22°C to 37°C, the optimal growth temperature for mycelium spawn rate with the *P. ostreatus* (oyster) strain was 22°C, while it did not grow at 37°C.[72] This finding is supported by another study which cited the optimal temperature range for *P. ostreatus* mycelium growth as 21-24°C.[73] A possible method of regulating temperature within a sterile environment would be using a growth chamber.[74] High relative humidity (RH) is required for basidiomycetes to absorb nutrients from their substrate effectively, as well as sporulate.[75] One study documented 85-95% RH as an optimal growth range for *oyster* mycelium.[76] Another study echoes this, citing that from a range of 65 to 85% RH, the most successful oyster mycelium growth occurred in conditions of 80-85% RH.[77] Mycelium growth typically occurs best in the absence of light, as light presence is one factor which signals the mycelium to channel energy toward fruiting.[78] Researchers found that the presence of light negatively impacted the growth patterns of seven mycelium strains tested.[79] Increasing ambient air exposure caused a brief acceleration in mycelium growth rate as it entered its early fruiting stage, however exact numerical impacts of this have yet to be determined.[80]

Substrate type greatly affects mycelium growth rate and contamination risk, since different mycelium species require different nutrients as food. A wide variety of organic substrates have been studied internationally, along with various combinations and supplementations, in terms of their efficacy in growing mycelium. One study found that from agar, seeds, straw,

61 Robert A. Samson, "Chapter 1 - Cellular Constitution, Water and Nutritional Needs, and Secondary Metabolites," in *Environmental Mycology in Public Health*, ed. Carla Viegas et al. (Amsterdam: Academic Press, 2016), 5–15, https://doi.org/10.1016/B978-0-12-411471-5.00001-6.
62 Thibaut Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*, 2020.
63 Noam Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture: Comparative Review and Experimental Analysis," *Journal of Cleaner Production* 246 (February 10, 2020): 119037, https://doi.org/10.1016/j.jclepro.2019.119037.
64 Yongjun Wang et al., "Diversity and Effects of Competitive Trichoderma Species in Ganoderma Lucidum–Cultivated Soils," *Frontiers in Microbiology* 13 (2022), https://www.frontiersin.org/articles/10.3389/fmicb.2022.1067822.
65 Magday Jc, Melfei Bungihan, and Dulay Rmr, "Optimization of Mycelial Growth and Cultivation of Fruiting Body of Philippine Wild Strain of Ganoderma Lucidum," *Current Research in Environmental & Applied Mycology* 4 (November 27, 2017), https://doi.org/10.5943/cream/4/2/4.
66 Insight Cambodia Journal of Basic and Applied Research, "Log and Bag Cultivation of Oyster (Pleurotus Ostreatus) and Lingzhi (Ganoderma Lucidum) Mushrooms in Cambodia" 1 (December 31, 2019): 32–42.
67 Ha Thi Hoa and Chun-Li Wang, "The Effects of Temperature and Nutritional Conditions on Mycelium Growth of Two Oyster Mushrooms (Pleurotus Ostreatus and Pleurotus Cystidiosus)," *Mycobiology* 43, no. 1 (March 1, 2015): 14–23, https://doi.org/10.5941/MYCO.2015.43.1.14.
68 Senzosenkosi Surprise Mkhize et al., "Performance of Pleurotus Ostreatus Mushroom Grown on Maize Stalk Residues Supplemented with Various Levels of Maize Flour and Wheat Bran," *Food Science and Technology* 36, no. 4 (December 12, 2016): 598–605.
69 Eugene Soh et al., "Effect of Common Foods as Supplements for the Mycelium Growth of Ganoderma Lucidum and Pleurotus Ostreatus on Solid Substrates," *PLOS ONE* 16, no. 11 (November 30, 2021): e0260170, https://doi.org/10.1371/journal.pone.0260170.
70 Taekyoung Lee and Jaeyun Choi, "Mycelium-Composite Panels for Atmospheric Particulate Matter Adsorption," *Results in Materials* 11 (September 1, 2021): 100208.
71 I. A. Fletcher, "Effect of Temperature and Growth Media on Mycelium Growth of Pleurotus Ostreatus and Ganoderma Lucidum Strains," *Cohesive Journal of Microbiology and Infectious Disease* 2, no. 5 (July 9, 2019), https://eprints.leedsbeckett.ac.uk/id/eprint/6111/.
72 Fletcher.
73 Jegadeesh Raman et al., "Cultivation and Nutritional Value of Prominent Pleurotus Spp.: An Overview," *Mycobiology* 49, no. 1 (n.d.): 1–14, https://doi.org/10.1080/12298093.2020.1835142.
74 Sean Campbell et al., *Modular Mycelia: Scaling Fungal Growth for Architectural Assembly*, 2017.
75 Constantine J. Alexopoulos and Charles W. Mims, *Introductory Mycology*, 3. ed., 1. print (New York: Wiley, 1979).
76 M. Jafarpour and S. Eghbalsaeed, "High Protein Complementation with High Fiber Substrates for Oyster Mushroom Cultures," *African Journal of Biotechnology* 11, no. 14 (2012): 3284–89, https://doi.org/10.4314/ajb.v11i14.
77 Hamed Aghajani et al., "Influence of Relative Humidity and Temperature on Cultivation of Pleurotus Species," *Maderas: Ciencia y Tecnología* 20 (December 4, 2018): 571–78, https://doi.org/10.4067/S0718-221X2018005004501.
78 Adam Sayner, "A Detailed Explanation of the Mushroom Life Cycle," *GroCycle* (blog), September 6, 2021, https://grocycle.com/mushroom-life-cycle/.
79 Sandra Furlan et al., "Mushroom Strains Able to Grow at High Temperatures and Low pH Values," *World Journal of Microbiology and Biotechnology* 13 (November 1, 1997): 689–92, https://doi.org/10.1023/A:1018579123385.
80 Parshan Fatehi, "Engaging Mycelium: Explorations of a Cultivated Architecture" (Master Thesis, University of Waterloo, 2018), https://uwspace.uwaterloo.ca/handle/10012/13339.

and wood substrates, seeds demonstrated the best potential for mycelium growth due to greater airflow between gaps in the substrate.[81] This finding is supported by another study which found mycelium growth within cotton seed substrate to be complete within 15 days, while sawdust substrate took 20 days.[82] Among a variety of substrate grain sizes, mycelium colonized quicker in finer substrates, and the final product was more dense and less elastic.[83] Hemp, corn stover, and a combination of sawdust, soy hulls and gypsum were examined as mycelium substrates, and the combined substrate was the most effective for surface area mycelium growth.[84] When supplementing a sugarcane bagasse substrate for pink oyster mycelium from a range of 0 to 50%, 40% bran demonstrated the highest running rate, while the lowest was with 0%.[85] These observations suggest that supplementing additional nutrients catered for the mycelium species will decrease growth time. The body of research on substrate type and composition is extensive, yet research has yet to document the expected reliability and variance of results associated with adjusting supplementation levels for mycelium.

The type of container utilized for mycelium growth profoundly impacts its growth patterns. Variations in air and moisture exchange, as well as geometry, have affected the mycelium growth rate, as well as risks of contamination. From three options for enclosing a mycelium growth frame, including a sealed bag, a box, or a housewrap tent, tents facilitated the highest mycelium growth and no contamination, due to greater oxygen exchange and filtration.[86] Surfaces exposed to ambient air displayed greater mycelium growth, which affected certain composite properties.[87] Determining the exact difference and consistency of this phenomenon requires additional investigation. A study catered mycelium growth containers to be spherical based on an observation that mycelium grows radially, to maximize colonization efficiency (Figure 2.1.3).[88] This observation is significant, as it suggests that mycelium can fully colonize a variety of three-dimensional shapes regardless of depth. Fungi can be observed living within three-dimensional surfaces in nature, one example being wood-rotting basidiomycetes occupying and decaying wood.[89] A dimensional study, conducted by growing mycelium in a brick-shaped formwork at multiple scales, found that inconsistencies in the mycelium spawn distribution and growth became more evident at larger scales.[90] This issue was alleviated by first inoculating the substrate with mycelium in a separate tub, and then pouring the composite into the formwork to resume growth.[91] Research can be further advanced through additional testing on the dimensional shrinkage of mycelium composites as moisture is lost within their container.

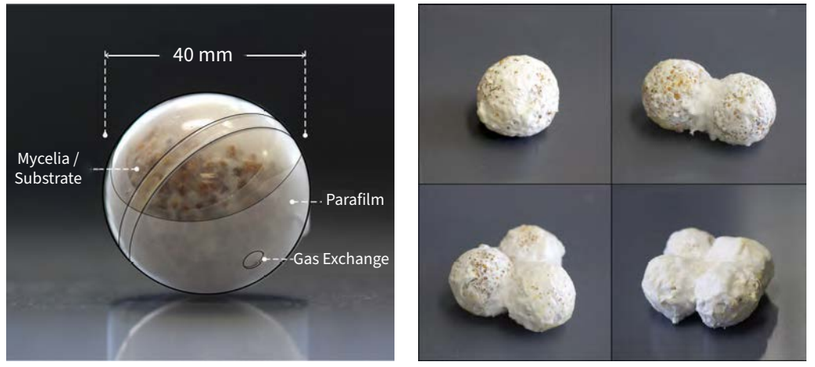


Figure 2.1.3: Spherical mycelium composite modules can utilize mycelium's unique hyphal bonding capabilities to self-aggregate and scale up. From "Modular Mycelia" by Campbell et al.

81 Sean Campbell et al., *Modular Mycelia: Scaling Fungal Growth for Architectural Assembly*, 2017.
82 Zenebe Girmay et al., "Growth and Yield Performance of Pleurotus Ostreatus (Jacq. Fr.) Kumm (Oyster Mushroom) on Different Substrates | AMB Express," October 4, 2016, https://link.springer.com/article/10.1186/s13568-016-0265-1.
83 Parshan Fatehi, "Engaging Mycelium: Explorations of a Cultivated Architecture" (Master Thesis, University of Waterloo, 2018), https://uwspace.uwaterloo.ca/handle/10012/13339.
84 Thibaut Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*, 2020.
85 Md Hasan et al., "Effect of Wheat Bran Supplement with Sugarcane Bagasse on Growth, Yield and Proximate Composition of Pink Oyster Mushroom (Pleurotus Djamor)," *American Journal of Food Science and Technology* 3 (November 1, 2015): 150–57, https://doi.org/10.12691/ajfst-3-6-2.
86 Thibaut Houette et al., *Growing Myceliated Facades.*
87 Thibaut Houette et al., "Growth and Mechanical Characterization of Mycelium-Based Composites towards Future Bioremediation and Food Production in the Material Manufacturing Cycle," *Biomimetics* 7, no. 3 (September 2022): 103, https://doi.org/10.3390/biomimetics7030103.
88 Sean Campbell et al., *Modular Mycelia.*
89 Diego Tamburini et al., "Distinguishing the Signs of Fungal and Burial-Induced Degradation in Waterlogged Wood from Biskupin (Poland) by Scanning Electron Microscopy," *Microscopy and Microanalysis* 24, no. 2 (April 2018): 163–82, https://doi.org/10.1017/S143192761800020X.
90 Fatehi, "Engaging Mycelium."
91 Fatehi.

2.1.2 Architectural Applications of Mycelium

In recent years, many types of applications have emerged for mycelium-based products. These range from industrial products and furniture to worldwide installations and pavilions, showcasing the capabilities of mycelium as a material. Despite this wide range of applications, the production of mycelium composites typically follows a structure, as described in Figure 2.1.4.[92] Options vary during the growth and ceasing stages, with three options for growth vessels and four types of mycelium post-growth treatment. Each method of cellular growth varies in complexity and level of waste produced during the process. A series of three case studies will cover each method of mycelium composite production, to analyze which carries the best potential for a modular wall assembly product.

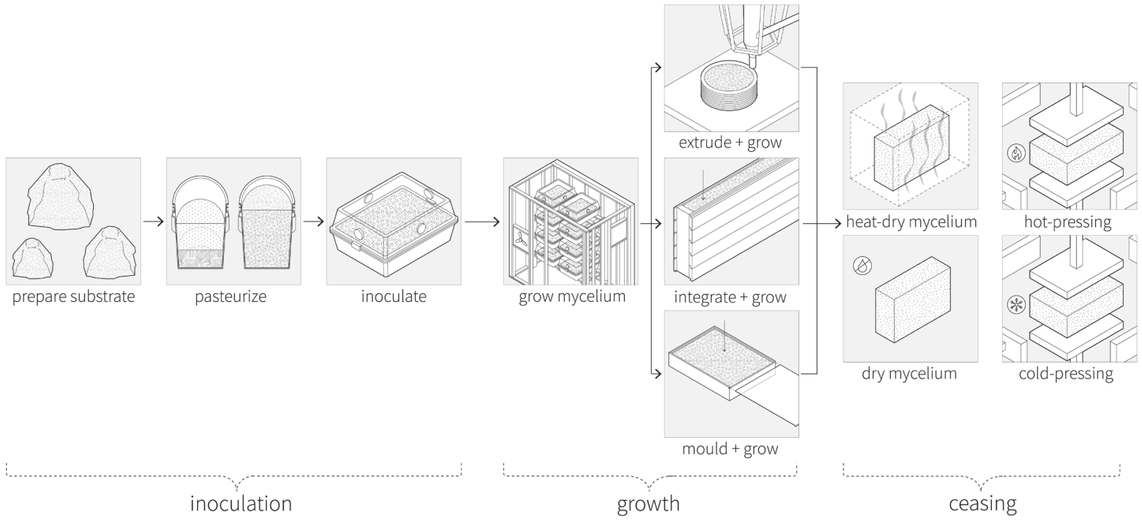


Figure 2.1.4: Typical production process for mycelium composites.

92 Ghazvinian and Gursoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES."

Production method 1: Mould + Grow, freeform blocks or panels extracted from mould.

In "*Mould + Grow*", the inoculated substrate is packed into a formwork, grown in a controlled environment, removed from the formwork, and then post-processed. One recent application of this method is "*In Vivo*", the Belgian pavilion at the Venice Architecture Biennale of 2023, designed and built collaboratively by Bento Architecture and Viciano Despret. This pavilion features a central space which is 12 m wide, 6 m tall, and 6 m long, comprised of 500 mm wide square mycelium composite panels, arrayed side by side (Figure 2.1.5).[93] Here, mycelium creates a multi-sensory (visual and acoustic) experience for visitors. The pavilion is a circular design, where the wooden frame, excavated earth floor and mycelium panels were all locally sourced in Brussels, and designed to be disassembled and reused after the exhibition.[94] Blocks were formed using a method of pressing mycelium-inoculated substrate onto a block-shaped acrylic formwork with a plywood bottom. After full growth, the mycelium blocks were removed from their form and installed onto their wooden scaffold.[95] One advantage of this form of production is that tolerance can be better controlled and predicted, as each composite block will undergo similar shrinkage levels. In the installation, designers could array the blocks adjacent to one another because of this. A disadvantage of this process is that the system involves double the parts, as each mycelium panel would require its dedicated formwork during the growth stage. In addition, the mycelium panels are inherently separate from their wooden scaffold and require a separate fastening method.

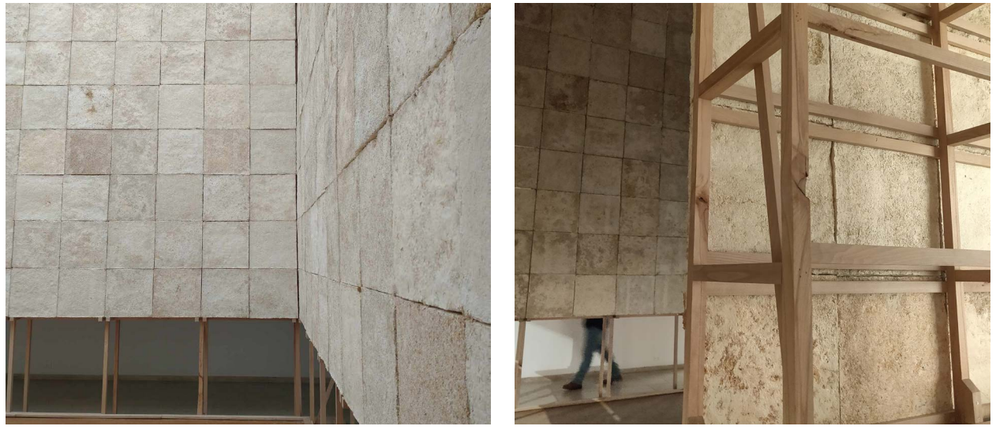


Figure 2.1.5: Belgian Pavilion "In Vivo" at Venice Biennale. Mycelium composite panels surround a central space, supported by a skeletal wooden frame.

93 "Belgian Pavilion | In Vivo," https://www.belgianpavilion.be/en/projects/belgian-pavilion-2023.
94 "Belgian Pavilion | In Vivo."
95 "Belgian Pavilion | In Vivo."

Production method 2: Integrate + Grow - Blocks Integrated into Form

With "*integrate + grow*", inoculated mycelium is poured into a formwork to grow, however, once growth is complete, it remains within its mould during its end use. Post-processing methods to cease mycelium growth are applied directly to the combined form. Ecovative, a company at the forefront of mycelium-based product development, prototyped a mycelium tiny home utilizing this method. The mycelium was packed and grown between two layers of shiplap wood planks to form a complete building envelope.[96] This configuration is intuitive, as since the wooden building skin acts as the cast, there is no need for any temporary synthetic casts throughout the process. The mycelium is also protected from external elements, meaning its lifespan will likely be much greater. The four control layers in most typical building enclosures are air, water, vapour, and thermal control.[97] In this system, the mycelium provides a continuous thermal control layer while the exterior siding acts as a rain screen. Since there is limited air and vapour control, humidity differentials between the interior and exterior could cause vapour to flow freely through the wall.[98] This is significant as high humidity may reactivate dormant spores and resume unwanted mycelial growth in the wall.[99] Another disadvantage of this method is that mycelial growth within the wall would be difficult to track, and replacing a damaged section would prove difficult. This example can be developed by integrating lightweight structural framing and modularizing the system to better adapt in response to contamination or structural damage. These adjustments could allow a wall system to be deployed for a wider range of building types.

It is crucial to consider the various implications of integrating mycelium with a permanent container made of natural wood. Basidiomycetes such as *P. ostreatus*, through digesting lignin, convert it into lignin-based radicals which can develop cross-links and cause adhesion between the mycelium and the wood.[100] Though this phenomenon has promise for a biodegradable component design, the long-term integrity and service life impacts of exposing wood to wood-rotting fungi would have to be studied. Furthermore, many fungi can release thermal-resistant chlamydospores that can embed themselves within a substrate and remain dormant for many years.[101] One strategy to address these points is baking the composite at a high temperature to kill the mycelium. Exposing a wood sample to an internal temperature of 76.7°C for 30 minutes successfully killed all fungi in the wood during processing.[102] A second strategy would be to provide a barrier against moisture accumulation in the formwork's design to prevent the reactivation of spores throughout the product's service life.[103]



Figure 2.1.6: Mycelium Tiny Home, designed and built by a team from Ecovative. The mycelium was grown between an interior and exterior layer of shiplap lumber.

96 "Mushroom Tiny House: The Part-Grown Portable Home," New Atlas, July 11, 2013, https://newatlas.com/mushroom-tiny-house/28248/.
97 John F. Straube and E. F. P. Burnett, *Building Science for Building Enclosures* (Westford, Mass: Building Science Press, 2005).
98 Straube and Burnett.
99 Zabel and Morrell, *Wood Microbiology*.
100 Volk et al., "Life Cycle Assessment of Mycelium-Based Composite Materials."
101 Zabel and Morrell, *Wood Microbiology*.
102 Zabel and Morrell.
103 Straube and Burnett, *Building Science for Building Enclosures*.

Production method 3: Extrude + Grow - Additive Manufactured Mycelium

The third production method for mycelium composites is "*extrude + grow*", where a 3D extruder deposits a mycelium substrate mixture to form a shell geometry. In many cases, the mycelium is inoculated within the substrate before extrusion and grows once it is printed in a sterile environment, binding the filament together. Figure 2.1.7 shows Blast Studio's 3D-printed mycelium column, where substrates inoculated with mycelium culture were deposited to form a column, and the mycelium grew as that shape.[104] An advantage of this production method is that it is theoretically waste-free, with most extrusion machines being reusable, and minimal formwork required. Though compelling, it would likely require access to a sizable controlled and sterilized environment, as the mycelium is easily susceptible to contamination in the open air during its early stages of growth.[105] Great care would also need to be taken to sterilize all components of the printer. This method affords a monolithic wall element composed of mycelium; however, it is unclear how this fabrication method could integrate weather-resistant materials into a wall system.



Figure 2.1.7: Blast Studio's 3D-printed mycelium-substrate column demonstrates the complexity of sculptural forms achievable with the intersection of mycelium hyphal bonding and additive manufacturing. Images from Blast Studio.

Additional additive manufacturing methods have explored mixing viable mycelium substrate within a filament, which is deposited to form an outer shell, within which mycelium can grow. Researchers have developed one such example in MyCera, where they sought to combine a sawdust substrate with clay and deposit the mixture using a clay extruder to create hollow forms.[106] Once the print was completed, it was sterilized, and a substrate inoculated with mycelium was inserted into the core of the form, as seen in Figure 2.1.8.[107] Afterward, the fully colonized mycelium grew within the formwork, and the combined block was dried through baking, then optionally firing the clay. [108] This production method can be interpreted as a combination of both the "*integrate + grow*" and "*extrude + grow*" methods. The formwork is 3D-printed, and the mycelium composite consumes the substrate in the formwork as it grows, allowing a strong adhesion between the core and shell. This example shows great potential for wall system application, as formworks can be customizable, and climate-resistant materials can be selected as the outer filament layer. Questions persist on how connections between modules are addressed, as the extruder machine typically limits print and module size.

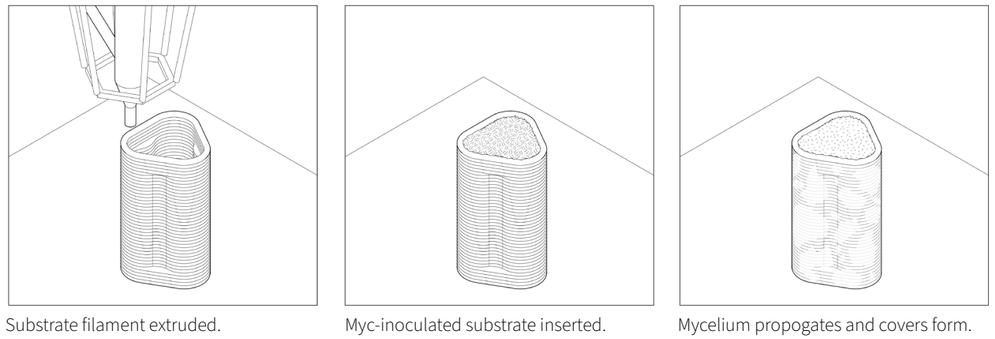


Figure 2.1.8: Drawing describing methods applied in "MyCera". Clay mixed with sawdust as form, with mycelium-inoculated substrate at the core.

Among these three branches of production, "integrate + grow" was selected as the most promising method to carry into a mycelium wall system design for this research project. This method reduces the number of parts involved from the beginning to the end of the system's life cycle and allows for the design of secure connection points between modules within a demanding cold climate. Strategies from other methods will also be applied to the cumulative design.

104 "Blast Studio 3D Prints Column from Mycelium to Make 'Architecture That Could Feed People,'" Dezeen, January 18, 2022, https://www.dezeen.com/2022/01/18/blast-studio-tree-column-mycelium-design/.
105 Campbell et al., *Modular Mycelia*.
106 Julian Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures," March 20, 2022, https://doi.org/10.1177/14780771221082248.
107 "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures."
108 "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures."

2.1.3 Material Performance Properties

Understanding mycelium's specific performance capabilities and limitations is crucial for determining its optimum role within an architectural assembly. Performance properties of mycelium-based composites documented and tested in research thus far include thermal and sound insulation, fire resistance, structural capacity, environmental degradation, and adhesion.[109]

Structure

Mycelium composites have limited structural capacity compared to other building materials, though varying species, substrate, and post-growth treatment can enhance their structural properties for certain applications. Compressive strength varied by fungal species for oat husk substrate composites, with *reishi* mycelium demonstrating strength of 125 KPa, compared to *oyster* mycelium with only 25 KPa.[110] From a group of organic substrates for mycelium composites, red oak sawdust and flax hurd were found to perform the best in compression, with ratings of 1.0 MPa, and 0.73 MPa, respectively. [111] Notably, another study highlighted that mechanical performance depends more on fibre processing and size than chemical composition.[112] The structural capacity of chopped hemp (0.77 MPa) and chopped flax composites (1.18 MPa) was greater than that of composites with loose hemp (0.51 MPa) and loose flax (0.28 MPa).[113] The structural capacities of mycelium composites can exceed those of typical synthetic foams in the construction market, such as Expanded Polystyrene, measured at 0.191 MPa.[114] However, mycelium's compressive and tensile strength is not comparable to typical wood products such as plywood and softwood lumber.[115] These comparisons suggest that mycelium composites require structural reinforcement within wall system applications. The impact of integrating dowels or fibres into substrates for improving the compressive or tensile stability of mycelium composites has yet to be explored.

109 Thibaut Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*, 2020.
110 Zeynep Tacer-Caba et al., "Comparison of Novel Fungal Mycelia Strains and Sustainable Growth Substrates to Produce Humidity-Resistant Biocomposites," *Materials & Design* 192 (July 1, 2020): 108728, https://doi.org/10.1016/j.matdes.2020.108728.
111 Mitchell Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review," *Materials & Design* 187 (February 1, 2020): 108397, https://doi.org/10.1016/j.matdes.2019.108397.
112 Elise Elsacker et al., "Mechanical, Physical and Chemical Characterisation of Mycelium-Based Composites with Different Types of Lignocellulosic Substrates," *PLOS ONE* 14, no. 7 (July 22, 2019): e0213954, https://doi.org/10.1371/journal.pone.0213954.
113 Elsacker et al.
114 Wensu Chen et al., "Static and Dynamic Mechanical Properties of Expanded Polystyrene," *Materials & Design* 69 (March 15, 2015): 170–80, https://doi.org/10.1016/j.matdes.2014.12.024.
115 Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries."

