Engaging Mycelium

explorations of a cultivated architecture

by
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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.

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ABSTRACT

This thesis presents a material investigation into understanding the architectural value of a biologically grown, fungal-based fabrication method. By utilizing the natural growth patterns of fungal mycelium, this matter-generating process challenges traditional means of production towards a low input, low impact material practice– a cyclical metabolism where materials can go back to the earth's carbon cycle at the end of their useful life.

Over the last decade, a handful of designers have displayed great interest in biofabricating with mycelium– the vegetative structure of fungi. Philip Ross, David Benjamin, and the founders of Ecovative are pioneers in this crossover field of design and cultivation; growing fabric, packaging, bricks, and common objects. Despite gaining recognition, this evolving material practice lacks development within design literature. With no standard accepted protocols yet to follow, this thesis initiates an intimate dialogue with fungi through tactile, process-based, material-driven experimentation. At the intersection of architecture and biology, this work is actively guided by a subtle organism, therefore inherently alternates scales from nano to macro. The research aims to: offer insight into designing with fungi as living collaborators, learn the characteristics of the material, and recognize the challenges and potentialities of material implementation for the purpose of architecture.

Experimentation is conducted in multiple stages, with every step contributing heavily to the next. The first is the initial interaction with fungi: testing a variety of substrates and growth techniques for basic form creation and evaluation. The next phase focuses on optimizing a growth method to achieve an accurate representation of the material's technical and experiential qualities. Subsequently, a series of artifacts are grown as a means of developing technique and material learning through active prototyping. Additionally, the notion of scale is explored through a dimensional study, with the objective of determining a correlation between the growth time, drying time, and size of specimens. Samples grown for this study are subjected to compression testing to better understand the technical properties of the material, and to further define the challenges and opportunities of a fungal-based future in design. The intention of this multi-stage material investigation is knowledge acquisition through an instinctual and tactile engagement, by cultivating artifacts and material experiences.

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INTRODUCTION

1. Introduction
Material and Architecture

"Architecture is defined by the physical components that are materials. Materials are the substance of things. And there is no way to convey oneself except by language – language created by means of an impression in a particular medium"[1]

Material is the medium of the built environment, it defines the physical reality of architectural expression– articulating: form, space, performance, and the overall palpable experience that is architecture.[2,3] Material is the dual source of technical implementation and sensorial expression. It is the reality of matter; "the tangible that executes the intangible... and the available resources and the craft of their joinery [that] define the history of architecture."[4] Through materiality, architectural ideas become processed into physical manifestations, thus material is undeniably central to the premise of architecture. To be an architect, therefore implies a strong level of material consciousness, as the connecting link between idea and artifact.

Prior to the Industrial Revolution, the relationship between material and architect was relatively direct, based on a sensitivity and an empirical learning of materials, their properties, and performances.[5] As an intuitive experimental process, material knowledge was generated through observation, and often trial and error.[6] With a limited material palette, the master builder, who had the amalgamated role of architect, builder, engineer, and scientist was responsible for understanding the potentials and constraints of locally available materials, and by obtaining a fundamental knowledge and technical skill-set, learning to pragmatically utilize these materials for the creation of architecture.[7,8] At this time, the rate at which materials were sourced and extracted for the purpose of construction was steady, reflecting the needs of the local populace, the technical

1 Erwin Viray, "Why Material Design?" in Material Design: Informing Architecture by Materiality, by Thomas Schröpfer (Basel: Birkhäuser, 2011) 8
2 Gail Peter. Borden, Material Precedent: The Typology of Modern Tectonics (Hoboken, NJ: John Wiley & Sons, 2010)
3 Erwin Viray, "Why Material Design?" in Material Design: Informing Architecture by Materiality, by Thomas Schröpfer (Basel: Birkhäuser, 2011)
4 Ibid., 8
5 D. Michelle. Addington and Daniel L. Schodek, Smart Materials and New Technologies: For the Architecture and Design Professions (Oxford: Architectural Press, 2006) 2-3
6 Ibid.,3
7 Ibid.,4
8 Stephen Kieran and James Timberlake, Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction (New York: McGraw-Hill, 2004) 27

limitations of the material, and the constraints of transport. Since materials were yet to be standardized, master builders worked within these confines, reliant on their own material knowledge, leading a thoughtful design process in which material and form were naturally entwined in the process of making.