Thermal Performance

The thermal insulation of mycelium biocomposites containing natural insulators as substrates has been studied extensively, with performance varying based on substrate type and size.[116] Thermal conductivity, *k*, indicates the rate at which heat energy is transferred through a material by diffusion and is dependent on the material's atomic structure.[117] Mycelium composites made of flax waste, hemp and straw substrates demonstrated a *k* of 0.0578, 0.0404 and 0.0419 W/mK respectively.[118] Within this similar range, a study utilized birch wood shavings as a substrate for a mycelium composite panel and measured its *k* to be 0.055 W/mK.[119] This evidence suggests that by varying the substrate of a mycelium composite, architects can tune its thermal performance to suit a more specific need. Though mycelium growth patterns are unpredictable, *k* values were relatively consistent across identical samples. From testing 8 identical samples of 70mm thick mycelium-silvergrass composite panels between hot and cold plates, their *k* ranged from 0.0882 to 0.104 W/mK.[120] Mycelium composites have the potential to match the thermal resistance of traditional insulating materials, including mineral wool, glass fibres and cork.[121] However, foam materials such as EPS (*k* = 0.35-0.4 W/mK) are still slightly better insulators, which may explain why mycelium insulation products have not yet broken the market.[122] Researchers have yet to map out variations in thermal resistance through the cross-section of a mycelium composite, as mycelium tends to grow most dense at the outer surface, and less in its core.[123]

Fire Resistance

The fire resistance characteristics of mycelium and its composites make it an asset to wall envelopes. As an adhesive, isolated mycelium demonstrated a lower heat release in Cone Calorimetry tests compared to thermoplastics such as PMMA (polymethyl methacrylate) and PLA (polylactic acid), due to the presence of Phosphorous.[124] A 70-mm thick mycelium

116 Jones et al.
117 Frank P. Incropera et al., eds., *Fundamentals of Heat and Mass Transfer*, 6th ed (Hoboken, NJ: John Wiley, 2007).
118 Elise Elsacker et al., *Mechanical, Physical and Chemical Characterisation of Mycelium-Based Composites with Different Types of Lignocellulosic Substrates*, 2019, https://doi.org/10.1101/569749.
119 G Wimmers et al., "Fundamental Studies for Designing Insulation Panels from Wood Shavings and Filamentous Fungi:: BioResources," 2019, https://bioresources.cnr.ncsu.edu/.
120 Patrick Pereira Dias, Laddu Bhagya Jayasinghe, and Daniele Waldmann, "Investigation of Mycelium-Miscanthus Composites as Building Insulation Material," *Results in Materials* 10 (June 1, 2021): 100189, https://doi.org/10.1016/j.rinma.2021.100189.
121 Elise Elsacker et al., *Mechanical, Physical and Chemical Characterisation of Mycelium-Based Composites with Different Types of Lignocellulosic Substrates*, 2019, https://doi.org/10.1101/569749.
122 Le Duong Hung Anh and Zoltán Pásztory, "An Overview of Factors Influencing Thermal Conductivity of Building Insulation Materials," *Journal of Building Engineering* 44 (December 1, 2021): 102604, https://doi.org/10.1016/j.jobe.2021.102604.
123 Eldy Lazaro and Katia Vega, *From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium*, 2019, https://doi.org/10.1145/3341162.3343808.
124 Mitchell Jones et al., "Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium - Biomass Composite Materials," *Scientific Reports* 8, no. 1 (December 4, 2018): 17583, https://doi.org/10.1038/s41598-018-36032-9.

insulation panel demonstrated a 40-minute fire rating during a fire resistance test using a Bunsen burner below its center.[125] Successful results were attributed to chitin in the mycelium, a compound known to retain its dense filamentous structure even at high temperatures. [126] Based on these results, mycelium composites are comparable to standard synthetic particleboard in improving the fire safety of a wall assembly.[127] ASTM 119 can be deployed as a standard test method to evaluate the fire rating of mycelium biocomposites further in a controlled laboratory furnace.[128]

Adhesion

Mycelium carries a unique adhesion property, which can allow bonding with adjacent components in a system and improve the structural capacity of its substrates. As they grow and spread, mycelium hyphae penetrate surrounding material at a microscopic scale to consume nutrients, causing a bond.[129] Adjacent placement of actively growing mycelium composite modules removed from their growth container caused modules to adhere, suggesting scalability.[130] Mycelium adhesion was also found to improve the tensile properties of composites. A 3D-printed earthen component mixed with substrate and subjected to mycelium growth exhibited 30% higher tensile strength than one without mycelium.[131] Similarly, one study found that the lap-shear strength of mycelium-bound wood samples was enhanced by increased surface mycelium coverage up to 8 days incubation (up to 1.74 MPa).[132] When used as a bonding agent in these applications, mycelium growth was comparable with typical wood glue, which provided similar shear resistance but weakened in excess moisture. [133] Future research can address the effectiveness of mycelium composites' adhesive properties in helping them maintain their form within a vessel despite moisture fluctuation and shrinkage.

125 Patrick Pereira Dias, "Investigation of Mycelium-Miscanthus Composites as Building Insulation Material,".
126 Jones et al., "Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium - Biomass Composite Materials."
127 Mitchell Jones et al., "Waste-Derived Low-Cost Mycelium Composite Construction Materials with Improved Fire Safety," *Fire and Materials* 42, no. 7 (2018): 816–25, https://doi.org/10.1002/fam.2637.
128 "Standard Test Methods for Fire Tests of Building Construction and Materials." https://www.astm.org/e0119-20.html.
129 *Mycelial Material Revolution*, 2022, https://www.youtube.com/watch?v=guC6ECF8rJk.
130 Sean Campbell et al., *Modular Mycelia.*
131 "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures."
132 Wenjing Sun et al., "Functionality of Surface Mycelium Interfaces in Wood Bonding," *ACS Applied Materials & Interfaces* 12, no. 51 (December 23, 2020): 57431–40, https://doi.org/10.1021/acsami.0c18165.
133 Sun et al.

Acoustics

Mycelium composites have demonstrated tremendous acoustic absorption properties, making them viable for acoustic panel applications. In addition, substrate, texture and density variations have resulted in differences in sound reduction performance. Mycelium exhibited strong low-frequency absorption (1500Hz) and was more effective than cork and ceiling tiles in road noise attenuation.[134] Acoustic absorbers (fibrous, porous, reactive resonators) can convert the mechanical motion of air molecules in sound waves to low-grade heat to reduce the reflected noise strength and prevent sound accumulation in an enclosed space. In a previous study, mycelium acoustic panels demonstrated a 70-75% acoustic absorption for perceived road noise and were found to be comparable to typical petroleum acoustic foams.[135] A-weighted decibels as a rating allow the interpretation of the perceived loudness of domestic noises such as human speech.[136] A series of mycelium composite acoustic panels, each with a different substrate, were tested and associated with lower perceptual road noise (51-55 dBa) than traditional reference absorbers including ceiling tiles, urethane foam, and plywood (65 dBa).[137] Mycelium-based composites' ability to absorb noise due to their unique fibrous and porous attributes makes them an effective biodegradable alternative to traditional acoustic insulators. Due to its adhesive nature, mycelium could be combined with other materials to improve their sound absorption at a greater range of frequencies, though this has not yet been tested.

Degradation

Mycelium-based materials tend to suffer from degradation, and their resistance to degradation is impacted by their species, substrate, and treatment. A study exposed mycelium composite panels with various finish treatments outdoors in a cold climate and found that compression and dehydration showed some success, though no panels maintained their integrity past the two-year mark.[138] This façade study demonstrated that mycelium requires protection from the elements if users wish it to last 30 years. Research has yet to study the relationship between environmental fluctuation and the dimensional stability of mycelium composites with varying post-treatments. Degradation of mycelium composites was tested by burying samples in potting soil for time intervals of 1 to 16 weeks,

134 M. G. Pelletier et al., "Acoustic Evaluation of Mycological Biopolymer, an All-Natural Closed Cell Foam Alternative," *Industrial Crops and Products* 139 (November 1, 2019): 111533, https://doi.org/10.1016/j.indcrop.2019.111533.
135 M. G. Pelletier et al., "An Evaluation Study of Mycelium Based Acoustic Absorbers Grown on Agricultural By-Product Substrates," *Industrial Crops and Products* 51 (November 1, 2013): 480–85, https://doi.org/10.1016/j.indcrop.2013.09.008.
136 Daniel J Maguire, "The Impact of A-Weighting Sound Pressure Level Measurements during the Evaluation of Noise Exposure," n.d.
137 Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries."
138 Thibaut Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*, 2020.

and results showed an average weight loss of 43% after 16 weeks, with the mycelium being the first to disintegrate.[139] These results further prove the sensitivity of exposed mycelium to degradation. A substantial decrease in maximum stress capacity was noted after subjecting dense mycelium-bound composites to tropical weathering conditions for 35 days and testing their flexural, tensile, and compressive loading.[140] A protective coating improved a mycelium composite's resistance to weathering conditions, however, structurally only a difference in tensile strength was found.[141] Further experimentation could investigate the impact of protective coatings on other physical properties of mycelium such as weight and dimensions.

Figure 2.1.9 compares mycelium composites with similar modular building materials based on these properties, to evaluate applicability to prefabricated wall systems. Mycelium performs best as a rigid thermal- and acoustic-insulating material which is fire-resistant. Compared to other standard construction materials, mycelium composites must be structurally supported and shielded from the elements due to their high degradation. Its unique adhesion characteristics suggest an opportunity to integrate this composite with complementary structural materials and environmental protection in a novel way. In summary, the architectural application of this material demonstrates great potential for reducing the number of disparate parts in the assembly of a biodegradable wall system.

Material Applicability to Wall Systems ●○○○○ Not applicable ●●●●● Highly applicable		Porotherm Brick	Unfired Clay Brick	CMU	Hempcrete Block	Corkbrick	Expanded Polystyrene	Mycelium Mycocomposite 029
Physical Properties	Dimensions (Typ. WxDxH)	500 mm x 188 mm x 224 mm	215mm x 65mm x 102.5mm	400mm x 200mm x 200mm	542mm x 203mm x 272mm	1000mm x 250mm x 220mm	1200mm x 150mm x 600mm	950mm x 50mm x 950mm
	Density (kg/m³)	850 kg/m³	1800 kg/m³	2000 kg/m³	433 kg/m³	160 kg/m³	20 kg/m³	110 kg/m³
	Weight (kg)	●○○○○ 18.7 kg	●●●○○ 2.4kg	●○○○○ 17.25kg	●●○○○ 13.00kg	●●●○○ 9.0 kg	●●●●○ 9.0 kg	●●●●○ 4.96kg
Performance Properties	Insulation (Thermal)	●●○○○ R-1.7-2.3 / 0.26 W/mK	●●○○○ R-1.5 / 0.9 W/mK	●○○○○ R-1.1 / 2.25 W/mK	●●●○○ R-2 / 0.138 W/mK	●●●●○ R-3.55	●●●●● 0.035 W/mK	●●●●○ R-3.5 / 0.05 W/mK
	Insulation (Sound)	●●○○○ NRC = 0.0015	●○○○○ NRC = 0.0015	●○○○○ NRC = 0.0015*	●●○○○ NRC 0.1	●●●●● NRC 0.7	●●○○○ NRC 0.4	●●●●○ NRC 0.6
	Fire-Safety	●●●●● 120 min	●●●●○ 120 min	●●●●● 120 min	●●○○○ 120 min	●●○○○ Class B	●○○○○ Flammable	●●●●○ up to 60 min
	Structural Capacity	●●●○○ 10 MPa	●●○○○ 2.5 MPa	●●●●● 17-28 MPa	●●●●○ 22.5 MPa	●●●○○ 30 +/-7 MPa	●○○○○ 0.191 MPa	●●○○○ 1.3 MPa
	Degradation Resistance	●●●●○ 150+ years	●●●○○ 80-100 years	●●●●● 100+ years	●●●●○ 100+ years	●●●○○ 50 years	●●●○○ 50+ years	●○○○○ 10-20 years

Figure 2.1.9: Mycelium composites compared with typical building materials in their applicability to prefabricated wall systems. Mycelium composites uniquely provide insulation and fire resistance while being lightweight.

139 Aurélie Van Wylick et al., *Mycelium Composites and Their Biodegradability: An Exploration on the Disintegration of Mycelium-Based Materials in Soil*, 2022, https://doi.org/10.4028/www.scientific.net/CTA.1.652.
140 Xin Ying Chan et al., "Mechanical Properties of Dense Mycelium-Bound Composites under Accelerated Tropical Weathering Conditions," *Scientific Reports* 11, no. 1 (November 11, 2021): 22112, https://doi.org/10.1038/s41598-021-01598-4.
141 Xin Ying Chan et al., "Mechanical Properties of Dense Mycelium-Bound Composites under Accelerated Tropical Weathering Conditions,"

2.2 Prefabricated Wall Systems

Prefabricated Wall Systems will be defined as systems which incorporate elements assembled offsite and are intentional with their material organization. These systems have made advancements in reducing the number of parts within wall assemblies, improving construction efficiency, and reducing opportunities for failure. Insulated Concrete Forms (ICF) and Structurally Insulated Panels (SIP) are noteworthy examples of efficient prefabricated wall systems.

2.2.1 ICF Systems

Insulated Concrete Form (ICF) Construction is characterized by interlocking modules featuring two panels typically made of Expanded Polystyrene (EPS), which create a formwork for poured concrete. These modules are stacked and assembled with all required rebar, and then concrete is sequentially poured into the formwork. [142] Webs spaced evenly between each module's EPS ensure some connectivity between the EPS and the concrete. Once the concrete is cured, all finishes are applied to the interior and exterior.[143] The concrete acts as the primary structure within the system, along with the air and water barrier, while the EPS provides two continuous layers of insulation inside and outside (Figure 2.2.1).[144] By considering the wall system itself as the formwork, ICF exemplifies an innovative, simplified construction process which ensures minimal formwork goes to waste. ICF is considered a very rigid system with an average projected lifespan of 70-100 years, which is beneficial for long-term applications. [145] Once the concrete is poured, there is limited opportunity to adapt the building layout in response to changing needs.

142 "Insulating Concrete Forms (ICFs)," accessed April 27, 2024, https://www.cement.org/cement-concrete/paving/buildings-structures/concrete-homes/building-systems-for-every-need/insulating-concrete-forms-(ICFs).
143 Maria Saxton, "ICF Construction: Everything You Need To Know," Rise, August 28, 2017, https://buildwithrise.com/stories/mythbusting-icf-sustainable.
144 "ETW: Wall - ICF Wall Construction | Buildingscience.Com," Building Science Corporation, November 15, 2014, https://buildingscience.com/documents/enclosures-that-work/high-r-value-wall-assemblies/high-r-wall-icf-wall-construction.
145 Saxton, "ICF Construction."

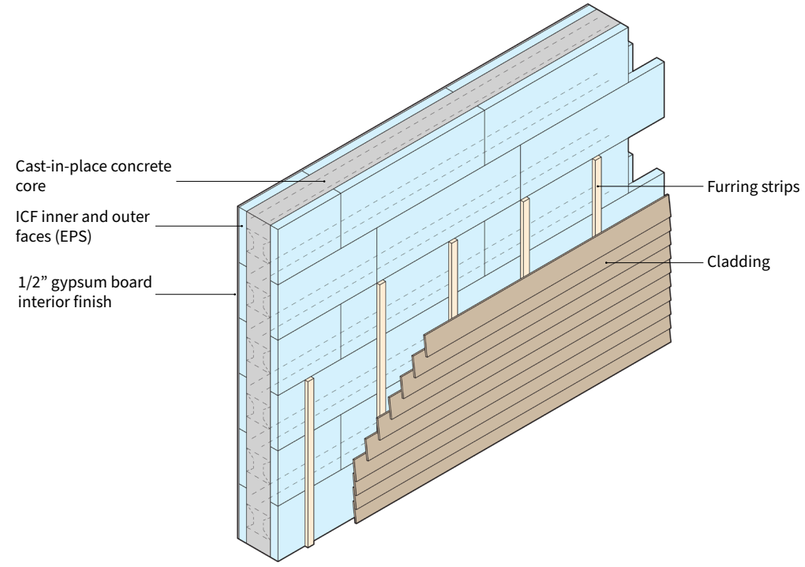


Figure 2.2.1: Axonometric sectional view of a typical ICF wall system with interior and exterior finishes. Adapted from Building Science Corporation.

ICF construction is relevant to mycelium applications because both concrete and mycelium-substrate mixtures require formwork to shape them. Mycelium wall systems can learn from ICF construction by considering the wall as the form, reducing the requirement for additional temporary formwork. A key consideration with ICF systems is that though concrete may slightly adhere to adjacent layers, the system does not depend on this adhesion. The concrete behaves as a continuous separate element within the system, but it is connected by encapsulating protruding elements such as ties and rebar.[146] One difference in the material organization of these systems is that mycelium is not structural like concrete. Therefore, its formwork would need to act as the primary structure. Additionally, concrete does not allow the free transfer of air, vapour, and moisture as mycelium would, and this difference should be factored into the designed wall section.

2.2.2 SIP Panels

Structurally Insulated Panel (SIP) systems consist of two plywood or OSB panels which sandwich an insulating block, typically EPS, ranging from 3 ½" to 5 ½" in thickness. Once adhered, they form one panel which can be prefabricated in multiple shapes and sizes,

146 "Insulating Concrete Forms (ICFs)."

typically 2.4 m in height and up to 7.2 m in length.[147] The wood panels on both sides provide the structure, while the core EPS provides a single continuous layer of insulation (Figure 2.2.2).[148] The rigidity of the EPS insulation is also harnessed to transfer lateral loads through the wall.[149] Adjacent panels are typically joined together through a spline, a flat piece of wood slid underneath the two plywood panels, to allow for fastening from the outside.[150] A layer of lapped water-resistive membrane is then applied to the exterior face to protect the wood and the overall wall system from water infiltration, followed by all exterior and interior finishes to the wall.[151] SIP construction can last up to 60 years and is suitable for a wide range of low-rise applications.[152] The primary advantage of this prefabricated wall system is that components are fabricated and customized offsite, expediting the onsite assembly process significantly. Material usage and waste are also reduced with this system, as it uses approximately ¼ of the wood compared to typical light wood frame construction.[153] One drawback is that polystyrene insulation is a complex synthetic material with a high embodied energy.

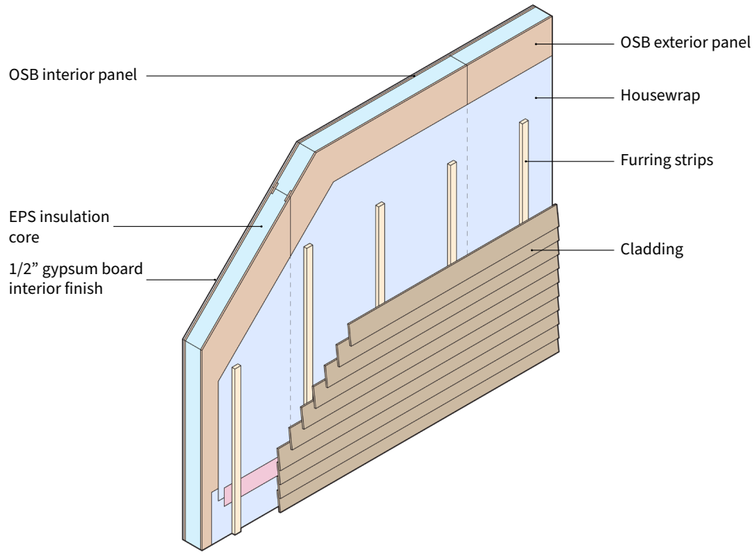


Figure 2.2.2: Axonometric sectional view of a typical SIP panel wall system with interior and exterior finishes. Adapted from Building Science Corporation.

147 “Structural Insulated Panels (SIPs) | WBDG - Whole Building Design Guide.” https://www.wbdg.org/resources/structural-insulated-panels-sips.
148 “ETW: Wall - SIPs Wall Construction | Buildingscience.Com,” Building Science Corporation, November 15, 2014, https://buildingscience.com/documents/enclosures-that-work/high-r-value-wall-assemblies/high-r-wall-sips-wall-construction.
149 “Structural Insulated Panels (SIPs) | WBDG - Whole Building Design Guide.”
150 Maria Saxton, “Guide to Structural Insulated Panels (SIPs),” Rise, September 11, 2017, https://buildwithrise.com/stories/building-with-structural-insulated-panels.
151 “ETW: Wall - SIPs Wall Construction | Buildingscience.Com.”
152 Saxton, “Guide to Structural Insulated Panels (SIPs).”
153 Saxton.

Innovations from SIP panel construction can be applied to the design of a mycelium wall panel system, specifically with the organization of the materials based on their function. The continuous EPS core insulation layer is protected from environmental conditions and structurally supported by its outer plywood shell. This organizational technique can translate to a mycelium wall system, where its integrated formwork acts as the structure and environmental protection. Like SIP panels, mycelium can take a customizable shape and dimension, however, its ability to be cut to size after fabrication remains a question. Additionally, the adhered rigid EPS insulation transfers lateral loads through the wall. This begs the question of whether the material-bonding properties of mycelium could similarly facilitate a reliable transfer of lateral loads, and whether this is a necessity to the overall system. It is also uncertain how a mycelium composite, which shrinks as it loses moisture, would behave within a sandwich system which requires tight tolerances.

2.2.3 Design Criteria For Wall Systems

The wall envelope is among the most complex systems in a building, as it is tasked with mediating numerous environmental conditions between the inside and outside based on human needs. To innovate on reducing the number of parts within the system, a prefabricated mycelium wall panel must first ensure that it satisfies a series of fundamental design criteria. These criteria include structure, fire resistance, insulation, air/water/vapour control, and longevity (Figure 2.2.3).

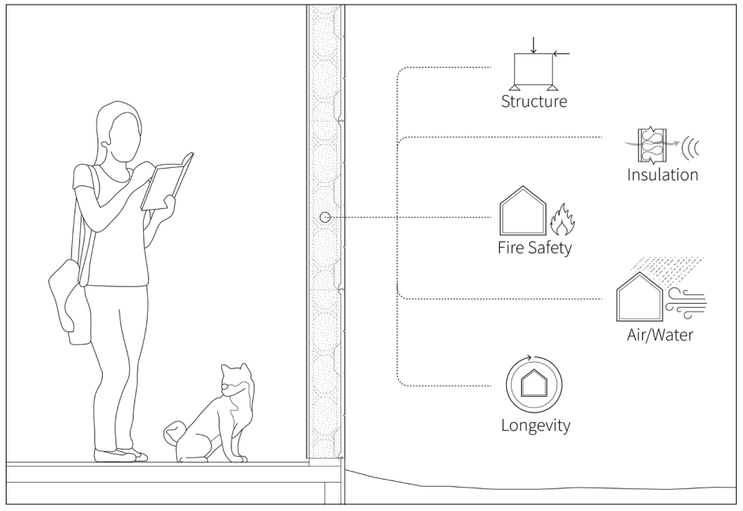


Figure 2.2.3: Diagram highlighting design criteria to consider when designing a new wall system.

Figure 2.2.4 compares prefabricated wall systems with mycelium based on these design criteria for wall assemblies. This serves to define a framework for designing a mycelium-based wall system, which should aim to excel in as many of these categories as possible. The ASTM (American Society for Testing and Materials) is an organization which catalogues approved test methods for evaluating specific performance characteristics of materials and assemblies.[154] These failure tests have historically been a pivotal step for new wall assemblies to become approved construction methods, ensuring consistency and predictability among assemblies. The objective of this section is to determine which of these tests would need to be performed on a new mycelium-based wall panel to begin comparing it to other assemblies on the market.

154 "ASTM International - Standards Worldwide," accessed June 21, 2024, https://www.astm.org/.

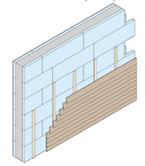
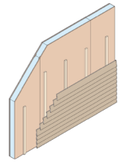
Design Criteria for Prefabricated Wall Panels ●○○○○ Low ●●●●● High	Insulated Concrete Form (ICF) 	Structurally Insulated Panel (SIP) 	Mycelium Composite 
Structure Compressive Strength	●●●●○ 20 MPa	●●●○○ 10 MPa	●●○○○ 1.3 MPa
Insulation RSI per m / *k*	●●●◐○ R-4.15 / 0.067 W/mK	●●●●○ R-3.7 / 0.044 W/mK	●●●●○ R-3.5 / 0.05 W/mK
Fire-Safety	●●●●○ 120 min	●●○○○ 60 min	●●●●○ 40 min
Air/Water/Vapour	●●●○○ Ease of Detailing	●●●○○ Ease of Detailing	○○○○○ N/A
Longevity	●●●●● 100+ years	●●●○○ 60 years	○○○○○ 2 years
Minimal Components	●●●○○ Few Layers, moderate parts	●●●●○ Few Layers, moderate parts	●●●●○ One layer, requires formwork
Adaptability	●○○○○ Not adaptable	●●●○○ Ease of adaptibility	●●●●○ Wide range of forms
Biodegradability	●○○○○ No components degradable	●●○○○ Some components degradable	●●●●● Fully degradable

Figure 2.2.4: Comparison of prefabricated construction systems with mycelium-based composite products highlights how mycelium provides many benefits for wall system applications, though requires an integrated shell.

Structure

A building's structure must transfer all axial and lateral forces applied onto the building to the ground. In many small to medium-scale architectural applications, the building envelope is responsible for part of, if not all its structural loads.[155] Therefore, the consideration of structure is significant for any wall envelope.

ASTM E72 is a document describing a method for testing a wall panel's axial compressive strength, transverse loading, and lateral resistance. [156] A panel is secured at two points at the bottom and subjected to compression from above, or lateral force parallel to the ground at its top corner.[157] Loads are applied sequentially to determine the maximum load it can withstand

155 Joseph Lstiburek, "BSI-001: The Perfect Wall," Building Science Corporation, July 15, 2010. https://www.buildingscience.com/documents/insights/bsi-001-the-perfect-wall.
156 "Standard Test Methods of Conducting Strength Tests of Panels for Building Construction," ASTM International, accessed April 1, 2024, https://www.astm.org/e0072-15.html.
157 "Standard Test Methods of Conducting Strength Tests of Panels for Building Construction."

before failure or significant displacement.[158] One study applied these methods to compare the compressive strength of structural insulated panels (SIP) with wooden stud walls and found SIP panels withstood up to 96.35 kN, while the stud wall resisted 100.05 kN before failure.[159] Critically, this study demonstrated that the structural capacity of SIP panels was comparable to typical light frame construction.[160] When applying these testing methods to an insulated concrete form (ICF) system, another study found the peak axial compressive load of ICF to be 500 kN.[161] Similar methods can be deployed for a mycelium wall system to determine its structural capacity compared to these assemblies, as well as document the failure modes for the system.

Insulation

Thermal insulation is essential for all building envelopes especially within cold climates, as it allows the building to regulate temperature between interior and exterior. Insulation is typically the primary response for buildings, as it addresses the root issue of temperature regulation directly, keeping the warm air inside, before implementing mechanical systems.

The insulating properties of wall systems are typically measured with thermal resistance, or R-Value, (m^2K/W) determined by dividing a material's thickness by its thermal conductivity, *k* (W/mK).[162] Evaluation methods exist for calculating the R-value of individual wall components as well as entire assemblies. ASTM outlines two common approaches for evaluating thermal resistance. ASTM C1363-19 utilizes a hot box apparatus to create a warm space on one side and a cold space on the other side of a material assembly.[163] Thermocouples are attached to both sides to measure the surface temperature difference over time.[164] Other methods (ASTM C518-21) include placing hot and cold plates between a specimen to measure heat flow, though this method is typically applied for individual materials. [165] One study applied hot and cold box methods to determine a thermal resistance of 3.937 m^2K/W for a typical SIP panel.[166] Similar tests performed on an ICF sample returned a thermal resistance of 5.22 m^2k/W, in comparison.[167] It is possible to calculate the thermal performance of a material assembly by factoring in the individual thermal conductivities of each component. Digital simulation can simplify these calculations for more complex geometries, as well as provide access to visual heat flow maps through a wall section.[168] As natural mycelium composites' thermal properties may fluctuate, comparing their simulated and experimental thermal resistance would be beneficial.

Fire Resistance

Building envelopes must provide inhabitants with fire resistance for a degree of time to allow safe evacuation from the building in the event of a fire. Fire resistance is measured typically with a rating given in minutes, based on the time of protection from fire it can provide. Fire resistance is a requirement for all building applications in any climate or context.

Standard methods have also been developed for testing the fire resistance of wall assemblies. Underwriters Laboratories of Canada, (ULC), supervises testing and provides standards for performance properties of specific wall assemblies.[169] They perform laboratory fire tests on wall assemblies to assign them with standard fire ratings and evaluate whether they meet building code requirements. In many ways, ULC is the Canadian equivalent of ASTM, and many testing methods have been described as transferrable.[170] ASTM E119 provides a standard method for testing the duration in minutes in which building elements can contain a fire and/or retain their structural integrity during exposure to fire. Temperature levels related to time are provided, along with standard structural loading amounts.[171] Though execution of these methods may vary by test, a study determined a fire rating of up to 60 minutes for SIP panels, using a similar test.[172] For ICF panels exposed to similar test methods, their fire rating was determined to be up to 4 hours.[173] These tests do not necessarily account for the benefits of charring provided by natural materials, which reduces the amount of harmful chemicals released during combustion. If a mycelium-based wall panel can meet a similar fire rating to SIP panels, it can be assumed to be more fire-safe to humans due to its ability to char, compared to synthetic foam.[174]

158 "Standard Test Methods of Conducting Strength Tests of Panels for Building Construction."
159 Hassan Abbasi, Ata Hojatkashani, and Khaled Sennah, "Experimental Study of SIP and Conventional Stud Walls Subjected to Compressive Load," *ICE Proceedings Structures and Buildings*, June 1, 2021.
160 "Section 9 of the Ontario Building Code," https://www.buildingcode.online/section9.html.
161 Arun Solomon A. et al., "Exploring the Impact of EPS Incorporation on Insulated Concrete Form (ICF) Wall Panels under Axial Compression and Flexure," *Journal of King Saud University - Engineering Sciences*, April 12, 2022, https://doi.org/10.1016/j.jksues.2022.04.002.
162 Incropera et al., *Fundamentals of Heat and Mass Transfer*.
163 "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." https://www.astm.org/c1363-19.html.
164 "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus."
165 "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." https://www.astm.org/c0518-21.html.
166 Qiang Du et al., "Experimental and Numerical Studies on the Thermal Performance of Structural Insulated Panel Splines," *Journal of Building Engineering* 44 (December 1, 2021): 103334, https://doi.org/10.1016/j.jobe.2021.103334.
167 A Arun Solomon and G Hemalatha, "Characteristics of Expanded Polystyrene (EPS) and Its Impact on Mechanical and Thermal Performance of Insulated Concrete Form (ICF) System," *Structures* 23 (February 1, 2020): 204–13, https://doi.org/10.1016/j.istruc.2019.10.019.
168 "THERM | Windows and Daylighting." https://windows.lbl.gov/software/therm.
169 Katie Daniel, "Understanding ULC-Listed Fire-Resistant Designs," Construction Canada, March 3, 2015, https://www.constructioncanada.net/understanding-ulc-listed-fire-resistant-designs/.
170 "Fire Resistance," The Canadian Wood Council - CWC, https://cwc.ca/en/why-build-with-wood/safe/fire-safety/fire-resistance/.
171 "Standard Test Methods for Fire Tests of Building Construction and Materials," https://www.astm.org/e0119-20.html.
172 Danny Hopkin and Tom Lennon, *Fire Performance of Structural Insulated Panel Systems*, 2010.
173 Larry Muszynski and S. Gulas, "Fire Resistance and Performance of Alternative Concrete Wall Systems" 6 (September 1, 2001): 146–54.
174 Jones et al., "Waste-Derived Low-Cost Mycelium Composite Construction Materials with Improved Fire Safety."

Air/Water/Vapour Control

Alongside insulation, wall envelopes are called upon to regulate air, water, and vapour between the interior and exterior of a building. The primary objective of these control layers is to prevent air and water from leaking into the interior while allowing certain layers of the wall to breathe, so accumulated moisture can dry out.[175] This promotes the longevity of the wall system by preventing the buildup of mould. The airtightness of an envelope also improves thermal performance, as heat is forced to travel through the wall, rather than leak through the air.

Testing methods have been developed to analyze the ability of a given wall system to mediate air, water, and vapour. ASTM E331 provides a method for testing water penetration through a wall assembly, by varying levels of water pressure on its exterior to test for leakage.[176] It is difficult to ascertain the specific differences by wall assembly, as performance in this category largely depends on how the builder details the openings and connection points. Therefore, proficiency in this criterion can be tied to the ease and flexibility of robust construction detailing. Since mycelium does not react well to water exposure, performing this test on a wall system which incorporates mycelium is highly relevant. Additionally, this highlights the relevance of designing the connection details between panels at critical points such as panel-to-panel, window/door openings and corners.

Longevity

The lifespan of a building depends on the longevity of its envelope. The exact desired lifespan depends on the occupants, certain large-scale buildings may desire a lifespan of 50-100 years, while some residential occupancies may only require 30 years of use. Climate conditions with seasonal cycles tend to negatively impact the longevity of building envelopes.[177] It is imperative that the longevity of the building envelope, in years, can be reliably estimated for the occupant.

Testing for the lifespan, in years, of any given material is often difficult, due to the long duration of time required to observe any change. Building materials' lifespans are typically simulated and predicted in an accelerated manner by exposing them to climate aging. This process involves manipulation of spatial parameters such as temperature freeze-thaw cycles, changes in relative humidity, water spray, as well as Solar and Ultraviolet radiation.[178] One study deployed an attenuated total reflectance (ATR) Fourier Transform Infrared (FTIR) radiation analysis to quantify the decay and aging of specimens such as wood.[179] In addition, ASTM C1512-10 provides test methods for exposing insulation products to environmental cycling. Like thermal testing, panel specimens are exposed to specific temperature- and relative humidity differences on either side to simulate seasonal climate changes.[180] Thanks to testing methods of this matter, the lifespan of comparable wall systems has been established, with SIP panels reliably projected to last 60 years, while ICF systems can last 100+ years.[181] [182] Similarly, these tests can be utilized to critically estimate the lifespan of a mycelium-based wall panel system, along with the consistency and transferability of these estimates.

For a mycelium wall panel design to be a relevant proposed solution for a sustainable, efficient and adaptable wall system, it must first demonstrate that it meets each of these basic criteria. The sustainability, adaptability and efficiency of comparable wall systems were explored through an overview in the previous section, 2.2.1. The ability of a mycelium-insulated panel to outperform its precedents in these three overarching categories will be evaluated in this research methodology through its design, development, and application.

175 "BSI-001."
176 "Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference." https://www.astm.org/e0331-00r16.html.
177 Marzieh Riahinezhad, Madeleine Hallman, and J.-F. Masson, "Critical Review of Polymeric Building Envelope Materials: Degradation, Durability and Service Life Prediction," *Buildings* 11, no. 7 (July 2021): 299, https://doi.org/10.3390/buildings11070299.
178 Bjørn Petter Jelle et al., "Accelerated Climate Aging of Building Materials and Their Characterization by Fourier Transform Infrared Radiation Analysis," *Journal of Building Physics* 36, no. 1 (July 1, 2012): 99–112, https://doi.org/10.1177/1744259111423367.
179 Jelle et al.
180 "Standard Test Method for Characterizing the Effect of Exposure to Environmental Cycling on Thermal Performance of Insulation Products." https://www.astm.org/c1512-10r20.html.
181 "Structural Insulated Panels' Advantages And Disadvantages | ProEst," September 5, 2022, https://proest.com/construction/tips/structural-insulated-panels/.
182 Saxton, "ICF Construction."

2.3 New Manufacturing Technologies

As observed in the current body of knowledge, mycelium has a set of specific requirements to grow, perform, and last within a wall system. Specific environmental conditions are required for its optimal growth, such as high humidity, no light, and adequate air exchange. Similarly, though mycelium composites excel in insulation, fire resistance, and acoustics, they struggle with providing structure and longevity. The key to designing a mycelium wall panel with reduced parts, which simultaneously accommodates these needs, is through customization. Traditional industrial fabrication cannot adequately address this, due to its tendency towards standardized parts. New fabrication technologies such as additive, and robotic timber manufacturing provide novel opportunities for intentional user-driven design to meet these needs.

2.3.1 Additive Manufacturing

Additive manufacturing (AM) has allowed designers to customize different material forms and interfaces within a wall system. AM allows for a threefold control; with the contents of the filament itself, the geometric form of the print, as well as the inner lattice support structure of the print. AM provides new formwork design possibilities for housing amorphous solid materials such as concrete. Designers of "*Smart Concrete Wall*" utilized the unique capabilities of AM to design a 3D-printed formwork for a porous concrete wall, which provides a route for embedded sensors that activate lights upon touch (Figure 2.3.1).[183] AM allows for greater control of interfaces between materials. In "*3D printed staircase*" by IAAC and WASP, cavities were designed in a 3D printed earthen wall to integrate cantilevered wooden steps seamlessly (Figure 2.3.2).[184] Within 3D printed wall systems, the infill material geometry can be designed to provide added benefits, such as structural optimization. In TECLA, the 3D printed home by WASP, the core infill structure of the printed earthen house took on a diagonal undulating pattern to optimize its structural capacity with minimum material (Figure 2.3.3).[185] Applied to a mycelium wall system, 3D printing can facilitate the seamless integration of specialized components such as ventilation. Additionally, greater control over geometry and texture can promote better adhesion at the interface between mycelium and its shell.

183 NOWlab, "The World's First 'smart Concrete Wall' Is Activated by the Touch of a Hand," designboom | architecture & design magazine, June 22, 2018, https://www.designboom.com/architecture/smart-concrete-wall-nowlab-bigrep-3d-printing-06-27-2018/.
184 "3D Printed Staircase," *Parametric House* (blog). https://parametrichouse.com/3d-printed-staircase/.
185 Paul Hanaphy, "WASP Finishes 3D Printing Sustainable Biomaterial-Based 'TECLA' Eco-Habitat," 3D Printing Industry, January 20, 2021, https://3dprintingindustry.com/news/wasp-finishes-3d-printing-sustainable-biomaterial-based-tecla-eco-habitat-182940/.

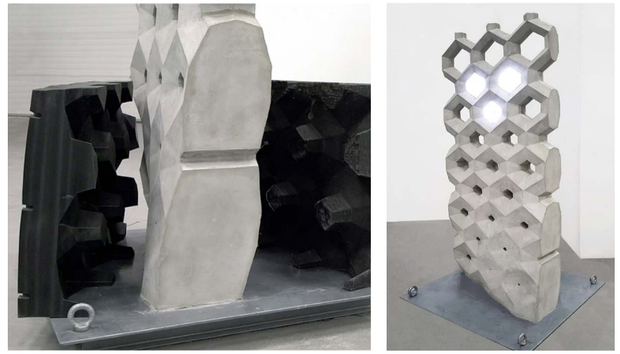


Figure 2.3.1: "Smart Concrete Wall" by NOWlab used a 3D printed formwork to create porous concrete geometry with embedded sensors.



Figure 2.3.2: "3D printed staircase" by IAAC and WASP facilitates cantilevered wooden steps through the discrete manipulation of form.



Figure 2.3.3: In "TECLA" by MC A and WASP, a 3D printed house incorporates structure through an undulating infill toolpath.

2.3.2 Robotic Timber Manufacturing

Current robotic subtractive manufacturing technologies allow for fine-tuning non-standard panel geometries to meet specific user needs, using natural materials such as wood. This technology expands the capabilities of wood as a material by allowing greater design intentionality with interlocking geometry, connections, textures, and voids. The BUGA Wood Pavilion in Stuttgart by ICD / ITKE is a prime example of this, as designers achieved a curved shell structure from individual panel modules consisting of thin inner and outer timber plates.[186] Between each plate in each module was a void, which provided the modules with depth and space for concealed connections while minimizing material use (Figure 2.3.4).[187] The rise of customizable user-driven modular home construction can be accredited to Robotic Timber Manufacturing. Automated Architecture's robotic assembled home showcases an affordable prefabricated house construction made of custom timber panels.[188] The robotic assembly process affords building customization based on specific site characteristics and user lifestyle preferences such as interior layout, window placement and mechanical systems (Figure 2.3.5).[189]

A grown mycelium wall panel system could similarly benefit from robotic manufacturing technology. Mycelium has been found to require air exchange for optimal growth, so exterior façade panels could house designated ventilation zones to regulate air exchange to and from the nested mycelium. Though mycelium is known to adhere well to other materials through bonding, textures applied to interior faces can promote better adhesion between the mycelium and the wooden panels. A material's insulating and fire-resistant properties could potentially be improved by creating voids and filling them with mycelium composite.



Figure 2.3.4: Individual robotic timber modules being assembled for the BUGA wood pavilion on site. By ICD/ITKE in Stuttgart.



Figure 2.3.5: Automated Architecture's robotic assembled home provides users agency on the layout of their modular home.

186 "BUGA Wood Pavilion / ICD/ITKE University of Stuttgart," ArchDaily, May 12, 2019, https://www.archdaily.com/916758/buga-wood-pavilion-icd-itke-university-of-stuttgart.
187 "BUGA Wood Pavilion 2019 | Institute for Computational Design and Construction | University of Stuttgart," https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/.
188 kat barandy I. designboom, "AUAR's Robotically Assembled Dwelling Is at Once Beautiful and Affordable," designboom | architecture & design magazine, October 19, 2021, https://www.designboom.com/architecture/automated-architecture-auar-robotically-assembled-dwelling-global-investment-summit-uk-10-19-2021/.
189 kat barandy I. designboom, "AUAR's Robotically Assembled Dwelling Is at Once Beautiful and Affordable".

Chapter 3 - Materials & Methods

This section describes the methodology applied in this research to develop a mycelium composite wall system. The methodology includes three experiments along with a design development component. Materials used for each experiment are listed in the first subsection. The following subsection describes the first experiment, dedicated to finding the most successful substrate nutrient composition for mycelium growth. The second experiment tested the adhesion of mycelium with varying interfaced materials within a specialized box formwork. In the next subsection, the iterative design strategy for an integrated mycelium wall panel was introduced. Finally, the third experiment procedure is described, in which a full-scale prototype of the wall panel is fabricated, after which, its thermal performance is evaluated experimentally. The results of each applied method will be documented in the following section (4).

Procedure of Analysis

Each of the three phases of mycelium experimentation followed a procedure, as overviewed in Figure 3.1. Sequential experiments provided feedback for the design process of the mycelium wall panel, leading up to the full-scale prototype. Black Oyster mycelium was selected and used for all experiments due to its flexible range of growth conditions and rigidity. Results will aid in evaluating the viability of integrating the mycelium composite within a natural prefabricated wall system, in terms of assembly logistics and thermal performance.



Figure 3.1: Methodology Flowchart each phase of experimentation with mycelium composites informing the Design Development, leading to the thermal resistance evaluation of the full-scale prototype.

3.1 Materials

Mycelium specimen (all experiments):

- *P. ostreatus* (Black Oyster) mycelium, from Grow-your-own Mushroom Kit, NatureLion.

Experiment 1 (Supplementation):

- Hardwood Fuel Pellets (Sawdust), Canawick
- Wheat Bran
- Gypsum Powder, Gaia Green
- Polypropylene (2.5 mil) grow bags with 0.2-micron filter patch, 5” x 5” x 19”

Experiment 2 (Adhesion):

- 1.75mm Wood (30%) PLA Filament, Hatchbox
- 1.75mm White PLA Filament, AMZ3D
- Sanded Birch Plywood, 6.25mm, 12.5mm
- Acrylic Plexiglass, 1.5mm, 3mm
- LePage Pro Carpenter’s Wood Glue
- PSH-516 Cone 6 Clay
- 2 mm Millboard
- 6.25mm Medium Density Fibreboard

Experiment 3 (Thermal Resistance of Full-Scale Prototype):

- Sanded Aspen Plywood, 19mm
- Sanded Birch Plywood, 12.5mm
- 1.75mm Wood (30%) PLA Filament, Hatchbox
- Twine rope, 6.25mm
- Dimensional softwood lumber, 19x38mm, 38x89mm
- Poly Vapour Barrier Membrane, Everbilt
- EPS “*DuroSpan*” Rigid Insulation Foam, 35mm, R-3.75, *Plastifab*
- 2mm Millboard

3.2 Experiment 1, Supplementation

The first experiment with mycelium supplementation followed the procedure illustrated in Figure 3.2.1. First, a substrate was prepared. All substrates were placed within 2.5 mil, 125 x 125 x 475 mm polypropylene grow bags with 0.2-micron filter patches. The base quantity of each new substrate was determined as 250g, based on the dimensions of the filter patch bags. Four substrate bags with a different ratio of sawdust to wheat bran were prepared. Hardwood sawdust was derived from compressed fuel pellets which expanded after submersion in hot water. Each substrate mixture was supplemented with varying ratios of wheat bran, at 5, 10, 15, and 20%, to the total 250g of new substrate. Amounts were based on a study which tested similar increments of wheat bran supplementation within a substrate and found a positive correlation in mycelium growth.[190] 5 grams of gypsum powder was added to each specimen to provide nutrients and stability.[191]

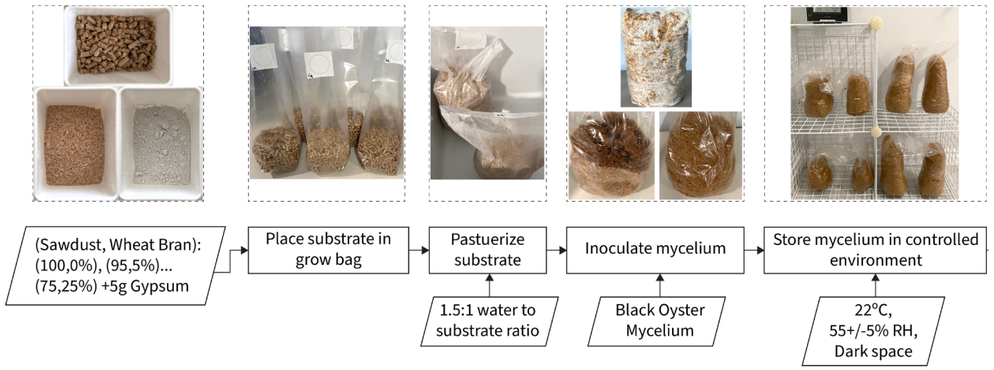


Figure 3.2.1: Process Diagram of substrate supplementation experiment for mycelium composite growth.

The substrates were pasteurized by pouring boiling water into each substrate bag. The ratio of water to substrate was determined as 1.5 times the weight of the substrate, as through preliminary testing, a 1:1 ratio caused the mixture to be too dry, while 2:1 caused an oversaturation of water. Thus, for 250 g of dry substrate, 375 mL of boiling water was measured and placed into each bag. Bags were immediately sealed with an impulse sealer and stored in a blanket-insulated storage container for 90 minutes. Afterwards, they were set out for 60 minutes until fully cooled to room temperature.

Once the substrates were pasteurized and cooled, they were inoculated with mycelium. The

190 Hasan et al., “Effect of Wheat Bran Supplement with Sugarcane Bagasse on Growth, Yield and Proximate Composition of Pink Oyster Mushroom (Pleurotus Djamor),” November 2015.
191 Thibaut Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*, 2020.

source of mycelium was a Mushroom Grow Kit, from a local mushroom farm, which contained a substrate fully colonized with *P. ostreatus* (Black Oyster) mycelium. After sterilizing the work area, the mycelium block was broken up by hand, and approximately 200g was transplanted to each new substrate bag. After which, each bag was immediately resealed. Old and new substrates were mixed within the sealed bags to improve growth consistency. Substrates were stored within a dark, sterile space, with conditions regulated at 22°C, and 55 +/- 5% Relative Humidity, for three weeks. Exterior humidity control was a precaution as the vapour-impermeable filtered grow bags were sealed, and 90-95% relative humidity from pasteurization was maintained inside each specimen. Specimens were photo-documented daily to track their growth progress. The most successful supplementation was carried over and applied to the subsequent experiments.

3.3 Experiment 2, Adhesion

In the next phase, the adhesion of the mycelium to various materials was explored utilizing a growth box with a variable front face, as outlined in Figure 3.3.1. Two growth boxes were designed and assembled for this experiment: one small box comprised of PLA for preliminary testing, and one modular brick-sized box constructed from plywood for larger-scale testing. Both boxes were specifically designed with one front face missing, for panels of a variable material to be inserted. Different materials tested for the front panel included 6.25mm Plywood, MDF, Wood PLA filament, 1.5mm millboard, and unfired clay. These options were selected based on a study which found mycelium bonded mechanically with wood at a microscopic scale, therefore the mycelium was predicted to adhere to wood-based materials.[192]

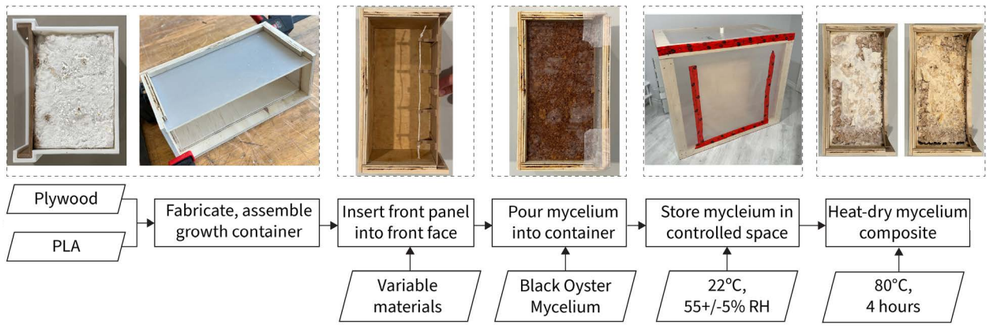


Figure 3.3.1: Process for testing interfacial adhesion of mycelium composites with different materials, within a growth box.

192 Sun et al., "Functionality of Surface Mycelium Interfaces in Wood Bonding."

PLA Container

The preliminary growth container to test the interface of mycelium with different materials was 3D-printed from PLA and is shown with its dimensions in Figure 3.3.2. The design of the PLA box was such that a singular module could be 3D-printed with minimized parts. The only separate PLA component in this container was the lid, which had a transparent opening for viewing the interface of the active mycelium with the front panel. A 1.5mm acrylic sheet with four 3mm diameter holes was embedded in the lid to reduce contamination and facilitate air exchange.

Once the container was assembled, front panels made from 2mm millboard, 6mm MDF, and Wood PLA were collected. The container was sterilized with 70% isopropyl alcohol. Next, fully inoculated mycelium composite was broken into a mouldable mixture and poured into each sterilized container. The composite mixture was evenly distributed into the form, leaving a small gap on top for adequate ventilation. Finally, the ventilated top lid was closed. Boxes were stored within a dark, temperature- and moisture-regulated space for three weeks. Results for all three materials were documented during and after the growth period and compared visually.

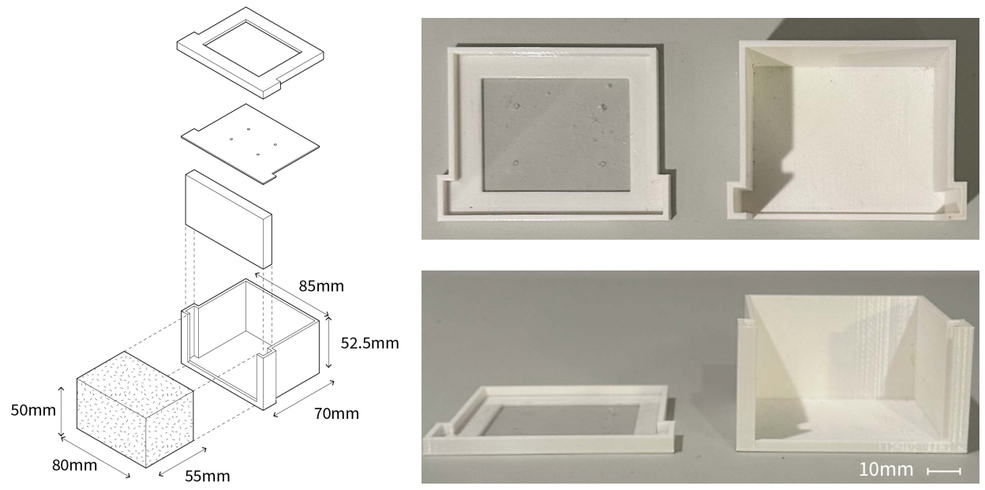


Figure 3.3.2a: PLA Experiment Growth box, with interior dimensions of 80 mm width, 55 mm depth and 50 mm height.

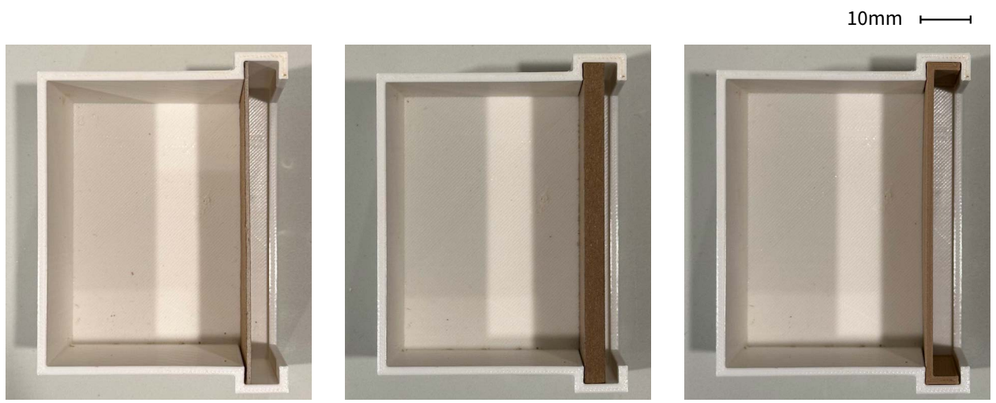


Figure 3.3.2b: Front panel materials tested with PLA Experiment Growth box.