Throughout the course of architectural history– industrial mechanization, mass production, changing technologies, and the recent surge of dependency on digital representational tools, this relationship has shifted away from an inherently integrated approach, towards a process autonomous of its sources in material knowledge.[9] Therefore architecture as a material practice has gravitated towards a process defined by "prioritizing the elaboration of form over its subsequent materialization." [10] In other words, materiality has become a secondary agency relative to form, geometry, structure, and environmental impact.[11] This notion has become relatively normalized in design culture, resulting in an inherited lack of material awareness. From an academic lens, emphasis on form is valued as the essence of vision and creativity within architectural education and practice. Material innovation however, is rarely taught or central to the academic discourse.[12] The absence of material mindfulness in design culture perhaps reinforces the separation between architect and medium, and the inevitable indifference towards the consideration of material resources in the design process.

"Under the imperatives of the growing recognition of the ecological failures of modern design, design culture is witnessing a new materiality" [13]

As a relatively new concept (pertaining to less than a quarter of a century), the increasing comprehension of resource scarcity suggests that high value materials can no longer be endlessly extracted from earth to maintain a hyper-linearity of use and disposal. In the context of earth's carbon cycle, traditional means of production do not sustain a healthy metabolism, expending resources and energy, through a wasteful and subtractive process which results in the

9 Neri Oxman, "Material-based Design Computation," Doctor of Philosophy in Architecture: Design and Computation. Massachusetts Institute of Technology, June 2010

10 Achim Menges, "Chapter 2: Material Systems, Computational Morphogenesis and Performative Capacity," in Emergent Technologies and Design: Towards a Biological Paradigm for Architecture (Oxon, U.K.: Routledge, 2010) 44

11 Gail Peter. Borden, Material Precedent: The Typology of Modern Tectonics (Hoboken, NJ: John Wiley & Sons, 2010)

12 Blaine Brownell, Material Strategies Innovative Applications in Architecture (New York: Princeton Architectural Press, 2012) 9

13 Neri Oxman, "Material-based Design Computation," Doctor of Philosophy in Architecture: Design and Computation. Massachusetts Institute of Technology, June 2010

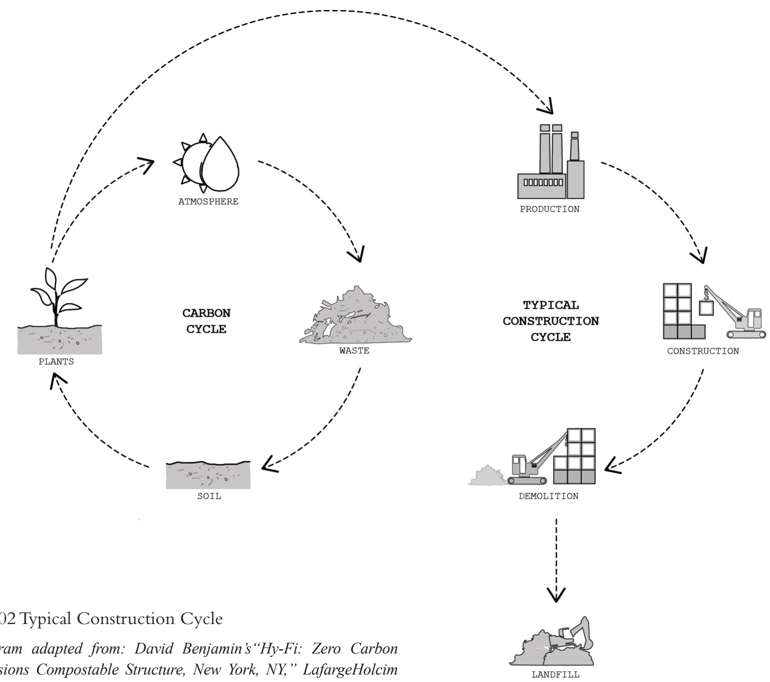


Fig. 02 Typical Construction Cycle

Diagram adapted from: David Benjamin's "Hy-Fi: Zero Carbon Emissions Compostable Structure, New York, NY," LafargeHolcim Foundation

unfathomable accumulation of waste. The building industry alone is responsible for 40% of the global energy usage.[14] Thus, architecture is considerably embedded in issues of waste and environmental challenges rooted in cycles of construction.

Towards a new paradigm of production, this research explores the emergent concept of a circular metabolism– tapping into the waste stream– starting with low value materials that do not require extensive energy converting for use. With the integration of biological systems within architecture, healthy cycles of growth, decay, renewal, and regrowth can potentially be achieved, where materials can eventually return to the carbon cycle at the end of their useful life.