Plywood Container

The second formwork for testing adhesion between mycelium and different materials was a formwork the size of a modular brick, made of ½" plywood, as highlighted in Figure 3.3.3. Each face was machined with interlocking corners to limit air and moisture exchange, and adhered with wood glue. A 1/8" acrylic sheet complete with four 1/8" diameter holes was used as the lid, which sealed the container by sliding into groove inserts at the top. The container's natural plywood composition meant the mycelium could adhere to all faces except the top. Variable front panel materials for the plywood growth container included plywood, wood PLA, and clay. The process of container preparation for mycelium remained the same, with one difference being that mycelium-inoculated substrate was mixed with new pasteurized substrate at a 1:1 ratio, to fill a larger volume. After the growth period, specimens within their respective container were heat-dried in an oven at 80°C for 4 hours. This was based on findings where an internal temperature of 76.7°C for 30 minutes successfully killed all fungi in a wood sample.[193] A longer exposure to more heat in this research accounted for possible heat loss between the ambient and internal temperature of the sample. Any shrinkage which occurred from the loss of moisture was documented and analyzed. Results were compared visually for all varied panel materials. Lessons learned from the efficacy of each material or configuration in achieving and maintaining interfacial adhesion with mycelium were applied to the wall system design.

193 Zabel and Morrell, *Wood Microbiology*.

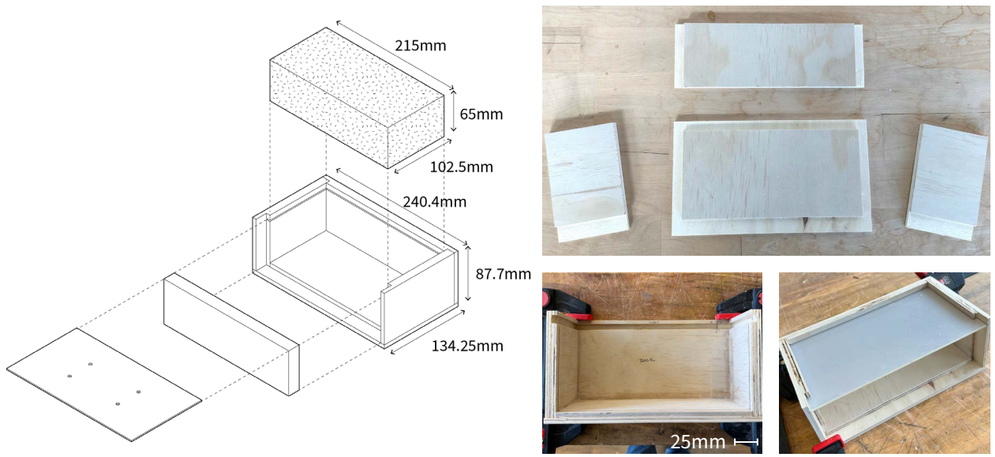


Figure 3.3.3a: Plywood Experiment Growth box, with interior dimensions of 215 mm width, 102.5 mm depth and 65mm height.



Figure 3.3.3b: Front panel materials tested with Plywood Experiment Growth box. (Middle) Additional clay was supplemented to the sides of the front panel after three days to account for shrinkage from the clay drying.

3.4 Design Development Workflow

This section will cover the design of a modular grown mycelium wall system, informed by each of the experiments. The design of this system evolved from one version to the next, aided by Rhinoceros 7, a digital modelling software, along with the 3D printing of scale models for each iteration. The evolution of the design will be highlighted step-by-step in the following section. To analyze the form and function of each design, scale models of the prototype at either 1:5 or 1:10 scale were printed, from a wood PLA (polylactic acid) filament. Upon exporting 3D models from Rhinoceros 7 as stereolithography (.stl) files, Creality slicer software was used to convert them into g-code files to be read by the 3D printer.

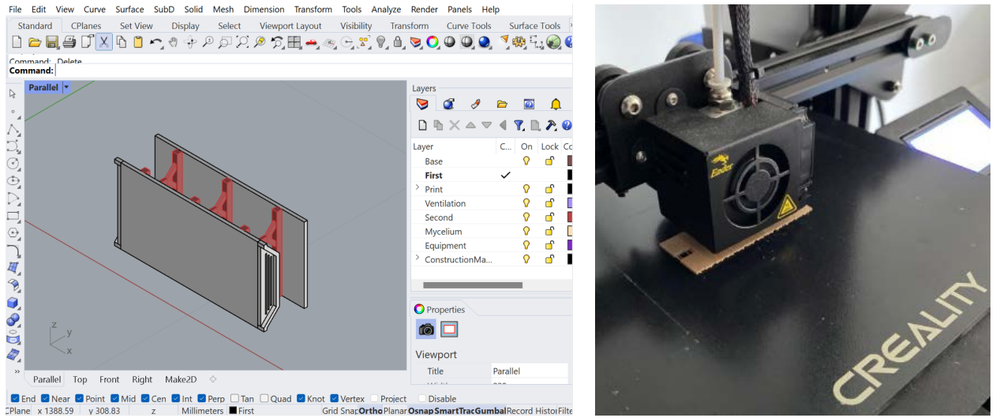


Figure 3.4.1: (Left): Rhinoceros 7 was utilized to create digital 3D models of design iterations. (Right): Creality slicer software then converted the models into g-code for the 3D printer.

As documented in the literature and observed through material experimentation, mycelium carries a set of needs to ensure successful growth within a substrate and desired performance properties. The objective of the design will be to facilitate these needs through the form, production process, and connection details of the wall system.

Preliminary Design Concept

The previous sections determined that mycelium composites excel in their thermal insulation, fire resistance, and acoustic properties while being considerably lightweight. However, they degrade quickly when exposed to outdoor environments, and are structurally insignificant compared to wood, steel, or concrete. These properties imply that mycelium composites can be applied as a renewable wall system, though they would require an integrated structure and shell.

The design concept of the wall system consisted of three elements: the structural form, the core mycelium, and the structural support in between. Two outer panels made of a robotic fabricated plywood act as the primary structural form which shields from exterior environments and transfers axial loads. The mycelium within the core provides thermal insulation, fire resistance, and sound insulation while adhering to the two panels. Intermediate wooden bracing provides structural support between the two panels while allowing the amorphous mycelium to distribute continuously. In the first design iteration, the combination of these three elements into a singular block module was speculated as shown in Figure 3.4.2. The modules were aggregated to form a brickwork pattern, with the support structure aligning at every third.

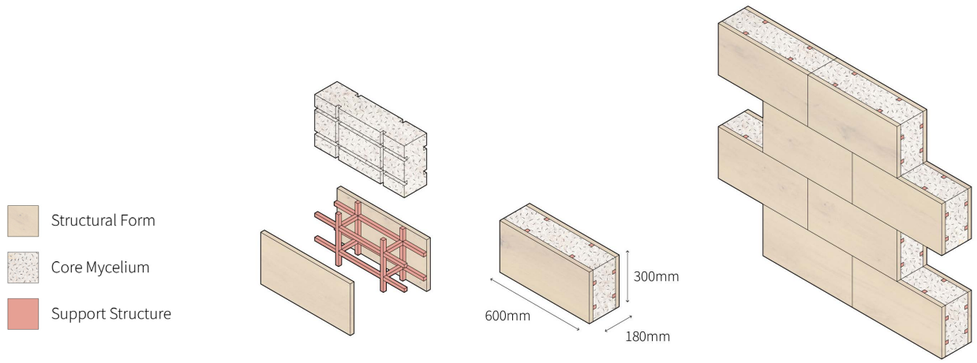


Figure 3.4.2: Preliminary design concept of a modular block panel which houses mycelium composite.

3.5 Thermal Resistance Evaluation

This subsection discusses the methods used to evaluate the mycelium wall panel's thermal resistance performance through digital simulation and physical experimentation. Thermal performance through a section of the proposed mycelium wall system was simulated using THERM software. A 1:1 sample section of the wall panel was constructed and placed within an insulated environment to test its resistance to heat flow.

Digital Simulation

THERM was utilized to simulate heat flow through the designed assembly digitally. THERM is a two-dimensional heat-transfer analysis tool which allows users to model and visualize heat transfer through various building components and assemblies.[194] Mathematical modelling allows users to accurately predict heat flux behaviour through material surfaces and geometries before taking the specimen to a specialized laboratory.[195]

List of *k*-values assumed for simulation input:
Plywood: 0.13 W/mK [196]
Mycelium composite: 0.08 W/mK [197]

194 "THERM | Windows and Daylighting."
195 Darya Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures," Energies 15, no. 12 (January 2022): 4230, https://doi.org/10.3390/en15124230.
196 "Solids, Liquids and Gases - Thermal Conductivities," The Engineering ToolBox, https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.
197 Patrick Pereira Dias, Laddu Bhagya Jayasinghe, and Daniele Waldmann, "Investigation of Mycelium-Miscanthus Composites as Building Insulation Material," *Results in Materials* 10 (June 1, 2021): 100189, https://doi.org/10.1016/j.rinma.2021.100189.

Physical Experimentation

Heat flow through the fabricated wall panel was evaluated experimentally to determine its thermal resistance (R-value) compared to similar wall panel products. R-value is a method of assessing the thermal resistance of a material or assembly. It describes a building element's resistance to heat flow. The higher the R-value, the better of an insulator that material is, whereas a low R-value indicates low resistance to heat flow.[198] The equation for calculating the R-value can be described as

$$R = \frac{\Delta T}{Q} \quad (1)$$

where Q represents heat flux through the wall in Watts per square meter (W/m^2), and ΔT defines the temperature difference between the interior and exterior surfaces, in °K.

Figure 3.5.1 describes the experimental setup for measuring the resistance to steady-state heat flow through a given assembly. To imitate cold climate conditions, a cold box test space was fabricated. The concept of this experiment was inspired by principles from *ASTM C1363-19 – "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus"* alongside a series of comparable case studies.[199]

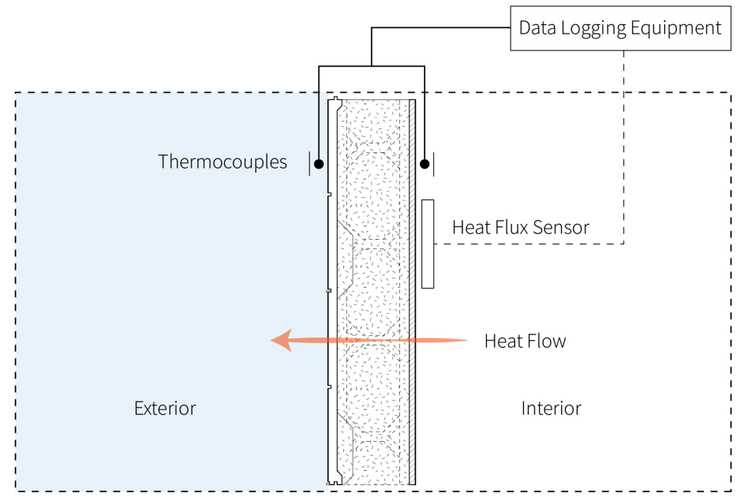


Figure 3.5.1: Diagram of experiment setup for determining material or assembly R-value.

198 Robert Madding, "Finding R-Values of Stud-Frame Constructed Houses with IR Thermography," *Inframation 2008* 9 (January 1, 2008): 261–77.
199 "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus."

Case Studies

Previous works have experimentally assessed the thermal resistance of wall samples. One study proposed a testing apparatus for evaluating 3D-printed ceramic wall samples.[200] The apparatus consisted of two nested boxes of 25 mm foil-faced insulation foam, separated by a 35 mm air gap, and sealed with expanding foam.[201] A foam frame which housed each sample was cut and fastened to the face of the frame with expanding foam and silicone caulk.[202] A DHT11 temperature sensor measured ambient air temperature within the box. The surface temperature of each sample was monitored throughout the experiment with a 10k thermistor attached to its inner surface, while an Arduino data logger took readings at 30-second intervals.[203] The apparatus was positioned outside at a 45-degree angle, and data was gathered over three days with similar weather conditions, for twelve hours from sunrise to sunset.[204]

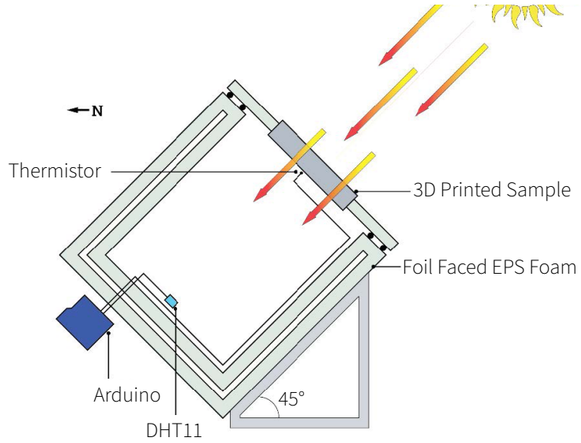


Figure 3.5.2: Experiment diagram of testing apparatus for evaluating 3D-printed ceramic wall samples. By Puppos.

Solomon et al fabricated an experimental apparatus for measuring the thermal resistance of ICF panels. The apparatus consisted of three layers of 10 mm-thick cement board forming a chamber 1000 mm in length and 500x500 mm in cross-section.[205] The sample was kept in the middle of the chamber, dividing the chamber into two compartments 'A' and 'B'. Two 50W

200 Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing," 2021, https://repository.arizona.edu/handle/10150/663222.
201 Puppos.
202 Puppos.
203 Puppos.
204 Puppos.
205 Arun Solomon and Hemalatha, "Characteristics of Expanded Polystyrene (EPS) and Its Impact on Mechanical and Thermal Performance of Insulated Concrete Form (ICF) System."

projection low-voltage halogen lamps heated Compartment A, while no temperature change was applied to Compartment B, allowing heat to flow from the 'A' side of the panel to the 'B' side. A digital thermometer was used to measure the temperature of the compartments.[206] The thermometer contained six thermocouples; three of which were fixed on the warm surface (A) of the panel while the other three thermocouples were fixed to the control surface of the panel facing compartment B. Surface temperature variation on both sides of the sample was observed and recorded at regular intervals for 72 hours.[207]

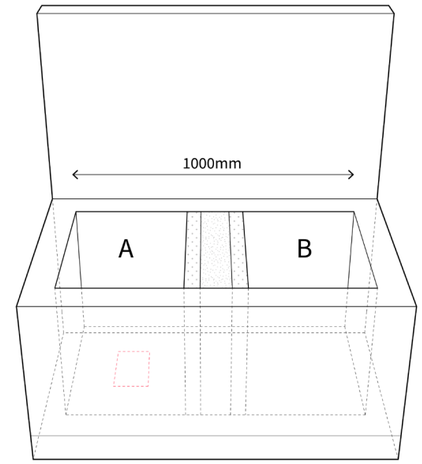


Figure 3.5.3: Diagram of Solomon et al's testing apparatus for measuring thermal resistance of sample ICF panels.

Thermal Resistance Experiment

A 1:1 prototype was constructed, and its thermal resistance performance was evaluated, as outlined in Figure 3.5.4. Interior back panels were cut to size with a table saw, while studs and front panels were fabricated to their specific shape using an AXYZ 3-Axis Computer Numerical Control (CNC) router. The front panel was machined with an air hole for a ventilation insert and slots for protruding hooks. Studs were positioned and adhered to the back panel, while a bolted connection from the front panel to the studs allowed it to be removable from the assembly. The combination of these components formed the skeleton of the wall, while 2 mm millboard sheets were fastened onto the narrow edges of the panels to create an enclosed mould for the mycelium. Supplementary hooks and vents were 3D printed with a recyclable wood filament.

206 Arun Solomon and Hemalatha.
207 Arun Solomon and Hemalatha.

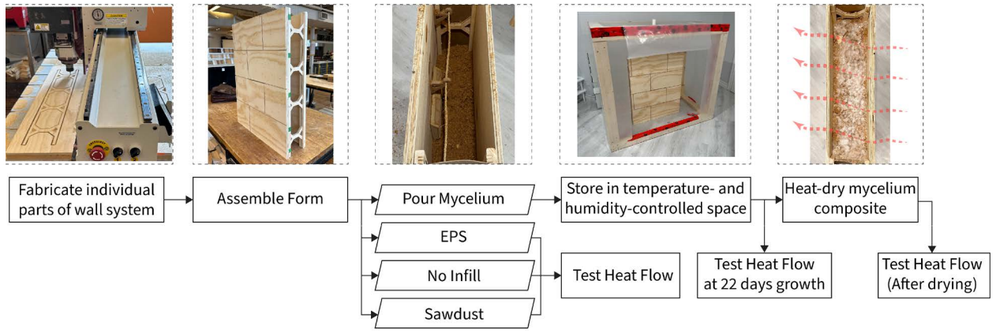


Figure 3.5.4: Process diagram for the construction & thermal resistance evaluation of full-scale sample wall panel.

Pre-grown, pre-inoculated mycelium was mixed thoroughly with a bulk pasteurized substrate mixture at a ratio of 1:1. Once the interior of the wall assembly and the work area were sterilized, the mixture was poured into the formwork and distributed evenly using a sterilized trowel. The wall was then stored in a tent frame, constructed from 2x4 softwood lumber and a vapour barrier, to provide a moisture- and temperature-controlled environment during mycelium growth, for 4 weeks (Figure 3.5.6). The wall was removed from its tent frame one day before drying to boost air exchange and stimulate the mycelium growth as it transitioned to fruiting. Finally, the complete panel was heat-dried at 60°C for 24 hours.

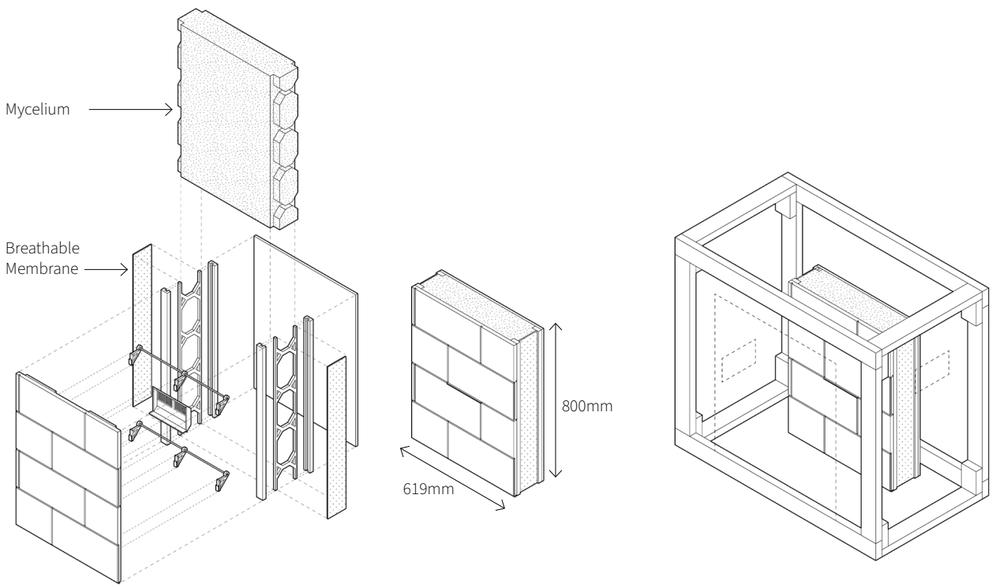


Figure 3.5.5: Left: Construction axonometric of full-scale wall panel prototype. Right: Placement of prototype in tent frame, complete with an operable opening and ventilation.



Figure 3.5.6: Mycelium-inoculated substrate was poured into the sterilized prototype, then stored within a tent frame.

The thermal effectiveness of the fabricated wall panel proposed in the design was evaluated through a physical experiment, illustrated in Figure 3.5.7. A commercially available wireless thermometer with four temperature sensor channels and a data logger was used to monitor the wall's surface temperature at 60-second intervals. The temperature of the ambient air remained constant at 19°C. A cooler apparatus was fabricated to imitate cold climate conditions. The mycelium-insulated panel was enclosed by 120 mm closed-cell EPS insulation foam, with an R-value of 0.66 m^2K/W per inch. Since 4.5 inches of foam were used for this experiment, this resulted in a continuous R-value of 3.0 m^2K/W. The interior and exterior edges connecting the wall panel to the foam were sealed with frame-sealing aluminum tape to ensure air tightness.

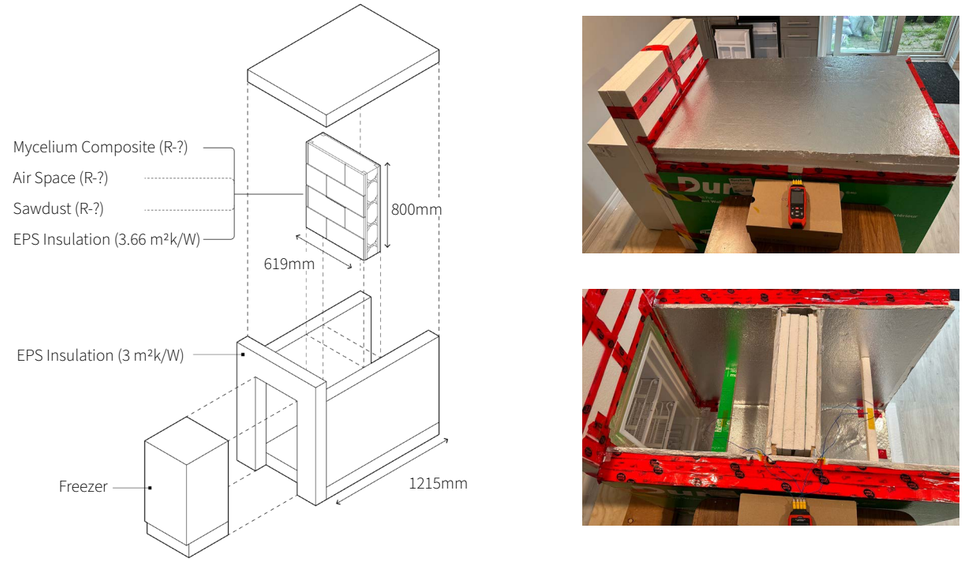


Figure 3.5.7: Diagram and images of the cold box apparatus for evaluating the thermal resistance of the prototype.

Different wall panel infills were tested to validate their experimentally determined thermal resistance, as shown in Figure 3.5.8. The first infill was EPS closed-cell foam insulation, with a known R-value of 0.66 m^2K/W per inch (see Section 3.1 for material specifications). The total R-value of this assembly could be calculated, as each component's thermal conductivity *k* (W/mK) was known. Using this reference point, the heat flux rate through any assembly within the apparatus could be accurately estimated. The second infill was the mycelium-substrate composite, grown within the wall cavity as highlighted in the earlier procedure. After the mycelium had grown, its thermal resistance was evaluated in its live and dried states. To simulate 0 days of mycelium growth, the thermal performance of a duplicate assembly filled with sawdust was tested. An assembly with a hollow core was also tested to provide an example of poor insulation.

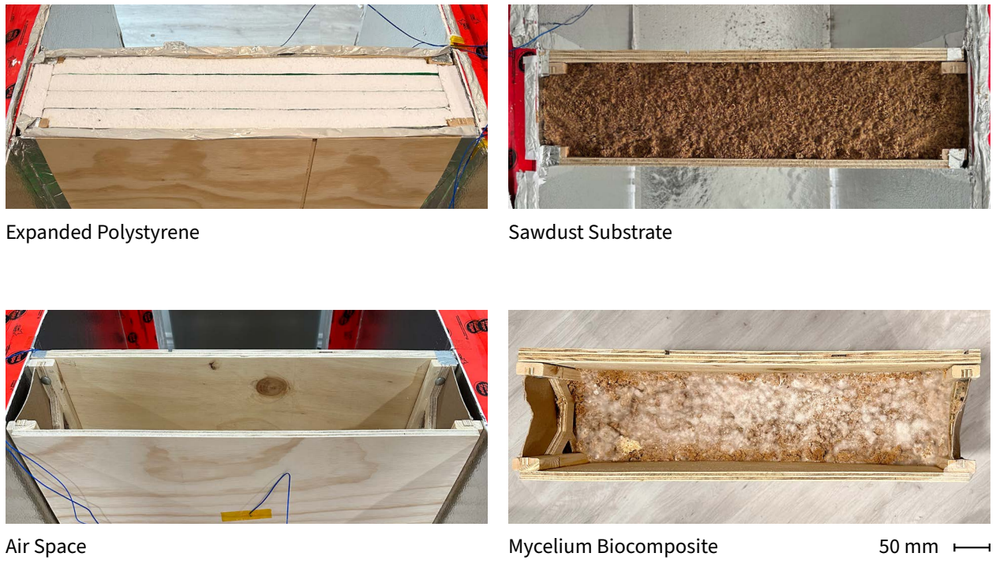


Figure 3.5.8: A duplicate prototype was filled with EPS insulation with a known R-value. Another duplicate filled with sawdust was tested, to imitate 0 days mycelium growth. Once the mycelium grew within its form, it underwent the same thermal evaluation as the EPS and sawdust assemblies.

This research developed an experimental procedure to assess the thermal performance of the proposed design as illustrated in Figure 3.5.9. One temperature probe was placed on the exterior surface of the wall (T_1), while another probe was placed on the interior surface (T_2) to measure the temperature difference for the full assembly. Sensors were positioned centrally on the prototype wall, assuming linear heat flow at the centre.[208] A third suspended sensor measured the ambient interior temperature (T_r).

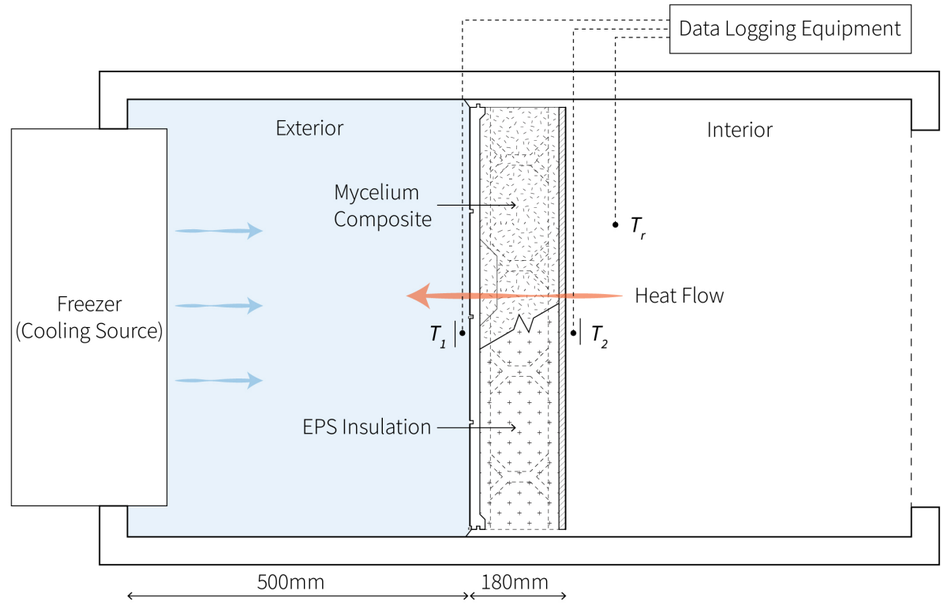


Figure 3.5.9: Diagram of the physical experiment, demonstrating the wall placement, thermocouples, the cooling source creating interior and exterior zones, and the direction of heat flow.

A source of cold air was placed 500mm away from the exterior side of the panel, with no cooling and free airflow at the control temperature on the interior side of the setup. Data was collected for 48 hours, and the average temperatures were determined starting from their stabilization point. Thermal resistance was calculated by measuring the temperature difference between interior and exterior surfaces, and between ambient and interior surfaces, for each assembly. Results of the experiment were demonstrated through graphs illustrating the time interval, in seconds, related to the temperature change in degrees Celsius (°C).

208 Incropera et al., Fundamentals of Heat and Mass Transfer.

Two equations utilized to determine the rate of heat flow (Q) were combined to isolate the R-value of the mycelium wall assembly. The first (2) was a variation of (1),

$$Q = \frac{(T_2 - T_1)}{\sum R} \quad (2)$$

where T_2 is the measured interior surface temperature and T_1 is the exterior surface temperature. Interior surfaces of the prototype composite wall were not factored into calculations as they were assumed to negligibly impact the results in the context of this research. The second heat transfer equation for determining Q can be expressed as

$$Q = h(T_r - T_2) \quad (3)$$

Where T_r represents the constant ambient temperature (°C) on the interior side, and h represents the heat transfer coefficient. The combined equation can be written as such.

$$\frac{(T_2 - T_1)}{\sum R} = h(T_r - T_2) \quad (4)$$

Since the R-values of plywood and EPS are known, performing the cold box experiment on the EPS assembly allowed for the calculation of h in this setup. R of each assembly material was calculated based on its thickness L as such.

$$R = \frac{L}{k} \quad (5)$$

List of k-values assumed for experiment calculations:

Plywood: 0.13 W/mK [209]

Extruded Polystyrene: 0.038 W/mK [210]

R-value calculations (known):

19.05mm plywood: R = 0.0127m / 0.13 W/mK = 0.0980 m^2k/W

12.7mm plywood: R = 0.0190m / 0.13 W/mK = 0.1465 m^2k/W

EPS insulation: R = 21 / 5.678 = 3.6985 m^2k/W

EPS Assembly ΣR = 3.9910 m^2k/W

209 "Solids, Liquids and Gases - Thermal Conductivities," The Engineering ToolBox, https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

210 "DuroSpan® Insulation | Plasti-Fab EPS Product Solutions." https://www.plastifab.com/products/durospan-insulation/durospan.html.

Chapter 4 - Results

This section will discuss the documented results of each physical experiment phase, beginning with the supplementation phase and followed by the adhesion experiment. Afterward, the evolution of the mycelium wall panel design will be visualized and described, leading to the final wall system design and prototype. Finally, the resulting thermal resistance of the full-scale prototype wall panel will be assessed relative to alternative assemblies.

4.1 Experiment 1 Results, Supplementation

Figure 4.1.1 shows a visual timeline of mycelium growth for four *Pleurotus Ostreatus* specimens in sawdust substrate with varying levels of wheat bran supplementation, over 22 days. Compared to 5% supplementation, samples with 15 and 20% supplementation showed visibly higher surface growth of mycelium by day 8. By day 22, 15% supplementation had the most consistent surface growth while surface growth of the 5% specimen was the least consistent. Based on visual assessment, it can be concluded that the optimal amount of wheat bran supplementation to sawdust substrate for increased growth rate of *Pleurotus Ostreatus* was 15%. Another study which tested wheat bran substrate supplementation for pink oyster mycelium observed the highest spawn run at 40%, while the lowest was at 0% supplementation.[211] Variation can be attributed to differences in mycelium species and substrate, though general trends in the results were consistent. This substrate composition was carried over to subsequent phases of experimentation.

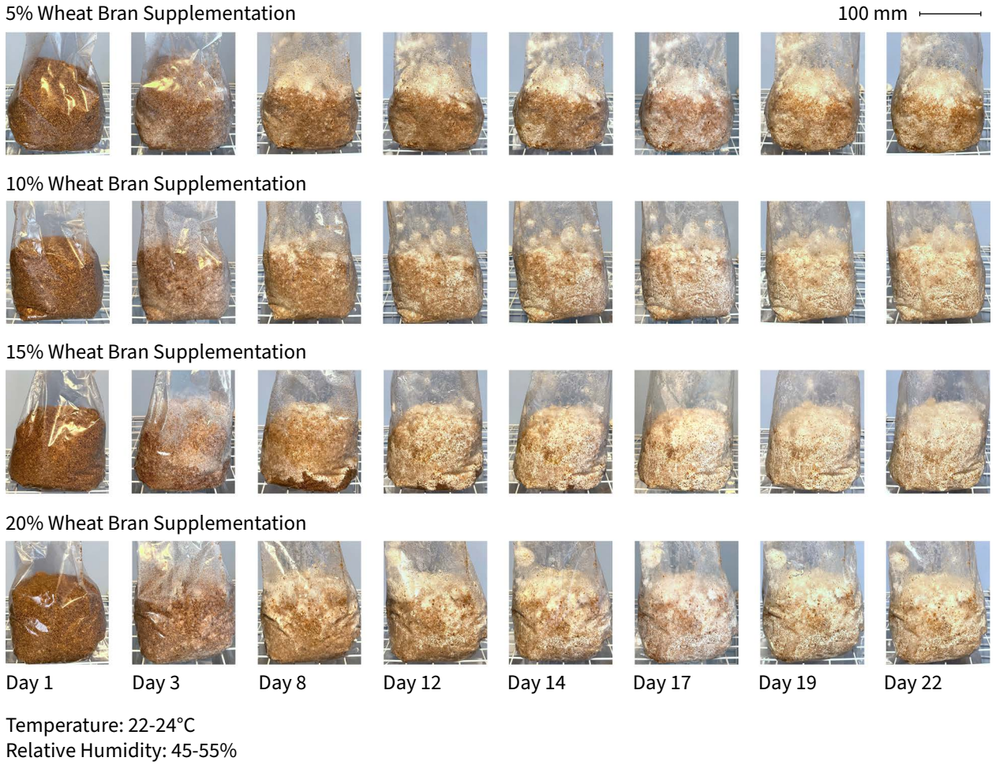


Figure 4.1.1: Timeline of mycelium growth for four Pleurotus Ostreatus specimens in sawdust substrate with varying levels of wheat bran supplementation, over 22 days.

211 Hasan et al., "Effect of Wheat Bran Supplement with Sugarcane Bagasse on Growth, Yield and Proximate Composition of Pink Oyster Mushroom (Pleurotus Djamor)."

4.2 Experiment 2 Results, Adhesion

Once the optimal supplementation ratio was determined for the mycelium substrate, the adhesion of the grown mycelium composite with adjacent materials was tested. The first series of tests within a miniature PLA growth container tested the adhesion of millboard, medium-density fibreboard and wood filament.

1/16” millboard was placed as the front panel of the mycelium growth container. During the first week of growth, the substrate adjacent to the front dried significantly, likely due to moisture escaping the container freely through the millboard (Figure 4.2.1). This resulted in reduced mycelium growth on this front surface, a high degree of mycelium composite shrinkage, and no interfacial bonding between the mycelium and millboard. Once this experiment was repeated, the container was encapsulated with a polyethylene bag with small, punctured holes for air exchange. After one week, signs of mycelium growth appeared on the millboard’s exterior. By three weeks, the mycelium fully spread and bonded with the millboard (Figure 4.2.1b). Shrinkage was also present in this specimen, though notably, the millboard became curved as it remained bonded to the shrinking mycelium composite. The difference in results from adding a moisture control layer proves the importance of maintaining high moisture and relative humidity during mycelium cultivation. As these results were qualitative, future research should evaluate the adhesive strength between mycelium and other materials through a shear test.



Figure 4.2.1a: Results of first adhesion test with 1/16” millboard, after full growth period.

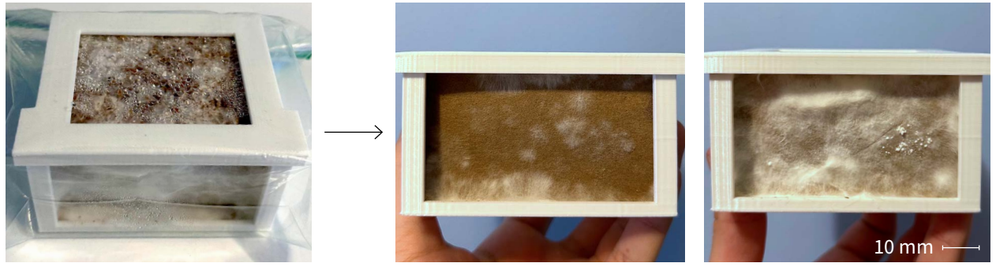


Figure 4.2.1b: Results of second adhesion test with 1/16” millboard, after full growth period.

Next, a 1/4” thick medium-density fibreboard (MDF) was tested as the front panel of the mycelium growth container. After one week, the view from the top showed the mycelium successfully forming an interfacial bond with the MDF as it grew, like the millboard (Figure 4.2.2). However, its greater thickness meant mycelium could not spread to the exterior face. The MDF successfully impeded moisture loss to sustain mycelium growth. Areas of mould contamination were visible on the MDF, likely from insufficient surface sterilization during preparation. Results proved that mycelium has difficulty fully colonizing thicker, high-density materials.

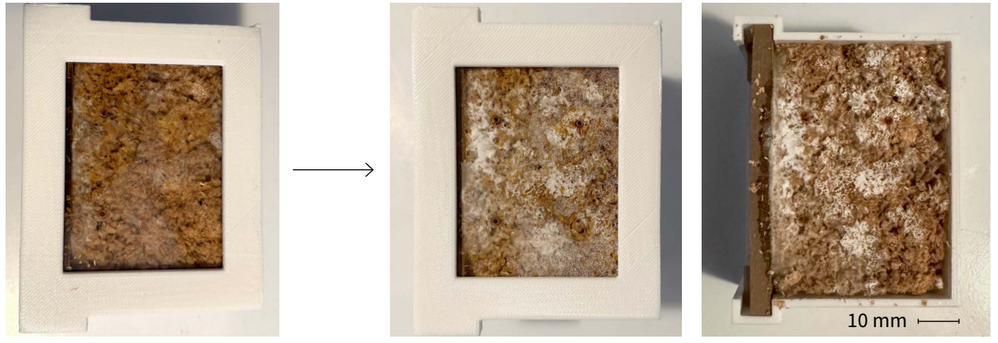


Figure 4.2.2: Results of adhesion test with 1/4” MDF.

PLA mixed with 30% wood microfibres was extruded as a panel 2 mm in depth and fit into the front of the growth container to test its surface adhesion. During the first week of mycelium growth, some shrinkage was observed on the white PLA surfaces, but the mycelium composite remained attached to the wood PLA front surface. By week two, some shrinkage also began occurring on the front face. Based on this delay, it can be inferred that the wood fibres encouraged slight interfacial mycelium bonding compared to standard PLA.



Figure 4.2.3: Results of adhesion test with wood PLA filament, after full growth period.

The next series of tests within a modular brick-sized plywood growth container tested the adhesion of plywood, clay, and wood filament with hooks and string.

Quarter-inch thick plywood was utilized for the first front panel, shown in Figure 4.2.4. It was observed after 2 weeks that high mycelium growth occurred at the interfaces of the substrate and the plywood. As the plywood front panel was allowed to move, it gradually demonstrated a “bowing” effect. This phenomenon could be due to adhesion pulling the panel inwards as the composite shrinks, and warping from moisture differential between the interior and exterior. Consistent moisture in the container allowed the mycelium to grow for the full period, though inconsistent growth and early fruiting were observed. This could be explained by the inoculated substrate and new substrate not being fully mixed before pouring into the form.

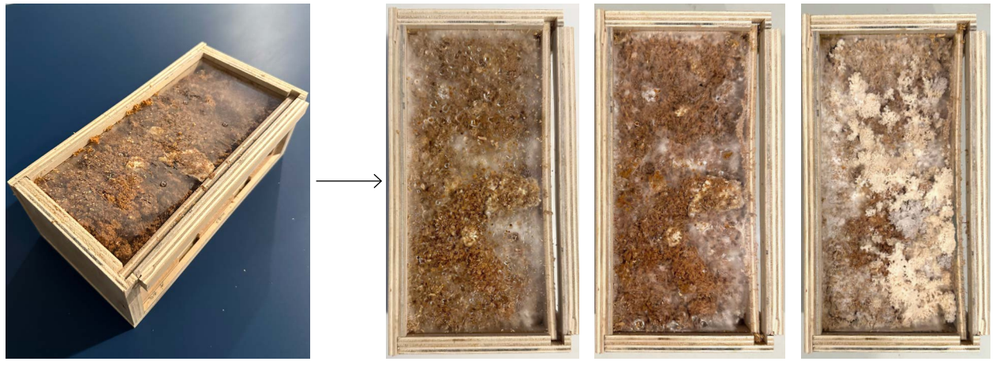


Figure 4.2.4: Results of adhesion experiment with 6.25 mm plywood, 230 mm W x 80 mm H. Right: Weekly growth of mycelium in substrate within the container, from 0 weeks to 3 weeks.

The next experiment explored the interface of mycelium with clay, a non-living material with a different chemical composition from wood, lacking viable nutrients for mycelium to consume. PSH-516 Cone 6 clay was hand-formed as the front panel, visualized in Figure 4.2.5. Additional clay was supplemented to the sides of the front panel after three days to account for shrinkage from the clay drying. The clay absorbed local moisture from the substrate mixture at the front interface, causing a reduction in mycelium growth and adhesion in that area. This was likely due to its hydrophilic properties. Improved mixing of inoculated and new substrate before pouring led to increased consistency in mycelium growth throughout this sample. Contamination observed on the edges of the growth container was likely caused by inadequate sterilization of the clay.

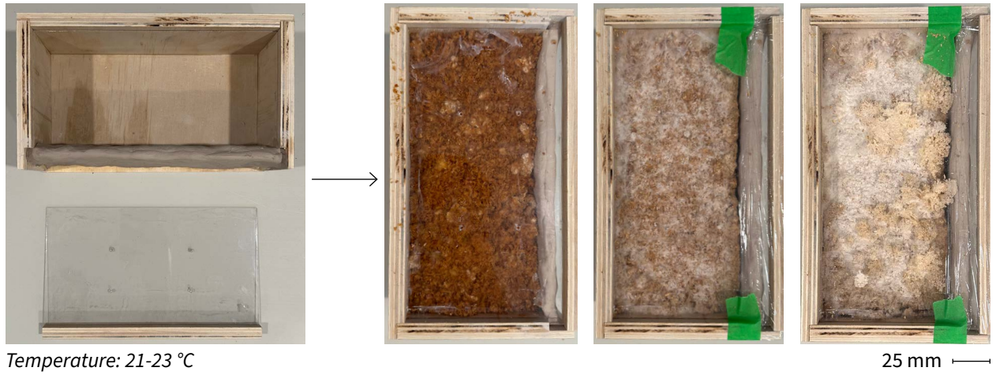


Figure 4.2.5: Results of adhesion experiment with clay after full growth period. Photographs on the right highlight the shrinkage gap, loss of moisture and reduced growth at the interface of the substrate and the clay.

The interface of mycelium composite with a front panel made of wood PLA with protruding elements was tested. The capabilities of 3D printing allowed for incorporating rope which could slack or move as the mycelium shrinks or expands. The front panel was fabricated as two components with slots for protruding hooks of the same material to be inserted. A string was fed through these hooks with moderate slack, as visualized in Figure 4.2.6. No visible shrinkage was observed during the growth period, though mycelium growth at the edge of the front panel was visibly less pronounced compared to the surrounding plywood. This trend remained consistent during all three weeks of growth.

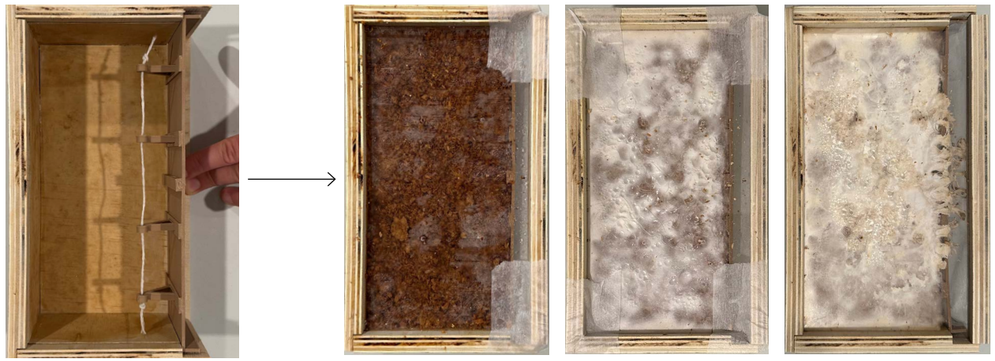


Figure 4.2.6: Construction of wood PLA front panel with string, for experiment mycelium growth container. Right: mycelium composite after three weeks of growth within the container.

Each of the growth container specimens was heat-dried at 80°C for four hours. Results were documented before and after the heat-drying process, to analyze the shrinkage effect. In Figure 4.2.7a, the shrinkage gap between the composite and the clay increased, while the composite also delaminated from the plywood on all other sides. Figure 4.2.7b shows no visible shrinkage and delamination after the 3-week growth period and before drying. After drying, shrinkage became most noticeable on the long axis, consistent with all samples. Despite this, the mycelium composite remained well-laminated to the 3D-printed front panel. The “bowing” effect was observed, as the side edges of the front panel resting on the plywood remained stationary, while the remainder moved inwards with the shrinking mycelium. Greater shrinkage on the longer axis suggests that mycelium shrinks consistently by a certain percentage after heat-drying. Future research should investigate the shrinkage behaviour of mycelium composites and specific percentages of shrinkage to be expected as they dry. This test proved that protruding elements successfully kept the mycelium composite adhered to its exterior shell.



Figure 4.2.7: a) Results of baking the mycelium composite grown within experiment box with clay front panel. L: Before drying. R: After drying. b) Results of baking the mycelium composite interfaced with wood PLA and protruding hooks with string. L: Before drying. R: After drying.

Lessons learned from the literature and previous experiments were applied to the mycelium wall system design. From previous experiments, wood adhered best to growing mycelium. Since wood is also structural and relatively weather-resistant, it was selected as the primary structural material. Progressive iterations were made to the relationship between the three main components; the structural form, mycelium, and structural support to develop the design of a prefabricated mycelium wall.

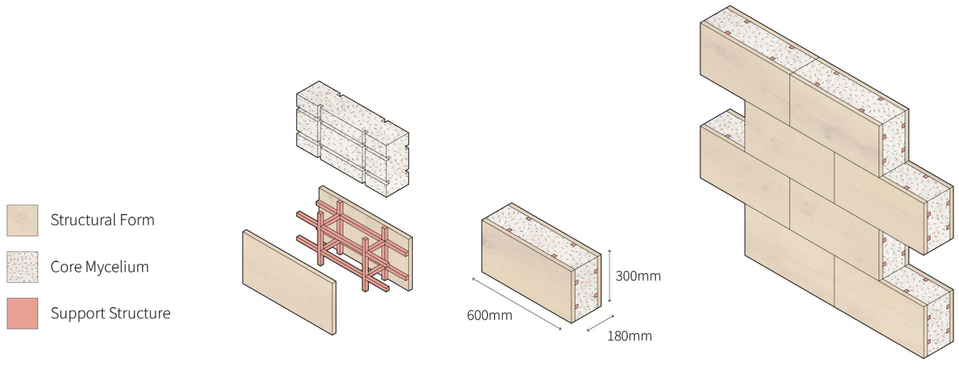


Figure 4.3.1: Illustration of the preliminary design concept of a modular block panel which houses mycelium composite.

The preliminary design concept was built upon by introducing a dedicated space for ventilation to the growing mycelium (Figure 4.3.2). Air exchange was shown to encourage mycelium growth by releasing trapped carbon dioxide from its form, so the design objective was to facilitate small ventilation gaps for the mycelium. The visual impact of the ventilation gaps in aggregation was considered by testing both horizontal and vertical conditions. The next two design iterations focused on developing a ventilation system which only exchanges air from the exterior. Growth containers for mycelium typically only require a small amount of air exchange, as evidenced by the small surface area of air filters for mycelium mono tubs or growth bags. For this reason, the area of the front panel dedicated to ventilation was greatly reduced, as seen in Figure 4.3.2a. Variations in modular block size were also tested as shown in Figure 4.3.2b, where the block width was increased from 600 mm to 800 mm. This increase was momentarily abandoned due to fewer customization options for the assembly. Since the primary wooden structural panels could adequately transfer lateral loads, horizontal structural support was deemed gratuitous, and removed. The focus was shifted to modelling and testing the visual impact of the ventilation grills when the modules were assembled into a 1 m x 1 m wall. Figure 4.3.2c shows that a simplistic vent would be quite visible and exposed if considering the front face of the module as an exterior façade, therefore further developments were required.

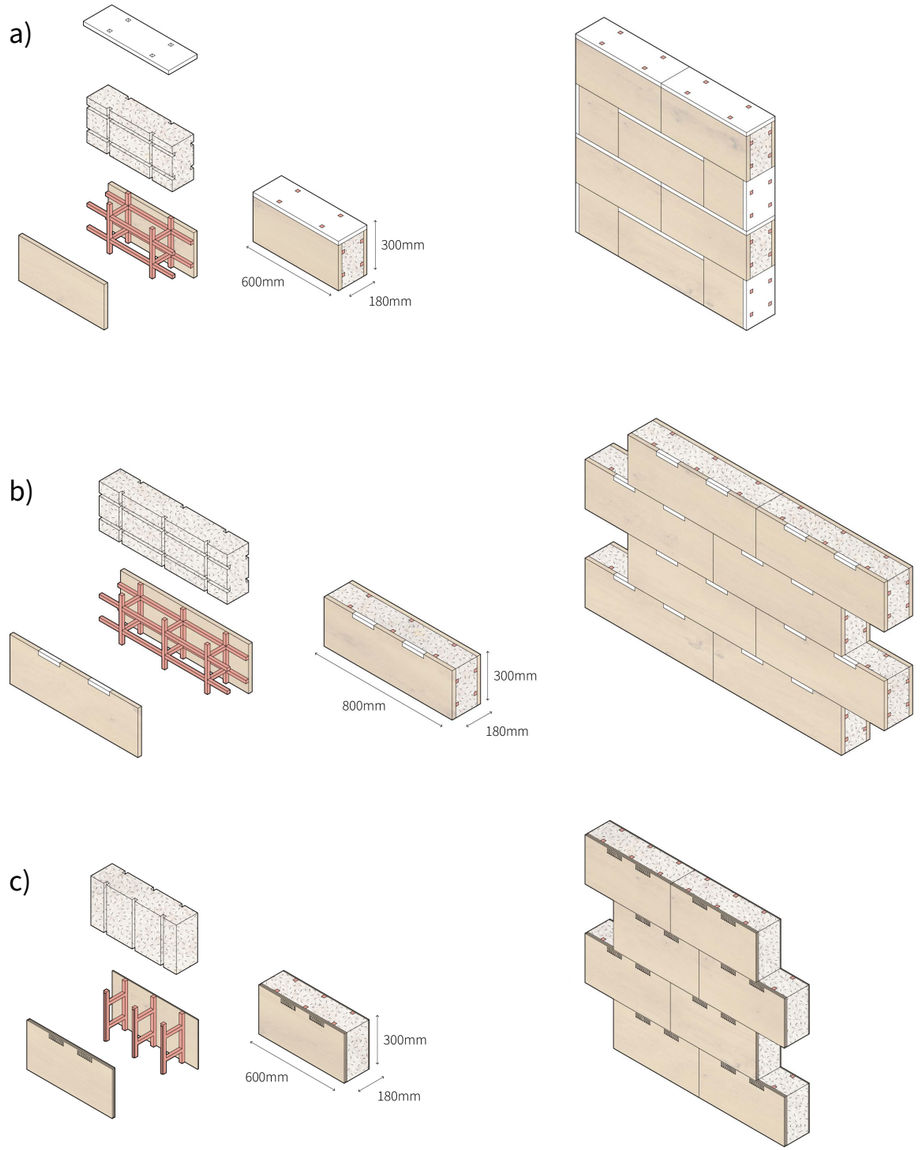


Figure 4.3.2: Design evolution of integrated mycelium module considering ventilation, with assembly highlighted on the left, and aggregation on the right.

The next design development was to streamline the ventilation with the seams between modules, enhancing aesthetics and functionality. Figure 4.3.3a demonstrates the placement of vertical vents on the left and right edges of the module's front panel. The assembly of modules resulted in a clear visual redundancy of openings in the façade. Doubled-up vents made the vertical connections practically delicate, and visually dominant within the sample assembly. The next model tested combining the left and right edge vents into one singular vent at the seam, as highlighted in Figure 4.3.3b. The sample assembly demonstrates how this combination reduced the openings by half and began to conceal the vents themselves, making the façade more seamless.