14 "United Nations Environmental Programme," Sustainable Buildings and Construction Programme | UN Environment, , accessed November 21, 2016, http://web.unep.org/10yfp/programmes/sustainable-buildings-and-construction-programme

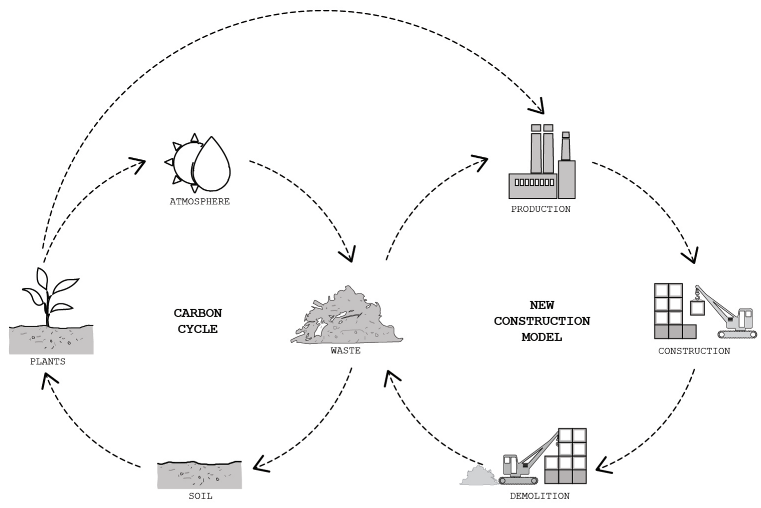


Fig. 03 New Construction Model

Diagram adapted from: David Benjamin's "Hy-Fi: Zero Carbon Emissions Compostable Structure, New York, NY," LafargeHolcim Foundation

In line with this cyclical approach, a biological integration of growth and cultivation is surfacing as a means of fabrication, through understated organisms like fungal mycelium. Utilizing fungi's capacity for the growth of useful materials and objects, a number of designers such as Phil Ross, David Benjamin, and Maurizio Montalti have shown great interest in biofabricating over the last decade. Based on the need to consider alternate resource streams, this concept of biofabrication is perhaps the beginnings of a new materiality and the start of an important dialogue that recognizes the need for material innovation in the design process.

The challenge, therefore, is designing with a new materiality, which in this research is initiated through intuitive, tactile, material-driven explorations of fungal mycelium as living collaborators, for the cultivation of a biofabricated architecture.

A BIOLOGICAL INTEGRATION

2. A Biological Integration

Having an elementary understanding of the mushroom life-cycle greatly encourages the learning of techniques and foundations that are essential for investigating the idea of a cultivated architecture.

2.1 Introduction to Fungi

Fungi are a specialized classification of organisms which unlike plants do not photosynthesize, and similar to animals obtain food by breaking them down into absorbable molecules, through an enzymic process.[15] Fungi absorb nutrients from their environment through mycelium– the root-like structure of fungi. Growth as their means of mobility, mycelium spreads in search of sustenance and creates connective tissues through a distinct process that converts cellulose within the substrate into a strong and resilient substance known as chitin within their cell walls– the same material that constitutes the exoskeleton of arthropods such as the shells of crustaceans like crab, lobster, and shrimp.[16]

Aside from their composition, fungi have a very important role in the ecosystem. They have the primary responsibility of decomposition, and break down dead organic matter. Fungi transform organic waste into soluble nutrients, which are normally difficult for plants and other decomposers (invertebrates) to digest. By releasing digestive enzymes, fungi can process complex organic compounds into soluble nutrients, such as sugars, nitrates, and phosphates. Plants for example rely on fungi to facilitate this transfer, which they can up-take through their roots. Additionally, some species of fungi form symbiotic relationships with plant life. Known as mycorrhizal fungi, this transfer is mutually beneficial, where there is an exchange of carbon for nutrients via fungi and plant roots. Furthermore, mycorrhizal fungi have the capacity to connect individuals within the forest, in sharing nutrients and information within species and inter-species.[17] This extensive underground network of mycelium has been described as nature's Internet.[18,19]

15 Michelle Rose. Gilman, Brian Peterson, and Peter Mikulecky, "Chapter 15: Taxonomy and Classification," in AP Biology For Dummies (John Wiley & Sons, 2008), 185

16 "Chitin: Structure, Function, and Uses," BiologyWise, accessed May 07, 2018, https://biologywise.com/chitin-structure-function-uses.