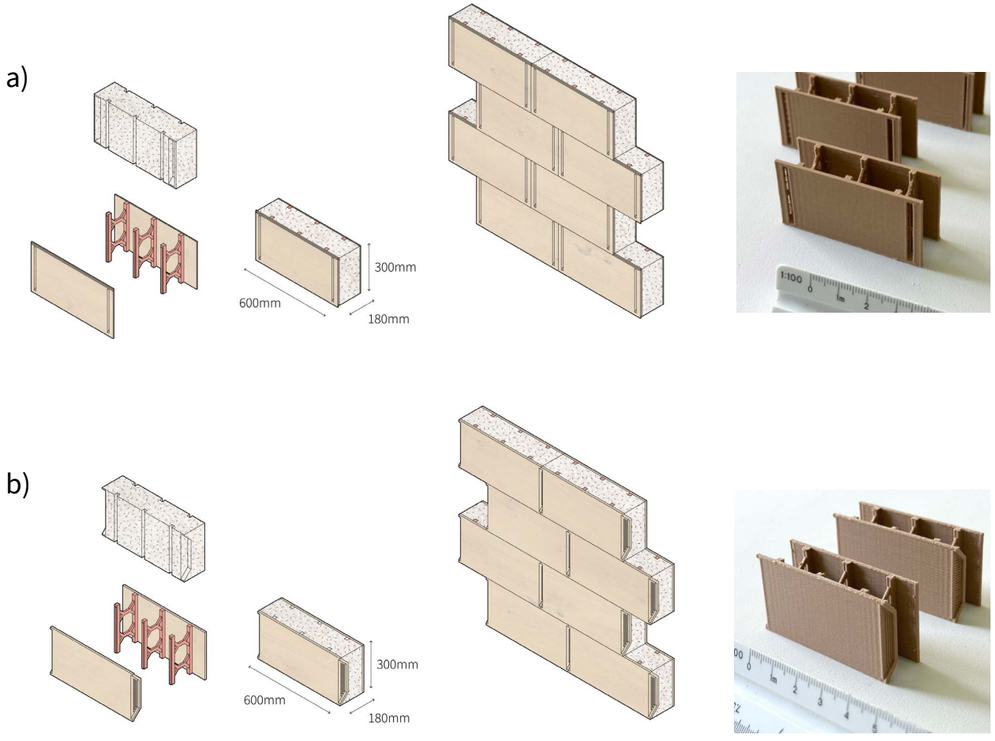


Figure 4.3.3: Design evolution of integrated mycelium module, streamlining and concealing exterior ventilation system. Right: 3D-printed maquettes of different ventilation systems, 1:10 scale.

The subsequent iteration further concealed the vents by establishing a ventilation chamber which feeds exterior air from the vertical seams into the wall (Figure 4.3.4). Concealing the vents further ensures that they are protected from water leakage. This iteration considered ventilation chambers as separate components integrated with the primary and support structure through interlocking. The addition of vents highlighted the increasing number of parts within the system, especially considering how modules are aggregated into a larger wall panel. Assembling each module individually would increase production time and the total number of parts within the system. There was an opportunity for further optimization based on the knowledge of mycelium growth patterns and the logistics of its production.

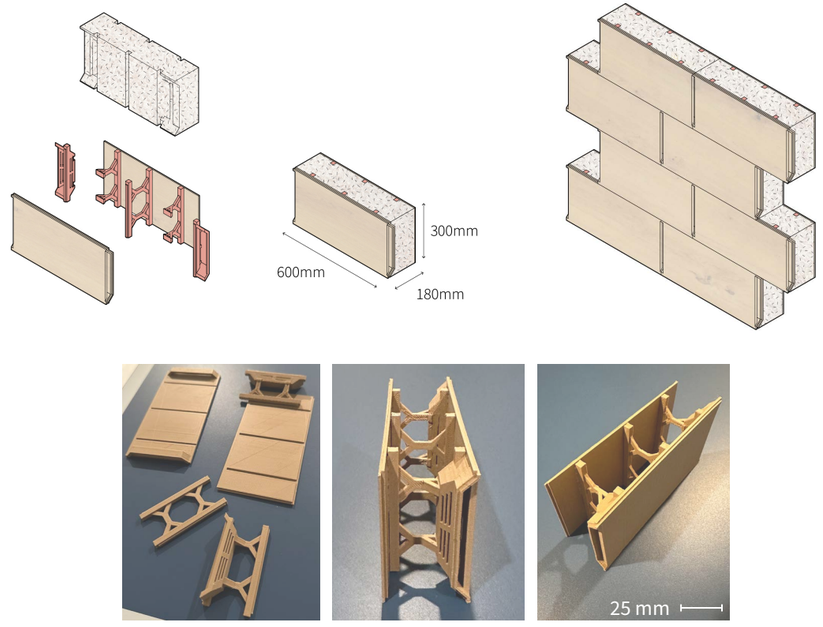
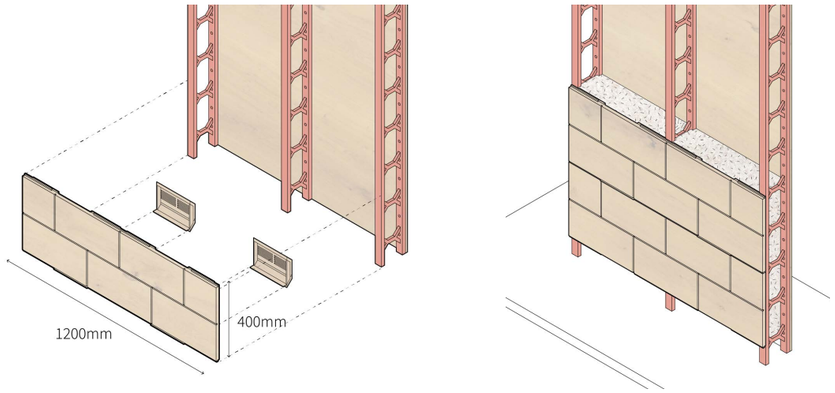


Figure 4.3.4: Design evolution articulating the ventilation chamber as a separate component. A 3D-printed maquette of the ventilation chamber component assembly was made, at 1:5 scale.

Each of the three elements' form was re-imagined with the next design evolution. Rather than aggregating multiple modules to form the wall panel, the wall was conceptualized as a larger prefabricated panel, as seen in Figure 4.3.5. The front panel is fabricated as a module which sequentially stacks up to form the exterior façade. Vent chambers are integrated behind the front panel and aligned with horizontal weep holes which allow air to travel upwards from the exterior. Vent grills are placed higher in the chamber to prevent water infiltration, and a sloped sill allows any water which enters to drain back out. Retaining the modularity of the front panels from previous iterations was essential for allowing the sequential pouring of mycelium-substrate mixture into the form, similar to ICF systems. The interior back panel is one piece, while full-height engineered studs comprise the support structure, spaced apart at 600 mm.



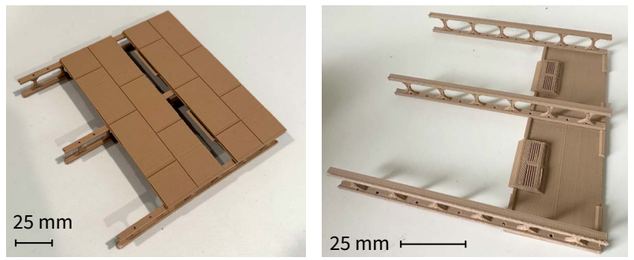


Figure 4.3.5: The module is considered one frame with front panels inserted to form the exterior wall. A 3D-printed maquette demonstrates the front panel(s) aligned with engineered studs, at 1:10 scale.

Finalized Mycelium Wall Panel Design

The freedom granted to the front façade panel from the studs provided an opportunity to also consider the visual continuity from one panel to the next. Front panels were given a puzzle-like geometry, allowing them to interlock side by side with shiplap edges, as visualized in Figure 4.3.6. This provides a seamless façade continuity once the panels are installed.

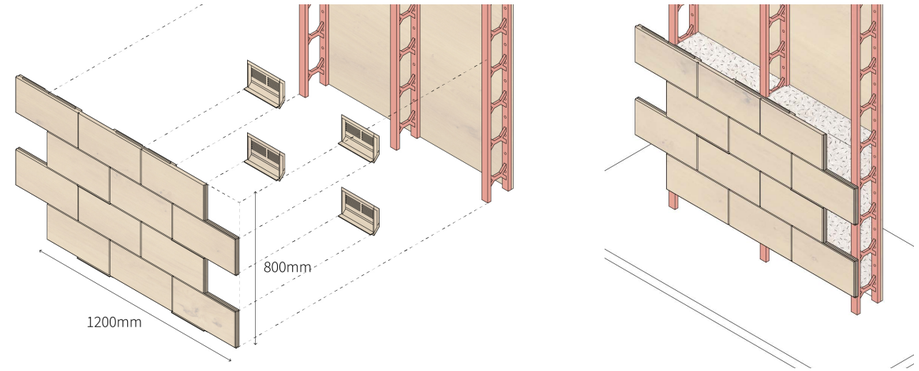


Figure 4.3.6: The final design considered adjacent assembly and visual continuity of prefabricated panels by making the front panels interlocking.

Experimentation with the drying of mycelium composites revealed a shrinkage differential between the mycelium and its shell, despite mycelium adhering to the surface. Adhesion experiments from this study proved that embedding tensile elements which moved with the mycelium allowed it to remain adhered to the panel after drying. Figure 4.3.7 illustrates a series of hooks added to the back of the front panel which support a string running across its full length horizontally, spaced vertically every 400 mm. As the mycelium is poured into the form, the string is embedded within the composite, assisting in connection.

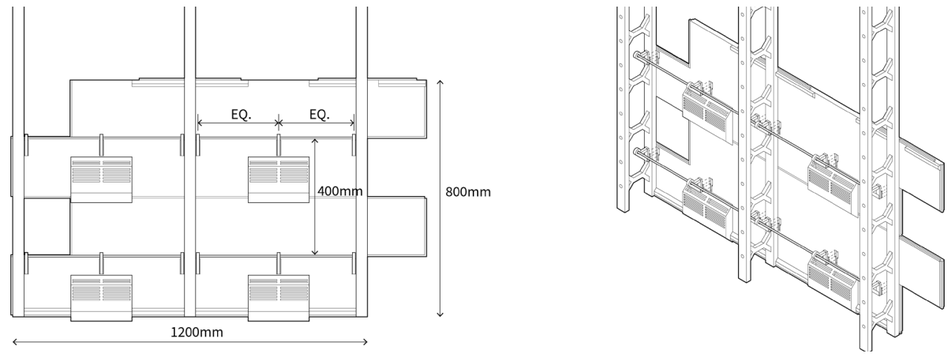


Figure 4.3.7: Diagram showing the placement of hooks and strings on the inverse side of the front exterior panel.

The sequencing of production for this proposed design follows the *"integrate + grow"* pathway of mycelium production, shared by previous precedents. Baking was selected as the method of halting mycelium growth after its interfacial bonding properties were utilized.

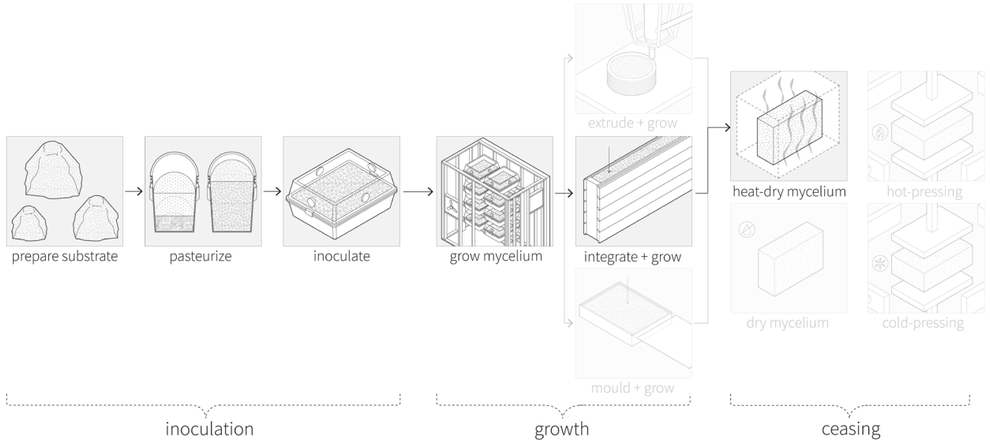


Figure 4.3.8: Mycelium production sequencing applied in this research, adapted from Ali Ghazvinian and Benay Gursoy, "Basics of Building with Mycelium-Based Biocomposites."

A unique sequencing was proposed for constructing the mycelium composite wall panel, as highlighted in Figure 4.3.9. This sequencing process is to take place in a temperature- and humidity-controlled environment, off-site. Interior plywood panels and engineered timber studs are first assembled, followed by placing the first interlocking exterior panel(s) to create 800mm of formwork. Edge panels comprised of breathable material are placed on the narrow sides of the wall, fully enclosing the form. Once the form is sterilized, mycelium-inoculated sawdust substrate supplemented with wheat bran and gypsum is poured into the form and gently evened out with a trowel. These steps are repeated every 800mm height until the entire wall panel is filled with substrate. The panel is then set to grow under controlled conditions for four weeks. After removing the panel from the environment and baking it in a curing chamber, it is ready to be transported to the construction site. The proposed method simplifies the assembly process by eliminating the need to aggregate individual smaller modules into a wall panel after growth. This reduction of construction steps is inspired by ICF wall systems, with the difference being that the concrete for ICFs is typically poured on-site. Concrete quality also benefits from controlled environments; however, its curing reaction occurs under various conditions while mycelium only grows within a small temperature and humidity window.[212]

212 Elissa Glad, "How to Pour Concrete for ICF Walls in Cold Weather," *Insulating Concrete Forms Manufacturers Association* (blog), February 23, 2023, https://icf-ma.org/how-to-pour-concrete-for-icf-walls-in-cold-weather/.

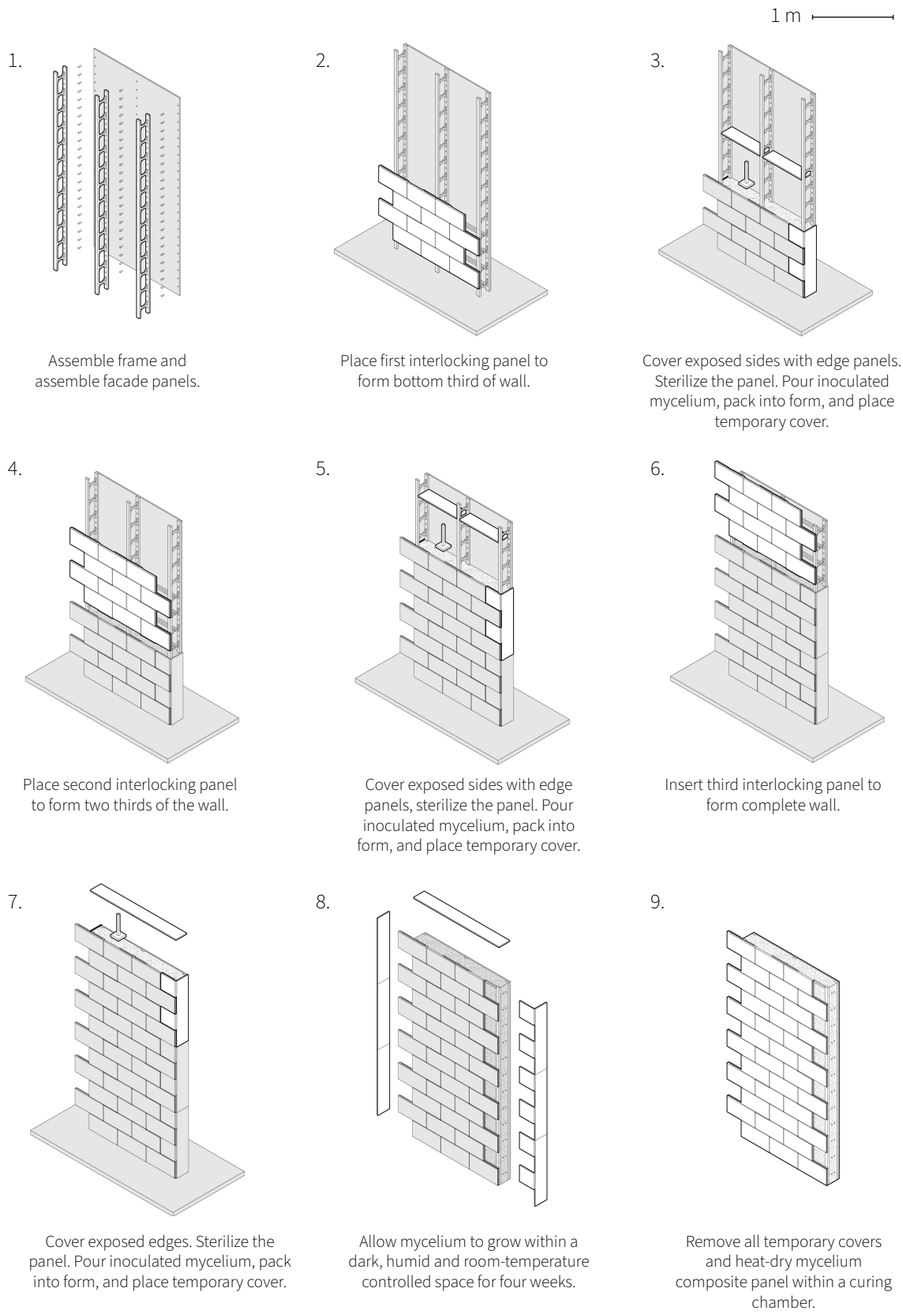


Figure 4.3.9: Sequencing diagram for assembling the mycelium-composite wall panel.

Figure 4.3.10 catalogues the multiple sizes and configurations for the front exterior panels. Front panels were sized up to 800 mm in height, to retain human accessibility for pouring mycelium into the formwork. Shorter 400 mm heights would also be available for design flexibility. The standard height for the full mycelium wall panel is 2400 mm, matching that of SIP panels.[213] Wall panels typically range from 600, 1200 or 2400 mm in width, though widths of up to 7200 mm would be possible, as this is the common maximum width for SIPs.[214]

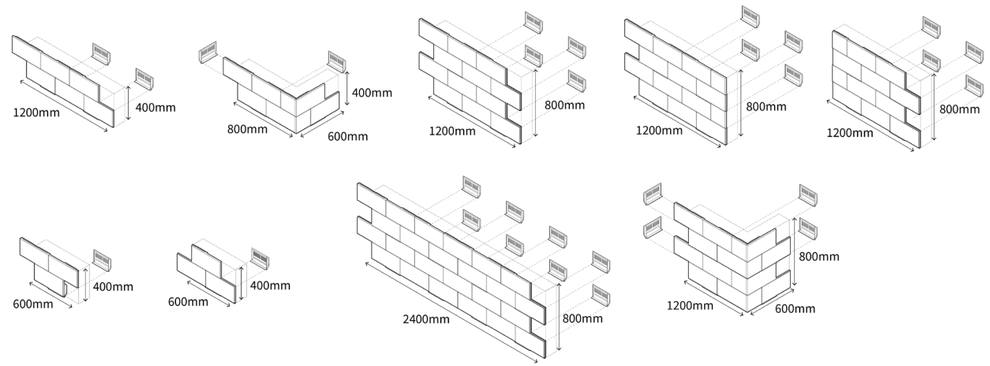


Figure 4.3.10: Catalogue of sizes and configurations for front exterior panels.

Variations in panel configurations allow them to form a near-complete building. Figure 4.3.11 highlights how the system addresses common assembly interfaces, namely corners, window or door openings, and panel-to-panel connections. This diagram also demonstrates the visual seamlessness granted by an interlocking assembly.

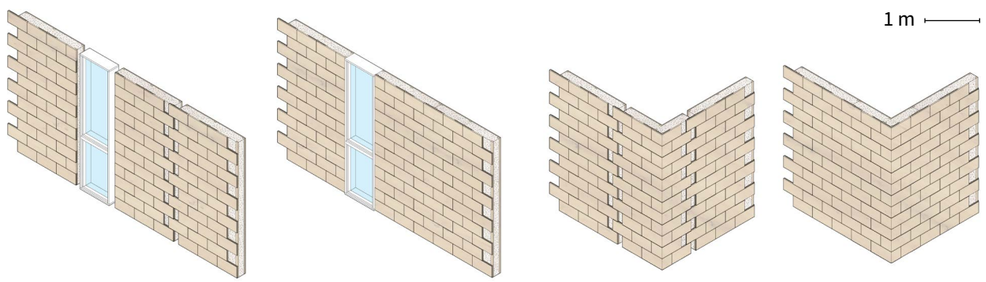


Figure 4.3.11: Diagram of typical interfaces found in a building. An interlocking pattern provides a seamless transition compared to a straight panel-to-panel adjacency, which would break pattern continuity with a vertical line.

213 Saxton, “Guide to Structural Insulated Panels (SIPs).”
214 Saxton.

Figure 4.3.12 provides a wall section showing the arrangement of all components in the system; details give insight into the shiplap stacking of façade panels and the integration of ventilation chambers. Robotic fabricated timber front panels act as the main interface and protection from exterior elements such as water. Ventilation at given points allows moisture to dry and escape from the exterior wall. Additional siding can be incorporated to further protect against water infiltration for more robust applications. The core mycelium composite provides a continuous layer of insulation and fire resistance. Air and vapour protection occurs on the interior side of the wall section, before the interior finish. This layer occurs outside the panel, like SIP panels, allowing it to seal and unify panel-to-panel connections. Ventilation chambers and hooks are vertically spaced evenly behind the front exterior panel. Robotic fabricated studs reduce thermal bridging by allowing the mycelium to weave through continuously. Assuming the exterior envelope successfully minimizes water infiltration and allows remaining moisture to escape the wall, the mycelium panel should last 20 years. This estimate is informed by the reported projected lifespan of interior mycelium product applications.[215]

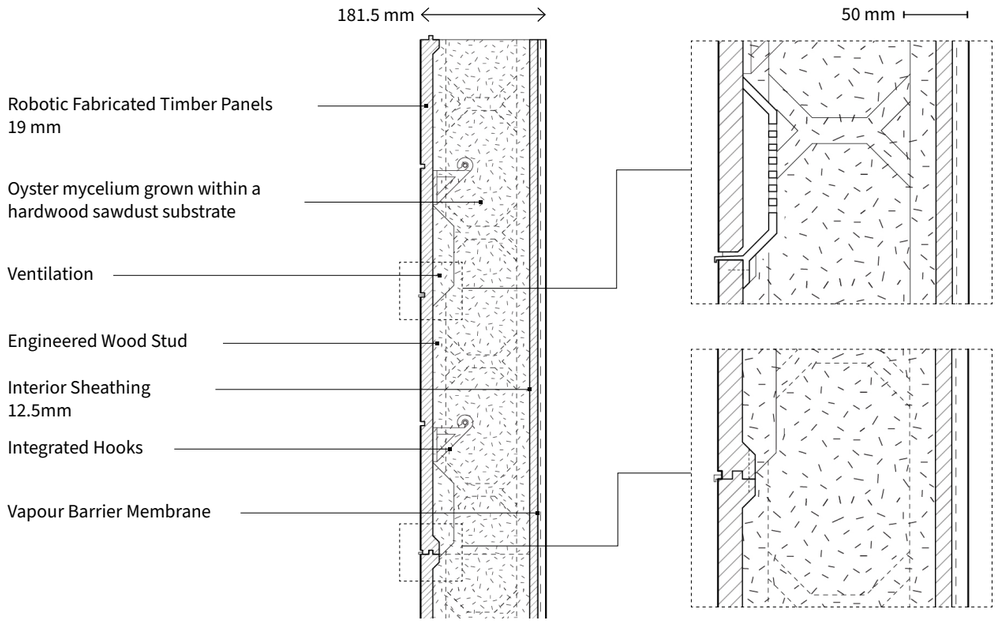


Figure 4.3.12: Section through prefabricated mycelium wall panel, showing each of its components, along with detailed callouts of stacked front modules and ventilation chambers.

215 Ioanna Protopapadaki and Samuel Kalika, “Building with Mushrooms,” *Critical Concrete* (blog), April 23, 2018.

4.4 Experiment 3 Results, Thermal Resistance

Digital Simulation

THERM software was utilized to simulate the thermal heat flow resistance of a mycelium composite wall panel, using its heat flow calculation and thermal renderings of the design. The software demonstrates how each design evolution impacted the thermal properties of the wall panel. For example, machined truss studs reduced thermal bridging by discouraging direct heat flow at these points. Tracking design evolutions with THERM ensured that introducing protruding components had negligible adverse impacts on the overall R-value of the wall system.

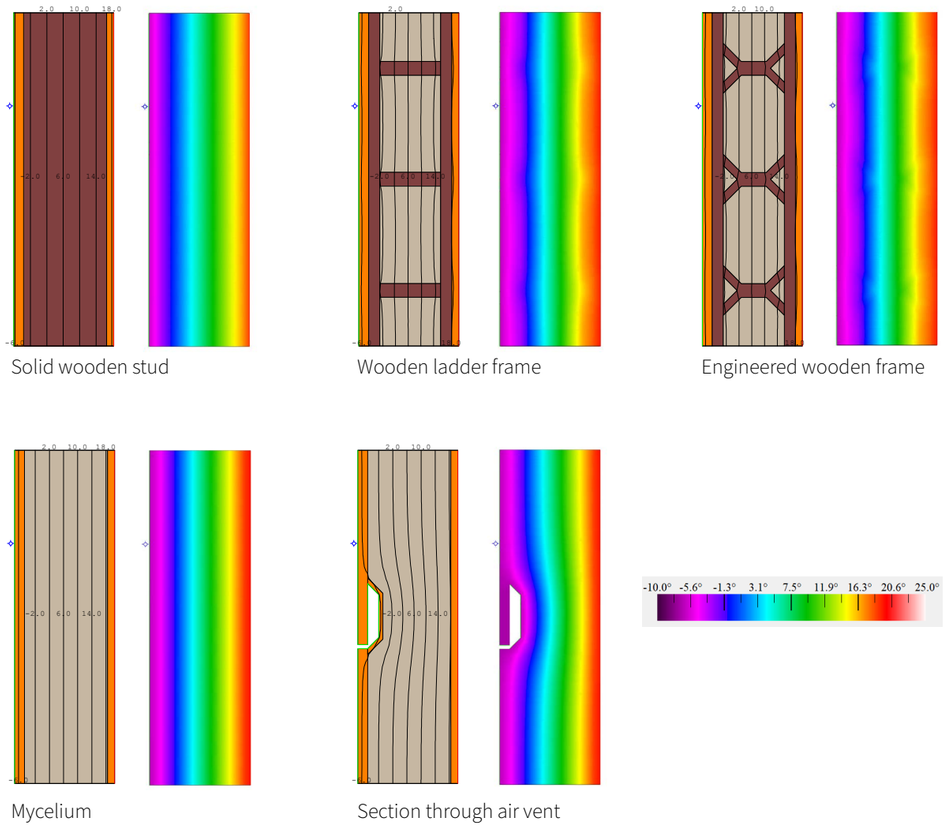


Figure 4.4.1: Results of THERM simulation of heat flow through wall section at vertical studs, and mycelium infill.

Physical Thermal Resistance Experiment

Once the final prototype mycelium wall was constructed, it was tested utilizing the cold box apparatus to extract the temperature difference between interior and exterior surfaces for calculation. To determine the heat flux coefficient for surface air films in the apparatus (*h*), the prototype was first filled with EPS, with a known *R*-value.

Figure 4.4.2 demonstrates the experimental temperature difference between the interior and exterior surfaces of the EPS wall assembly logged by the thermocouples over twelve hours. T_r remained constant at a mean temperature of 19.547°C (+/-0.2°C) throughout the experiment, however, T_1 and T_2 needed to stabilize before input into equation (4). This occurred by the six-hour mark. After which, the average of their temperature readings for the remaining duration was taken, with T_1 measured at -8.676°C, and T_2 measured at 18.473°C. By inserting these values into the combined equation (4), *h* was estimated as 6.333 W/m^2. This value was within the acceptable range of *h* for air, 0.25 -25 W/m^2.[216]

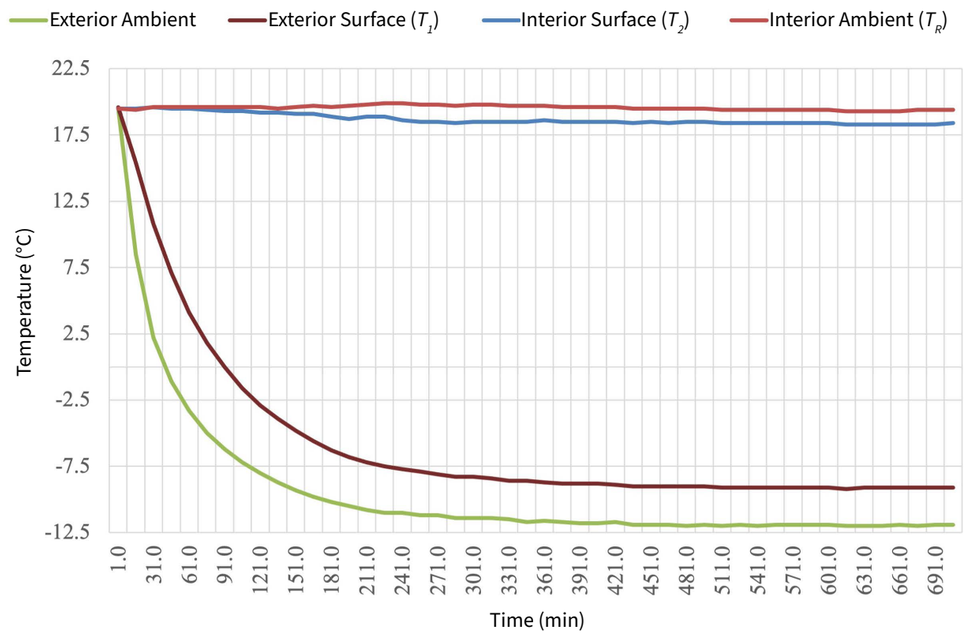


Figure 4.4.2: Graph showing the experimental temperature difference between interior and exterior surfaces of the EPS wall assembly logged by the thermocouples over 720 minutes.

216 Philip Kosky et al., "Chapter 12 - Mechanical Engineering," in Exploring Engineering (Third Edition), ed. Philip Kosky et al. (Boston: Academic Press, 2013), 259–81, https://doi.org/10.1016/B978-0-12-415891-7.00012-1.

Table 4.1 highlights the experimentally calculated thermal resistance *(R)* and conductivity (*k*) values through each tested assembly infill condition. The five infills tested were EPS insulation, air space, sawdust substrate, live mycelium, and heat-dried mycelium. The EPS provided the wall with the greatest total R-value, at 3.991 m^2k/W, while the hollow air wall had a relatively low R-value at 0.514 m^2k/W. Between these, the baked mycelium composite wall provided moderate heat flow resistance, at 1.767 m^2k/W. This shows that mycelium has potential as an alternative biodegradable insulator, though it is not as effective as EPS. The *k*-value of the baked mycelium composite was calculated as 0.092 W/mK, comparable to the *k*-value of mycelium composites in another study ranging from 0.0882 to 0.104 W/mK.[217] Composites in other publications have demonstrated greater insulating performance (lower *k*-value), such as mycelium insulation grown on wood shavings with a *k* of 0.055 W/mK.[218] This discrepancy may be due to differences in substrate type. Wood shavings being less dense than sawdust often correlates to a lower thermal conductivity.[219] Other explanations for the discrepancy could include the incomplete drying of the robust wall panel or reduced mycelium growth in areas of the wall.

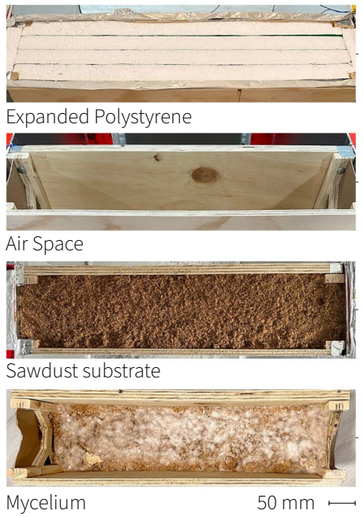
Assembly Infill Type	$(T_1 - T_2)$	$(T_r - T_2)$	*k* (material) (W/mK)	*R* (material) (m^2K/W)	*R* (assembly) (m^2K/W)
EPS (Reference)	27.149	1.074	0.038	3.6985	3.991
Air Space	17.168	5.278	0.521	0.270	0.514
Sawdust Substrate	22.320	2.250	0.105	1.334	1.578
Mycelium (live)	21.290	2.175	0.108	1.301	1.545
Mycelium (dried)	21.434	1.915	0.092	1.523	1.767

Table 4.1: Table highlighting the differences in core material and assembly R-value based on assembly type.

The increase in the R-value of the baked compared to non-baked mycelium composite from 1.301 to 1.523 m^2K/W confirms that mycelium insulation should be dried for best performance. This finding is in line with additional studies on the negative impacts of moisture on insulation.[220] The increased R-value of the baked mycelium compared to sawdust suggests that growing mycelium in a substrate marginally improves its thermal resistance. However, these findings are inconclusive as the sawdust carried high moisture content, so

217 Dias, Jayasinghe, and Waldmann, "Investigation of Mycelium-Miscanthus Composites as Building Insulation Material."
218 Wimmers et al., "Fundamental Studies for Designing Insulation Panels from Wood Shavings and Filamentous Fungi."
219 Shawn C. Stacy et al., "The Effects of Density on Thermal Conductivity and Absorption Coefficient for Consolidated Aluminum Nanoparticles," *International Journal of Heat and Mass Transfer* 73 (June 1, 2014): 595–99, https://doi.org/10.1016/j.ijheatmasstransfer.2014.02.050.
220 David Stassi, "What You Need to Know About Moisture and Insulation," Building Enclosure, April 30, 2018, https://www.buildingenclosureonline.com/articles/87569-what-you-need-to-know-about-moisture-and-insulation.

it is unclear whether drying or mycelial growth caused the increase. One study found that adding mycelium resulted in a 10% reduction in the heat its grain substrate released when subjected to fire.[221] These findings show potential for future research to investigate the exact correlations between mycelium growth amount and thermal resistance.



Assembly Infill Type	*k* (material) (W/mK)	*R* (material) (m^2K/W)	*R* (assembly) (m^2K/W)
EPS (Reference)	0.038	3.6985	3.991
Air Space	0.521	0.270	0.514
Sawdust Substrate	0.105	1.334	1.578
Mycelium (live)	0.108	1.301	1.545
Mycelium (dried)	0.092	1.523	1.767

Figure 4.4.3: Visual reference highlighting the test specimens represented in each row of Table 4.1.

221 Jones et al., "Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium - Biomass Composite Materials."

This research aimed to test the potential of mycelium within a natural prefabricated wall panel with reduced layers compared to typical construction. The strategy was to explore the material's growth patterns and performance properties through three experiments and prototype a wall assembly formwork catered to these properties.

This research began with a literature review of mycelium composites' growth patterns, architectural applications, and performance properties. It was validated that certain mycelium species prefer certain substrates and specific environmental conditions for growth and colonization. In construction and industrial production technologies, formworks are used to provide amorphous materials like concrete and ceramics their shape as they cure. They were also introduced and adapted here to improve mycelium growth by controlling air exchange and moisture retention. Applications were explored that integrated the mycelium with its formwork, however, studies have not yet explored mycelium's integration within a prefabricated wall panel. Mycelium excels as a thermal insulator and is comparable to common insulation products while also being lightweight and naturally fire-resistant. However, as a wall system, mycelium composites require additional structural support and environmental protection. Thankfully, mycelium's natural adhesive properties allow it to combine efficiently with structural and protective members. ICF and SIP construction systems serve as valid precedents for a mycelium wall system due to their construction methods and the organization of their materials by performance properties. Though ICF and SIPs reduce parts compared to traditional systems, they are not considered sustainable due to their selection of materials such as EPS insulation and concrete.

This thesis conducted two preliminary experiments which examined mycelium's growth patterns, and material adhesion in an architectural formwork.

The first experiment tested mycelium substrate supplementation as a key variable for growth amount and speed. A visual analysis of documented results confirmed that a 15% ratio of wheat bran to sawdust substrate was optimal for mycelium growth. This research focused on wheat bran and sawdust but could have benefited from a wider range of substrate tests to select the substrate most suitable for insulation. Straw was another viable substrate for oyster mycelium which demonstrated a low density (57–99 kg/m^3) and low thermal conductivity (0.04–0.08W/mK).[222] Future research should consider testing growth patterns of many substrates to determine which is both most efficient and applicable to performance goals.

222 Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries."

The second experiment tested different types of panel materials as variables for the interfacial adhesion with mycelium composite. It was confirmed that wood-based products adhered strongest to live mycelium composites as they grew. Some of this adhesion was lost after the mycelium was baked, but this loss was mitigated by integrating hooks and strings embedded within the mycelium. Possible next steps would be conducting tests on a broader scope of materials and textures to catalogue their bonding capacity with mycelium.

Design Development

The initial design was intended to be a structural modular block catered for mycelium growth that can aggregate into a larger assembly. The assembly sequencing of the original scheme was deemed inefficient and complex with many parts. Therefore, the design developed into a larger interlocking prefabricated panel within which mycelium could be sequentially poured and grown. Initially, the support structure was considered a series of dowels running vertically and laterally in each block to reinforce the module in both directions (Figure 4.3.1). Their design evolved to vertical engineered studs placed at typical stud spacing, while lateral loads were covered by the primary structural face panels (Figure 4.3.5). This design development process dramatically simplified and reduced the number of parts within the system.

Full-scale Prototype Wall

Based on the final design, a full-scale sample prototype wall was constructed for thermal testing. As an original objective, the biodegradability of the model was largely maintained, apart from the use of wood glue and a steel bolted connection between the studs and the front panel. This can be replaced in future iterations by wood joinery techniques. The large volume of space within the wall required a large-scale substrate pasteurization and a plentiful stock of fully inoculated live mycelium to fill it. Approximately 12 grow bags plus 4 additional 452mm L x 300mm W x 89mm H monotubs of mycelium were used, along with two 19L buckets of new pasteurized substrate. This quantity was not initially accounted for, which meant that half the fully inoculated substrate was poured two weeks after the first half. Though the mycelia grew in the wall for its intended four-week period, this may have caused inaccuracies in thermal performance results. Initial planning for the large volume of substrate before the experiment would have mitigated this issue.

Due to limited equipment, the method used for baking the full-scale prototype mycelium wall was to repurpose the cold box apparatus and apply heat to the wall via a residential

space heater. Exterior surfaces reached 60°C over 24 hours, and the panel lost 5% of its weight following baking, however some of the core mycelium kept its moisture. Access to a curing chamber or oven to heat the panel to 80°C for 24 hours would ensure more thorough drying.

Physical experimentation with mycelium biocomposites revealed a requirement for specific features to be integrated into the design of the wall system. The first feature was a concealed vent for fresh air exchange with the mycelium growing within the wall. The second feature was a series of hooks with a rope which would be embedded into the mycelium, tying it to the exterior wall irrespective of shrinkage. The integrated hooks were successful as no major shrinkage gaps were observed after the mycelium in the wall was baked, though results were inconclusive at this scale. The benefit of the vents in the assembly for growth remained unclear, although conceptually they would still allow any moisture which gets in the wall to be released. Future research should compare mycelium growth within an airtight and ventilated wall to prove the benefit of ventilation.

Key Limitation, Contamination

Contamination was an issue encountered throughout all stages of experimentation. Reishi mycelium was investigated but abandoned, as it did not grow at temperatures above 22°C, and Trichoderma was found in many samples. For oyster mycelium, regardless of pasteurization, higher percentages of wheat bran supplemented with sawdust caused a greater risk of darkened mold spots in the sample. Oyster mycelium was not always successful at outcompeting these darker spots over time, leading to regions of little to no mycelial growth within the sample, as seen in Figure 5.1. Additionally, many grow bags and monotubs used for mycelial growth became contaminated with mold if sealed incorrectly.



Figure 5.1.1: A dark patch of limited mycelium growth developed in substrate supplemented with 20% wheat bran after two weeks, suggesting a competing contaminant.

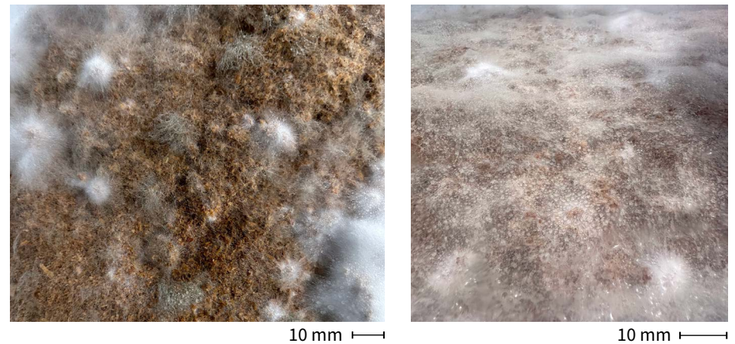


Figure 5.1.2: Left: Improperly sealed growth tub caused rapid contamination of a grey cobweb-like mold on the top surface. Right: Hydrogen Peroxide spray allowed the mycelium to eventually fully colonize the substrate.

Growth containers made of plywood required more thorough sterilization, as contaminants were found to seep easily into the mycelium substrate during growth and spread to the plywood. Building a specialized growth tent provided a sterile environment, however the space was still prone to contamination over time. As shown in Figure 5.3, plywood exposed to high levels of moisture in still air was highly susceptible to contamination. Since high humidity is required for mycelium growth, methods of filtering ventilation to the growing mycelium samples must be considered. The growth tent's failure to mitigate contamination was likely due to inadequate consideration of filtered ventilation and exhaust. Additionally, the final prototype's formwork further reduced airflow to the mycelium in an already poorly ventilated environment, causing localized contamination. The resulting mycelium growth discrepancies in the wall may have partially hindered its tested thermal performance. These limitations can be resolved by implementing a proper ventilation and exhaust system to provide fresh air through the environment to regulate its moisture. Future research should take the utmost care with sterilization to prevent contamination of mycelium composites.

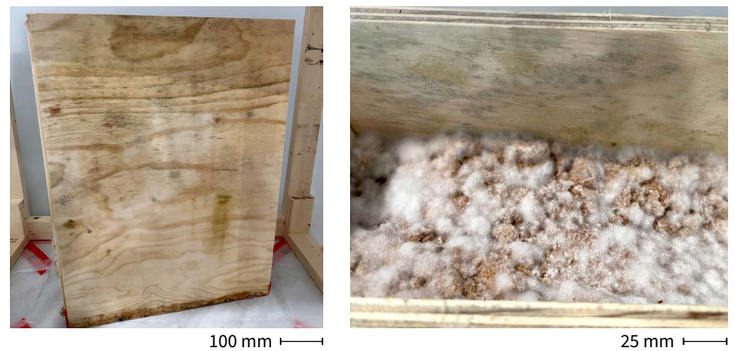


Figure 5.1.3: Poorly ventilated growth chamber with excessive Relative Humidity caused plywood panel to become contaminated after two weeks.

Thermal Experimentation

This research tested the thermal performance of the prototype assembly by measuring resistance to heat flow (R-Value) from indoors to outdoors, through simulation and experimentation. Additional test methods beyond this research including structural and fire resistance tests will be integral to the designed prototype wall becoming an architectural product. These tests were not performed within the scope of this thesis due to time constraints.

THERM was used to evaluate the thermal performance of various areas of the assembly through digital IR renderings of the wall sections. The software successfully visualized the implications each design iteration had on the thermal properties of the wall. For future research, utilization of THERM earlier in the design process would provide further insight into design opportunities for greater performance improvements.

The thermal performance of the assembly was measured via a physical cold box experiment. The heat transfer coefficient for the setup and the temperature difference between the wall's two outer surfaces had to be measured to determine the assembly's R-value. Since it was not possible to measure the heat flux of the proposed design due to a lack of measuring equipment, a parallel assembly filled with EPS insulation was tested to solve for the experimental heat flux density. An assumption that had to be made with this setup to simplify calculations was that boundary conditions within the wall with differential heat loss were considered identical. The R-value of this assembly could be accurately estimated since the thermal conductivity and thickness of each material within the EPS assembly were known. Once the heat flux was determined, it was input into the same equation for the mycelium assembly to solve for its R-value. This experiment successfully determined the R-value of the prototype mycelium assembly as 1.767 m^2K/W, compared to 3.991 m^2K/W for the EPS assembly, 1.578 m^2K/W with sawdust, and 0.514 m^2K/W with still air. These results show that mycelium composite has some potential as a natural insulator, though it is not as effective as EPS. The findings also provided early signs that adding mycelial growth to a substrate marginally improves its thermal resistance (1.523 m^2K/W compared to 1.301 m^2K/W). However, these results can only be cross-validated by measuring the heat transfer coefficient for the experiment using the proper equipment. Hence, future research should consider utilizing a heat flux sensor to verify the accuracy of results.

Chapter 6 - Conclusion

This section will discuss the outcomes of this thesis, highlighting key contributions and areas for future research. First, a summary of each chapter will be provided, followed by a conclusion on the findings of this research. Next, the key contributions of this thesis to the architecture, engineering and construction fields will be described. Finally, recommendations will be provided on avenues for future research.

6.1 Summary

The first chapter of this thesis described the primary motivations for this research. Traditional construction strategies for addressing the complex needs which building façades must mediate, such as multiple wall layers, are practically and environmentally inefficient. Mycelium biocomposites can combine effective performance properties for wall systems with reduced layers while being biodegradable. This thesis introduced a novel methodology for utilizing construction prototyping to integrate mycelium biocomposites within a natural prefabricated wall panel.

The second chapter provided a literature review of mycelium biocomposites' growth patterns, architectural applications, and performance properties. Formworks were adapted in this research from their traditional use in construction and production technologies, to improve mycelium growth by controlling air exchange and moisture retention. Applications which integrated the mycelium with its form were explored, however, studies have not yet explored mycelium's integration within a prefabricated wall panel.

The third chapter outlined the methodology of this thesis. Digitally and physically modelled prototypes were produced for a prefabricated wall panel which supports a growing mycelium composite core with minimal components. Digital simulations of the wall panel's thermal resistance were also conducted. Three physical experiments supported the construction prototyping process. Mycelium's growth patterns were tested by varying the substrate supplementation ratio in different samples. The interfacial adhesion of mycelium composites with various materials was tested through specialized growth containers. A full-scale prototype panel of the final design was constructed to test its thermal resistance performance.

The fourth chapter discussed the documented results of each physical experiment, beginning with the supplementation experiment, followed by the adhesion experiment. Afterward, the evolution of the mycelium wall panel design was visualized and described. Digital simulation rendered the projected heat flow through the wall assembly at critical points to analyze the impacts of design decisions made with the construction prototyping. The experimental thermal resistance of the final full-scale mycelium biocomposite wall panel was compared to that of alternative assemblies. The fifth chapter discussed the key findings and limitations discovered in this research.

6.2 Conclusion

This thesis introduced a novel methodology for utilizing construction prototyping to integrate mycelium biocomposites within a natural prefabricated wall panel. Nine digitally and physically modelled iterations were produced for a permanent structural wall formwork which supports a growing mycelium composite core with minimal components. Three physical experiments supported the design development, along with digital simulations of the wall panel's thermal resistance.

Progressive prototyping ensured the mycelium biocomposite wall system featured minimal parts with practical assembly sequencing while remaining biodegradable. By integrating mycelium biocomposites, this wall system achieves its function with fewer material layers and is more biodegradable than typical light frame construction. The need for temporary formwork was successfully nullified through prototyping by adapting a permanent structural form to suit requirements for mycelium growth such as air exchange. Mycelium's insulating and fire-resistant properties were harnessed in a wall system which provided structural support and environmental protection. By varying the substrate supplementation and visually comparing mycelium growth over 22 days, a 15% wheat bran to sawdust ratio resulted in the fastest, most consistent growth. Testing mycelium's adhesion to adjacent materials yielded that mycelium synergized best with wood, however, additional protruding elements were required to compensate for differential shrinkage. From testing the thermal resistance of the full-scale prototype panel, the R-value of the mycelium composite was 1.523 m^2K/W, compared to 3.698 m^2K/W for standard EPS insulation. During mycelium growth in the prototype panel, high humidity and inadequate ventilation led to a risk of contamination in both the mycelium composite and the wooden formwork.

In summary, the methodology of progressive construction prototyping introduced in this research allowed the development of a natural prefabricated wall system which integrated growing mycelium biocomposites. Physical experimentation in this thesis revealed key limitations, which may prompt researchers to explore alternative design strategies to

mitigate these limitations. Despite these limitations, mycelium showed the potential to be integrated within a prefabricated wall while retaining its simplicity and biodegradability. This thesis guides architects, engineers and fabricators to develop comprehensive building envelope designs based on a material's full capability, by harnessing prototyping and material experimentation in the early design stages. As the climate crisis raises demands for environmental stewardship, working closely with materials can aid a collective transition towards a more adaptive and sustainable built environment.

6.3 Contributions

- **A novel methodology for mycelium biocomposite material assemblies:** A new methodology was introduced for utilizing construction prototyping to integrate a new material (mycelium biocomposites) within the design of a natural prefabricated wall panel.

- **Combining digital and physical prototyping to optimize the growth and performance of mycelium:** Applied physical prototyping methods and digital thermal performance simulations with mycelium biocomposites, to accommodate their specific growth requirements and performance properties in a permanent integrated formwork. Progressive construction prototyping ensured the mycelium biocomposite wall system featured minimal parts with practical assembly sequencing. Simulation software informed the design of a modified ladder frame support structure which allows mycelium composite to weave through it and mitigates any localized thermal bridging.

- **Simplification of wall assemblies with fewer material layers:** Due to the combined properties of mycelium biocomposites, this wall system achieves its function with fewer material layers than typical light frame construction.

- **Interfacial adhesion within the wall assembly:** Testing the interfacial adhesion of mycelium composites with various materials (e.g., millboard, plywood, clay, wood PLA) yielded that mycelium adhered best with wood. However, additional adhesion methods were required to compensate for differential shrinkage. Protruding hook elements with string were implemented to maintain adhesion between the mycelium composite and its interfaced material. These elements successfully compensated for any adhesion loss from differential shrinkage caused by the drying process.

- **Façade-integrated ventilation chambers to provide air exchange for optimal mycelium growth:** The permanent structural form was adapted to provide necessary air exchange for the growing mycelium through concealed ventilation grills in the façade. These grills were designed to protect from moisture infiltration while allowing moisture to escape from the wall assembly to the exterior gradually.

6.4 Research Outlook

This research demonstrated the potential of applying mycelium biomaterials as a prefabricated wall assembly. This architectural application can be further developed through numerous research avenues. These include performing a comprehensive life cycle analysis, cataloguing different textures for mycelium adhesion, and alternative designs to optimize fresh air exchange (FAE). Additionally, this research provides a framework for applying any standard performance test method to a new material or assembly by demonstrating a thermal resistance test. Further research on structural failure modes, fire resistance, and environmental degradation will be crucial for the material's development as a product.

6.4.1 Life Cycle Analysis

A Life Cycle Analysis (LCA) can be performed to further develop the case for a new mycelium wall assembly as a viable product in the current construction market. The objective would be to quantify the carbon costs throughout its life cycle and compare them numerically to other assemblies. This method will help identify the potential for the system as a more sustainable alternative within the current market. In an LCA, quantities of materials and processes are gathered into an inventory and multiplied by their estimated environmental impact to determine a building's overall embodied carbon.[223] Environmental impact is typically estimated using a material's Global Warming Potential (GWP), measured in $kgCO_2$ equivalent, typically per square metre. These values refer to the A1 to A3 stages of a material's life cycle, which cover its extraction, transportation to the factory, and manufacturing.[224] In this case, where a mycelium assembly does not require additional formwork, its substrate would be input, along with all other primary components of the wall. A sample calculation of the wall would be as follows, for any given sample size (800 x 619 x 180mm sample used here):

43 kg plywood	x	0.3814 $kgCO_2e$ /kg plywood	= 16.4 $kgCO_2e$
27 kg hardwood sawdust	x	0.0773 $kgCO_2e$ /kg sawdust	= 2.08 $kgCO_2e$

The total embodied carbon may then be compared with other wall assemblies. For greater accuracy, future research should seek to quantify energy use associated with operating a conditioned space for growing mycelium, and for post-processing the mycelium.

223 Monica Huang, "Life Cycle Assessment of Buildings: A Practice Guide," May 30, 2018, https://digital.lib.washington.edu:443/researchworks/handle/1773/41885.
224 "Buildings & Infrastructure Priority Actions for Sustainability: Embodied Carbon, Timber," ARUP, June 5, 2023, https://www.istructe.org/IStructE/media/Public/Resources/ARUP-Embodied-carbon-timber_1.pdf.

Studies have utilized various software for estimating the carbon impacts of construction assemblies.[225] Among these is *One Click LCA*, which provides a database of Environmental Product Declarations (EPDs) containing data on materials' environmental impacts during each life cycle stage.[226] The software includes building life cycle simulation and calculation tools, and templates for generating EPDs for new building products.[227] *EC3* similarly provides a database and automates life cycle assessment calculations.[228] Developing an EPD for a mycelium building product would allow architects to calculate its life cycle carbon impacts for a whole building.