17 Suzanne Simard, "How Trees Talk to Each Other." TED, Ideas Worth Spreading. June 2016. Accessed September 2016. https://www.ted.com/talks/suzanne_simard_how_trees_talk_to_each_other/transcript.

18 Ibid.

19 Stamets, Paul. Mycelium Running: How Mushrooms Can Help save the World. Berkeley: Ten Speed Press, 2005, 2

Fig. 05 Lingzhi Primordia

2.2 Understanding Mycelium

More explicitly, mycelium is the vegetative structure of fungi. The edible mushrooms or the ones seen in nature are in fact just a small visible portion; the fruit of the organism. Generally unnoticed is the vast mycelial network that emanates from the fungal spore– the main body of the organism and the system responsible for obtaining nutrients to the rest of the growing mass. The fruitbodies are the reproductive organs, responsible for producing and dispersing spores. Under favorable conditions (temperature, humidity, nutrients), spore germination will occur. Fine branching filaments called hyphae will grow from the spores, and compatible hyphae will fuse to create a mycelial network. This network is so dense "there can be hundreds of kilometers of mycelium under a single footstep".[20]

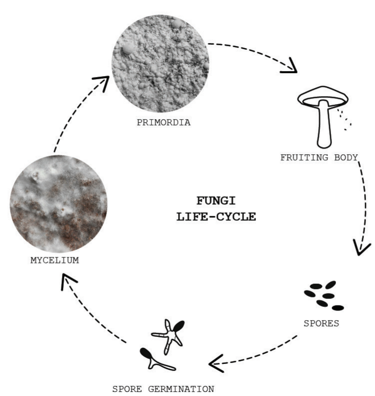


Fig. 06 Fungi Life-Cycle

In the lifecycle of the mushroom, fruitbodies are ephemeral, while the mycelial network lives perennially. This network can be in a state of slow growth or dormancy for months, or even years, becoming reactivated, only by very specific environmental triggers.[21] In the phase anticipating fruitbodies, the mycelium experiences a "frenzied state of growth"[22], accumulating and reserving nutrients, while growing exponentially at a remarkable rate. Radical changes in metabolism occurs during this stage, in preparation of supporting

20 Suzanne Simard, "How Trees Talk to Each Other." TED, Ideas Worth Spreading. June 2016. Accessed September 2016. https://www.ted.com/talks/suzanne_simard_how_trees_talk_to_each_other/transcript.

21 Paul Stamets and J. S. Chilton, The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home (Olympia, WA: Agarikon, 1983) 4

22 Paul Stamets and J. S. Chilton, The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home (Olympia, WA: Agarikon, 1983) 140

the dense little masses called primordia which eventually turn into fruitbodies.[23] During this metabolic change, the organism is most resilient despite its fiercely competitive environment, and is in a peak state of growth, maximizing nutritional intake.

To put into perspective the scale and means of mycelial growth, the following images are taken at the University of Guelph Laboratories, from samples grown and nurtured personally for the purpose of this study. Hyphae are magnified from their original size, and would not be visible to the naked eye otherwise.

Fig. 07-08 are microscopic images that show the mycelium fusing fragmented pieces of substrate. Adhered together like a natural glue, this binding quality is one of the most intriguing for designers, where formless organic waste has the potential to be radically transformed into a diverse typology of objects and formations.

Taken in a scanning electron microscope, Fig.10 shows hyphae at a higher magnification, collectively forming the mycelial network. Fig.11 is a fragment of sawdust colonized by mycelium.

Fig. 07 Microscopic Image Zoom
Sawdust fragments colonized by mycelial network- zoom.

Fig. 08 Microscopic Image
Sawdust fragments colonized by mycelial network

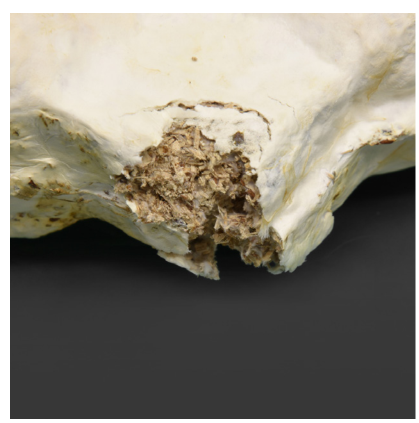


Fig. 09 Specimen Used for Microscopy
Lingzhi- Sawdust Specimen Corner used for microscopy