6.4.2 Costing Analysis

An estimation of the construction cost for a mycelium assembly would be beneficial in determining the economic feasibility of building with this product in the current market. SIP construction can serve as a baseline for estimating the cost per square foot, as they are similarly prefabricated offsite, and uncommon versus light frame construction in terms of labour. One study estimated a 5 to 15% increase in the cost of building a home compared to traditional light frame construction.[229] Mycelium insulation panels are beginning to emerge as building products, therefore their pricing may be investigated and compared with other insulation such as EPS. A one-inch-thick board currently costs $0.66 per square foot, compared to $0.42 per square foot for EPS.[230] This is expected because mycelium is a new material; although it often costs more upfront, new materials can offer additional long-term benefits.[231] An in-depth analysis of mycelium's production logistics through its lifecycle may uncover specific opportunities to offset these cost premiums.

225 Beznogova et al., "New Design Resources for Embodied Carbon Targets."
226 "LCA & EPDs for Construction & Manufacturing | One Click LCA," https://oneclicklca.com.
227 "LCA & EPDs for Construction & Manufacturing | One Click LCA," https://oneclicklca.com.
228 "Embodied Carbon in Construction Calculator (EC3)," *Carbon Leadership Forum* (blog), October 6, 2021, https://carbonleadershipforum.org/ec3-tool/.
229 David Wright, "SIPs Building – Mother Earth News," Mother Earth News, August 3, 2011, https://www.motherearthnews.com/diy/structural-insulated-panels-zm0z11zphe/.
230 Terry Schultz, "What Is Mycelium Insulation?," Homedit, November 27, 2023, https://www.homedit.com/insulation/what-is-mycelium-insulation/.
231 Charles McGowan, "The Benefits of Using Architectural Zinc in Roofing and Wall Claddings," Construction Specifier, June 3, 2023, https://www.constructionspecifier.com/the-benefits-of-using-architectural-zinc-in-roofing-and-wall-claddings/.

6.4.3 Cataloguing Textures for Adhesion

Investigating various textures at multiple scales can unlock new design possibilities for adhering mycelium to complementary materials. In “Symbiocene Living”, PLP Labs developed 3D-printed wood filament block moulds for integrated mycelium growth.[232] The form was customized with a specific texture, which mitigated shrinkage that would otherwise be present if the mycelium composite’s formwork was separate.[233] Additive manufacturing inherently provides materials with a layered texture, which can be harnessed for numerous applications including promoting adhesion.[234] In this vein, future research may begin to catalogue textures and porosities at a microscopic scale for their effects on adhesion with mycelium.



Figure 6.4.1: Mycelium integrated within 3D-printed wood filament blocks, part of “Symbiocene Living” by PLP Labs.

232 “Symbiocene Living: Exploring the Potential of Mycelium Blocks for Sustainable Architecture,” ArchDaily, July 20, 2023, https://www.archdaily.com/1004032/symbiocene-living-exploring-the-potential-of-mycelium-blocks-for-sustainable-architecture.
233 “Symbiocene Living: Exploring the Potential of Mycelium Blocks for Sustainable Architecture.”
234 Tatiana Pereira, Sónia Barroso, and Maria M. Gil, “Food Texture Design by 3D Printing: A Review,” *Foods* 10, no. 2 (February 2021): 320, https://doi.org/10.3390/foods10020320.

6.4.4 Alternative Designs for Mycelium

Consideration of ventilation carries numerous benefits when designing an integrated form for mycelium. Promoting high amounts of fresh air exchange throughout a substrate can enhance mycelium growth, particularly on its surface.[235] Additionally, ventilation has been noted in general to prevent mold buildup and contamination by regulating relative humidity and replacing stale air with fresh air.[236] The application of textiles in architecture is being investigated, as they are often organic and highly porous materials. They also carry high tensile strength and are customizable in their shape.[237] Notably, designers have begun investigating textiles as formwork for mycelium. One architect investigated woven scaffolds using the tri-axial Kagome weaving method, to create a basket-like scaffold for substrate inoculated with mycelium.[238] This technique allowed for clarity of controlling shape and a high degree of customization.[239] “The Living Room” by BBE is a prototype bioknit installation where woven Herdwick wool shapes mycelium growth to create solid double-curved forms at a large scale.[240]

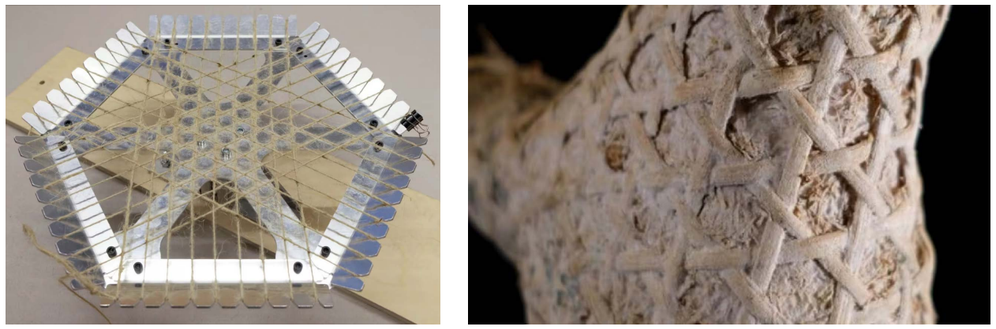


Figure 6.4.2: Fibres woven using Kagome weaving techniques form a basket-like scaffold for mycelium-inoculated substrate, by Phil Ayres.

235 Houette et al., *Growing Myceliated Facades - Manufacturing and Exposing Experimental Panels in a Facade Setting*.
236 Alaa Alaidroos and Ibrahim Mosly, “Preventing Mold Growth and Maintaining Acceptable Indoor Air Quality for Educational Buildings Operating with High Mechanical Ventilation Rates in Hot and Humid Climates,” *Air Quality, Atmosphere & Health* 16, no. 2 (February 1, 2023): 341–61, https://doi.org/10.1007/s11869-022-01277-x.
237 ATA, “Fabric Structures,” Fabric Architecture Magazine, April 1, 2009, https://fabricarchitecturemag.com/2009/04/01/fabric-structures/.
238 Adam Jacobson, “Why Fungi Could Be the Future of Environmentally Sustainable Building Materials,” *CBC Radio*, February 28, 2020, https://www.cbc.ca/radio/spark/why-fungi-could-be-the-future-of-environmentally-sustainable-building-materials-1.5479660.
239 “Why Fungi Could Be the Future of Environmentally Sustainable Building Materials.”
240 “The Living Room – HBBE,” http://bbe.ac.uk/the-living-room/.



Figure 6.4.3: Knitted yarn provides the undulating form for grown mycelium in an interactive installaltion. By Hub for Biotechnology in the Built Environment (BBE).

Figure 6.4.4 describes an alternative design sequencing concept for constructing the mycelium composite wall panel developed in this research. Here, a light woven bio-textile is integrated for greater ventilation during the growth stage. The process is to take place off-site, in a controlled environment. A sterilized ventilated tent would provide a barrier against contamination and moisture loss during the early growth stages. First, engineered timber studs are secured to an interior plywood panel, providing a base to support the woven bio-textile. The textile is wrapped around the front resulting in a “basket” which is then sterilized in preparation for the mycelium. The mycelium-inoculated substrate is fully poured into the form and gently evened out with a trowel. The panel is then set to grow under controlled temperature and humidity for four weeks within which time it should consume the basket. Then, the mycelium panel is baked, resulting in a controlled shrinkage gap at the front. Interlocking ventilated front faces are installed for the full height, completing the prefabricated panel.

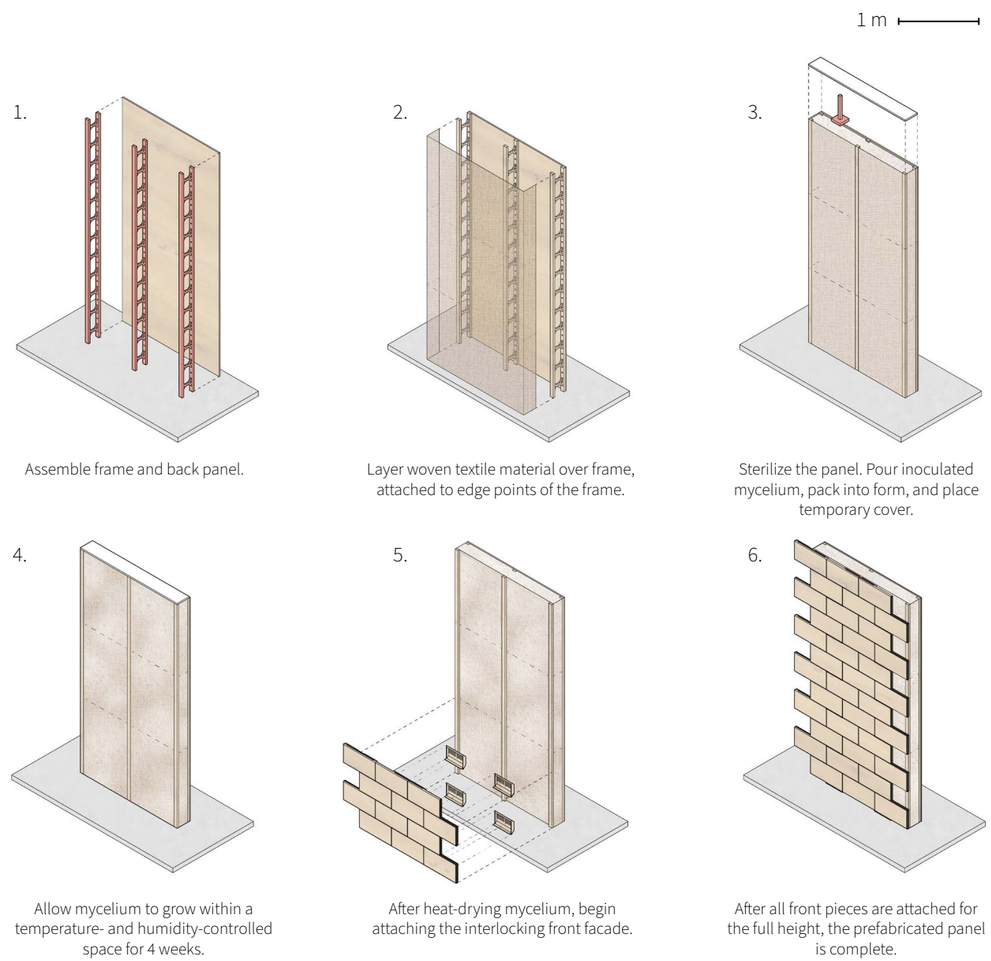


Figure 6.4.4: Alternative sequencing diagram for assembling the mycelium-composite wall panel, incorporating light bio-textiles to provide form and air exchange for the mycelium during growth, after which exterior timber panels are installed.


Sporing
Germination
Mycelium
Extract
Cultivate
Upscale
800mm
619mm
180mm



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Appendix

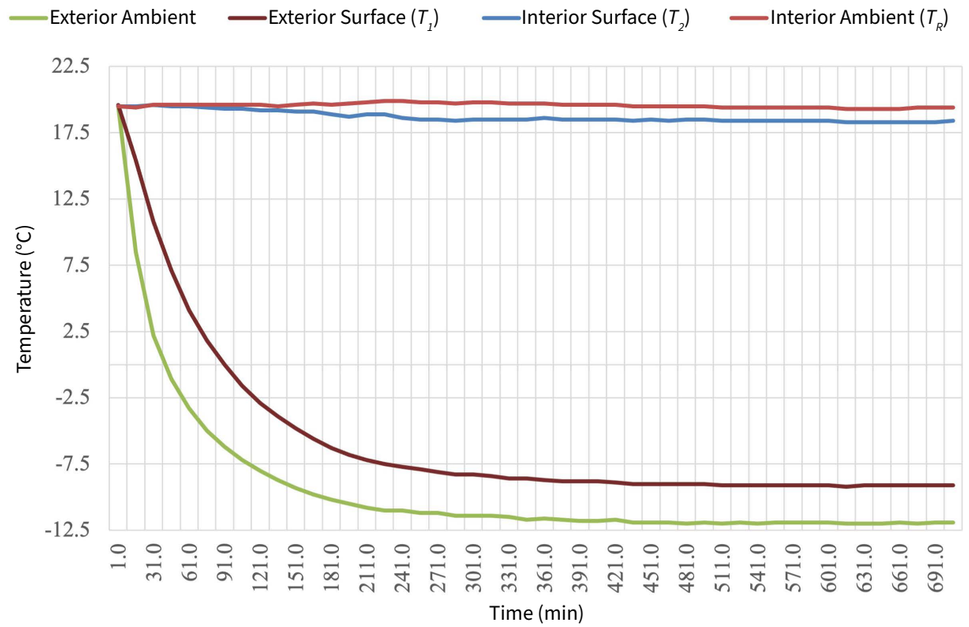


Figure A.1: Graph showing the experimental temperature difference between interior and exterior surfaces of the EPS wall assembly logged by the thermocouples over 720 minutes.

Heat Transfer Coefficient Calculations (EPS Assembly as base reference):

$$\frac{(T_2-T_1)}{\sum R} = h(T_r - T_2) \tag{4}$$

$$\frac{\left(18.473°\mathrm{C} - (-8.676°\mathrm{C})\right)}{3.991\ \mathrm{m^2K/W}} = h(19.547°\mathrm{C} - 18.473°\mathrm{C})$$

$$\frac{27.149°\mathrm{C}}{3.991\ \mathrm{m^2K/W}} = h(1.074°\mathrm{C})$$

$$6.802\ \mathrm{W/\ m^2} = h(1.074°\mathrm{C})$$

$$\frac{6.802\ \mathrm{W/\ m^2}}{1.074°\mathrm{C}} = h$$

$$6.333\ \mathrm{W/\ m^2K} = h$$

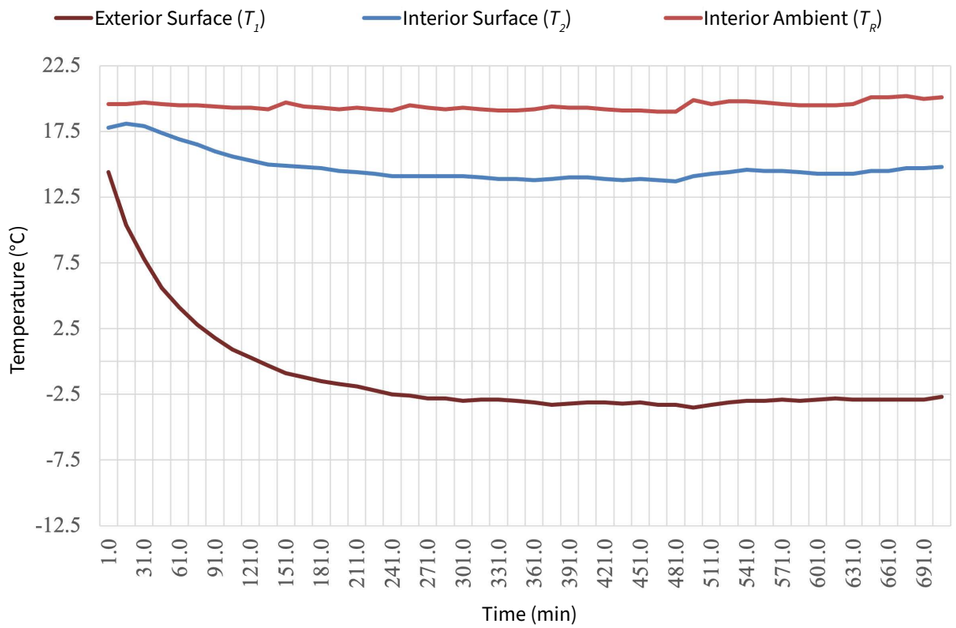


Figure A.2: Graph showing the experimental temperature difference between interior and exterior surfaces of the Air Space wall assembly logged by the thermocouples over 720 minutes.

R-value of Assembly with Air Space:

$$\frac{(T_2-T_1)}{\sum R} = h(T_r - T_2) \quad (4)$$

$$\frac{\left(14.233°\text{C} - (-2.936°\text{C})\right)}{\sum R} = h(19.511°\text{C} - 14.233°\text{C})$$

$$\frac{17.168°\text{C}}{\sum R} = 6.333\ \text{W/ m}^2\text{K}(5.278°\text{C})$$

$$\frac{17.168°\text{C}}{\sum R} = 33.420\ \text{W/m}^2$$

$$\frac{17.168°\text{C}}{33.420\ \text{W/m}^2} = \sum R$$

$$0.514\ \text{m}^2\text{K/W} = \sum R$$

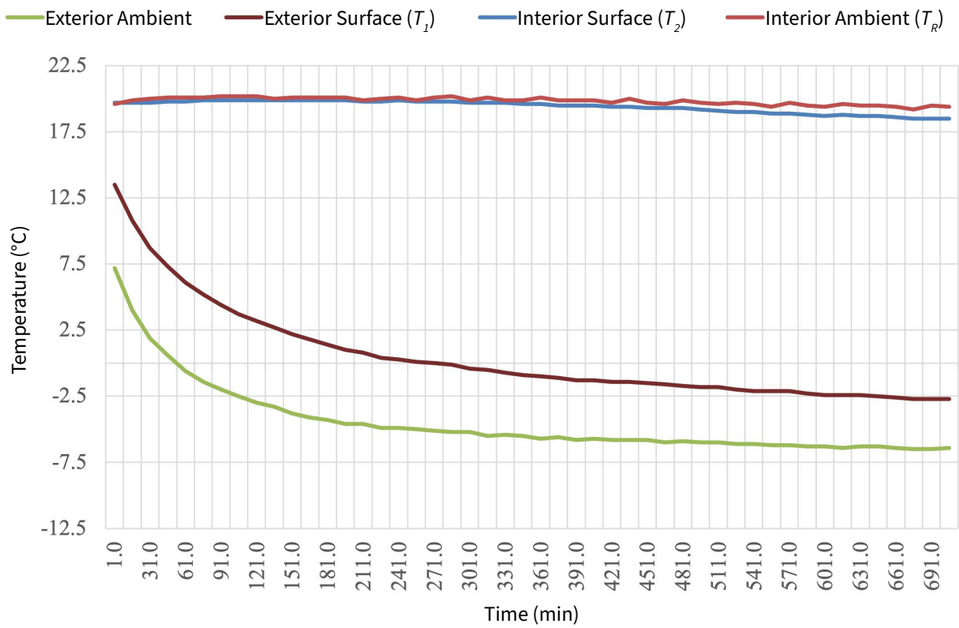


Figure A.3: Graph showing the experimental temperature difference between interior and exterior surfaces of the Sawdust wall assembly logged by the thermocouples over 720 minutes.

R-value of Sawdust Assembly:

$$\frac{(T_2-T_1)}{\sum R} = h(T_r - T_2) \quad (4)$$

$$\frac{\left(17.721°\text{C} - (-4.600°\text{C})\right)}{\sum R} = h(19.954°\text{C} - 17.721°\text{C})$$

$$\frac{22.321°\text{C}}{\sum R} = 6.333\ \text{W/m}^2\text{K}(2.233°\text{C})$$

$$\frac{17.168°\text{C}}{\sum R} = 14.141\ \text{W/m}^2$$

$$\frac{17.168°\text{C}}{14.141\ \text{W/m}^2} = \sum R$$

$$1.578\ \text{m}^2\text{K/W} = \sum R$$

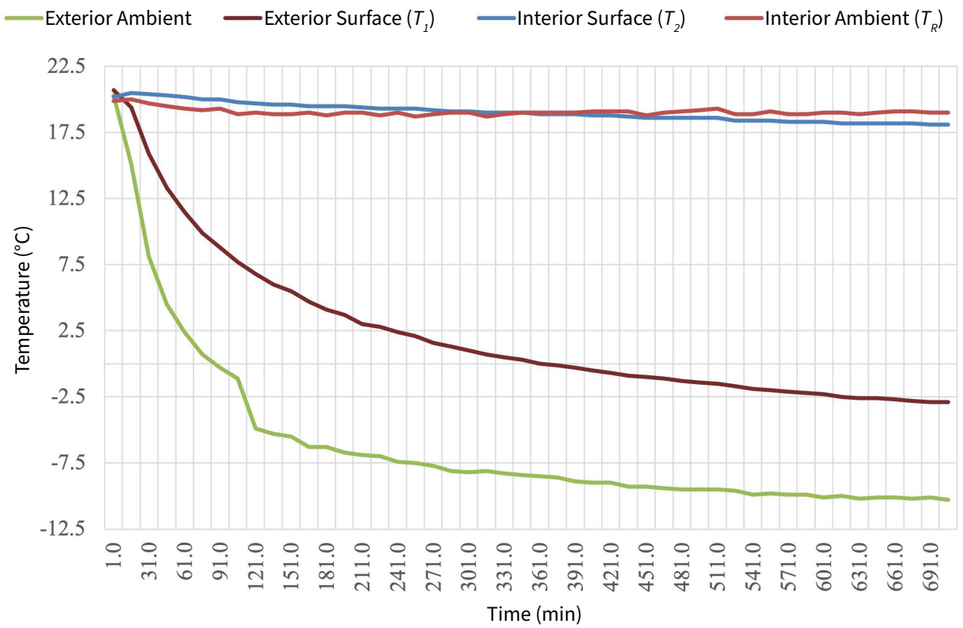


Figure A.4: Graph showing the experimental temperature difference between interior and exterior surfaces of the Live Mycelium wall assembly logged by the thermocouples over 720 minutes.

R-value of Mycelium Assembly (Live):

$$\frac{(T_2 - T_1)}{\sum R} = h(T_r - T_2) \quad (4)$$

$$\frac{\left(17.066°\text{C} - (-4.221°\text{C})\right)}{\sum R} = h(19.242°\text{C} - 17.066°\text{C})$$

$$\frac{21.287°\text{C}}{\sum R} = 6.333\ \text{W/m}^2\text{K}(2.176°\text{C})$$

$$\frac{21.287°\text{C}}{\sum R} = 13.781\ \text{W/m}^2$$

$$\frac{21.287°\text{C}}{13.781\ \text{W/m}^2} = \sum R$$

$$1.545\ \text{m}^2\text{K/W} = \sum R$$

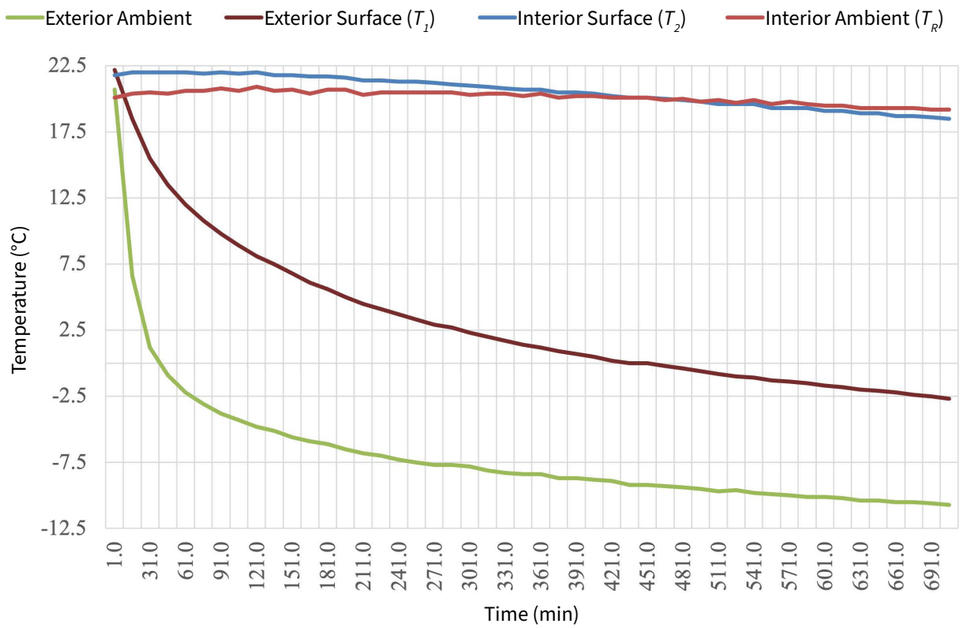


Figure A.5: Graph showing the experimental temperature difference between interior and exterior surfaces of the Dried Mycelium wall assembly logged by the thermocouples over 720 minutes.

R-value of Mycelium Assembly (Dried):

$$\frac{(T_2 - T_1)}{\sum R} = h(T_r - T_2) \quad (4)$$

$$\frac{\left(17.538°\text{C} - (-3.890°\text{C})\right)}{\sum R} = h(19.454°\text{C} - 17.538°\text{C})$$

$$\frac{21.435°\text{C}}{\sum R} = 6.333\ \text{W/m}^2\text{K}(1.916°\text{C})$$

$$\frac{21.435°\text{C}}{\sum R} = 12.132\ \text{W/m}^2$$

$$\frac{21.435°\text{C}}{12.132\ \text{W/m}^2} = \sum R$$

$$1.767\ \text{m}^2\text{K/W} = \sum R$$

k-value Calculations:

$$k = \frac{L}{R} \quad (5)$$

$\sum R = R_{(Infill)} + R_{Plywood}$

$R_{Plywood}$ = 0.098 m²K/W + 0.1465 m²K/W = 0.2445 m²K/W

R_{AirGap} = 0.514 m²K/W – 0.2445 m²K/W = 0.2695 m²K/W

$$k_{AirGap} = \frac{0.1405\ \text{m}}{R_{AirGap}}$$

$$k_{AirGap} = \frac{0.1405\ \text{m}}{0.2695\ \text{m}^2\text{K/W}}$$

$$k_{AirGap} = 0.521\ \text{W/mK}$$

$R_{Sawdust}$ = 1.578 m²K/W – 0.2445 m²K/W = 1.534 m²K/W

$$k_{Sawdust} = \frac{0.1405\ \text{m}}{R_{Sawdust}}$$

$$k_{Sawdust} = \frac{0.1405\ \text{m}}{1.334\ \text{m}^2\text{K/W}}$$

$$k_{Sawdust} = 0.105\ \text{W/mK}$$

$R_{Mycelium\ (Live)}$ = 1.545 m²K/W – 0.2445 m²K/W = 1.301 m²K/W

$$k_{Mycelium(L)} = \frac{0.1405\ \text{m}}{R_{Mycelium(L)}}$$

$$k_{Mycelium(L)} = \frac{0.1405\ \text{m}}{1.301\ \text{m}^2\text{K/W}}$$

$$k_{Mycelium(L)} = 0.108\ \text{W/mK}$$

$R_{Mycelium\ (Dried)}$ = *1.767 m2K/W – 0.2445 m2K/W = 1.523 m2K/W*

$$k_{Mycelium(D)} = \frac{0.1405\ \text{m}}{R_{Mycelium(D)}}$$

$$k_{Mycelium(D)} = \frac{0.1405\ \text{m}}{1.523\ \text{m}^2\text{K/W}}$$

$$k_{Mycelium(D)} = 0.092\ \text{W/mK}$$