23 Paul Stamets and J. S. Chilton, The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home (Olympia, WA: Agarikon, 1983).9

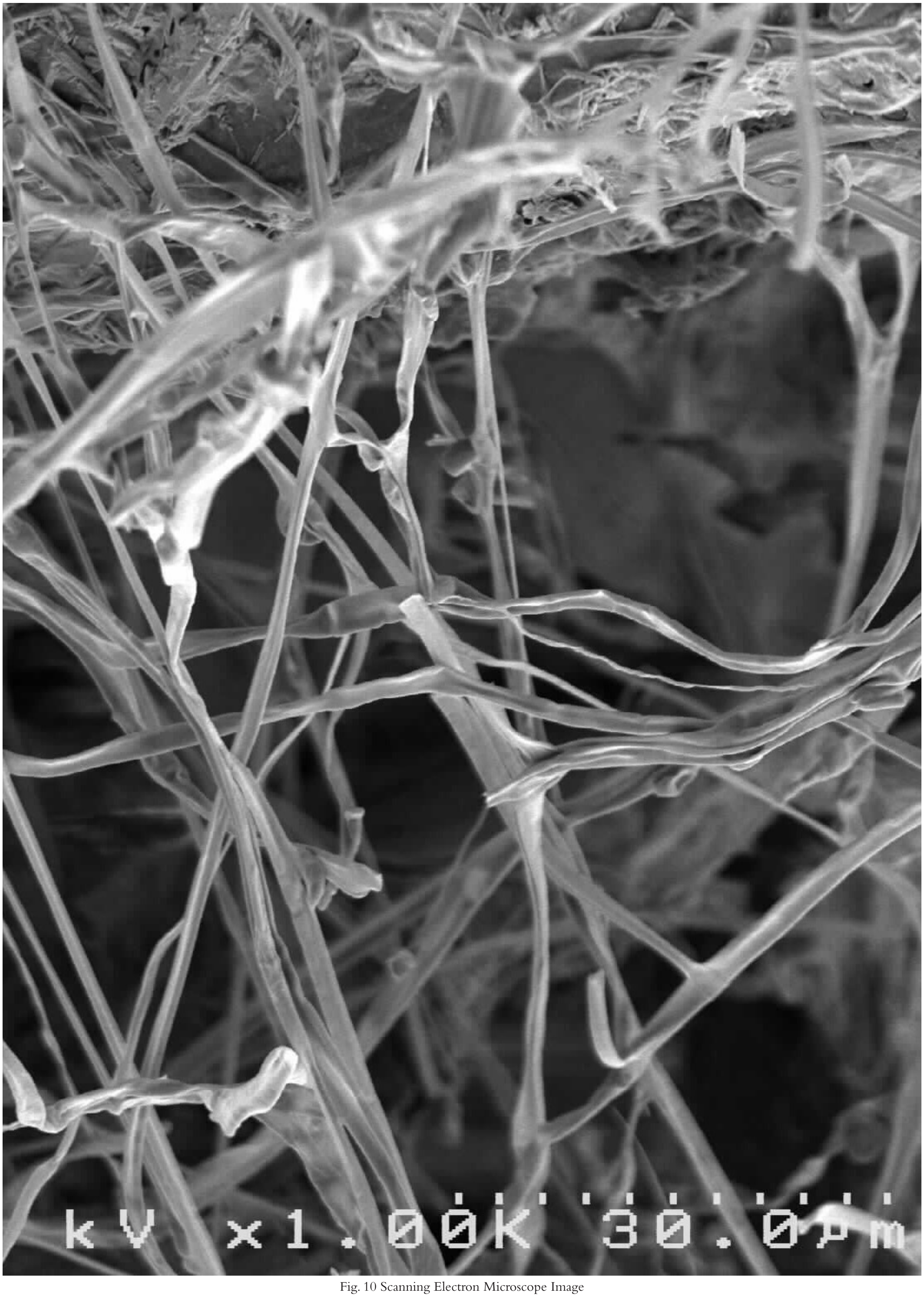


Fig. 10 Scanning Electron Microscope Image
Hyphae forming mycelial network

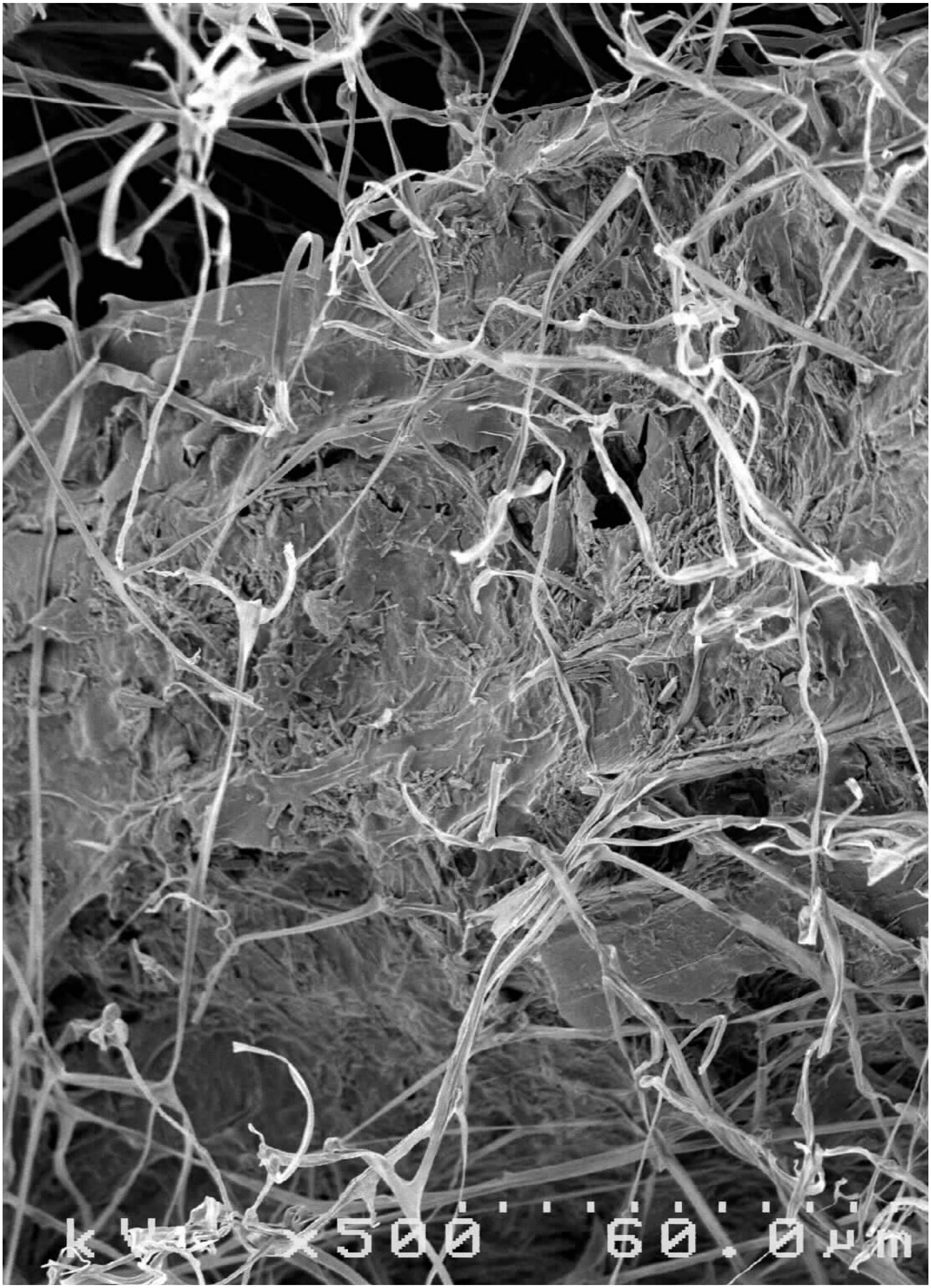


Fig. 11 Scanning Electron Microscope Image
Mycelial network colonizing sawdust fragment

2.3 Design Integration
Precedents

By providing the appropriate nourishment from the waste stream, and suitable growth conditions such as temperature, humidity, and sanitation, a process of biofabricating with fungi has emerged as a new material practice. This organic manufacturing process utilizes the growth of mycelium by colonizing and binding formless organic waste into desired formations. A growth process, which requires minimal energy input, is then completed by terminating the growth of the fungi through dehydration. This last step prevents fruitbodies, future contamination, and further strengthens the grown object. At the junction of design and mycology (a branch of biology dedicated to the study of fungi), a range of cultivated projects have been significant to the development of this practice.

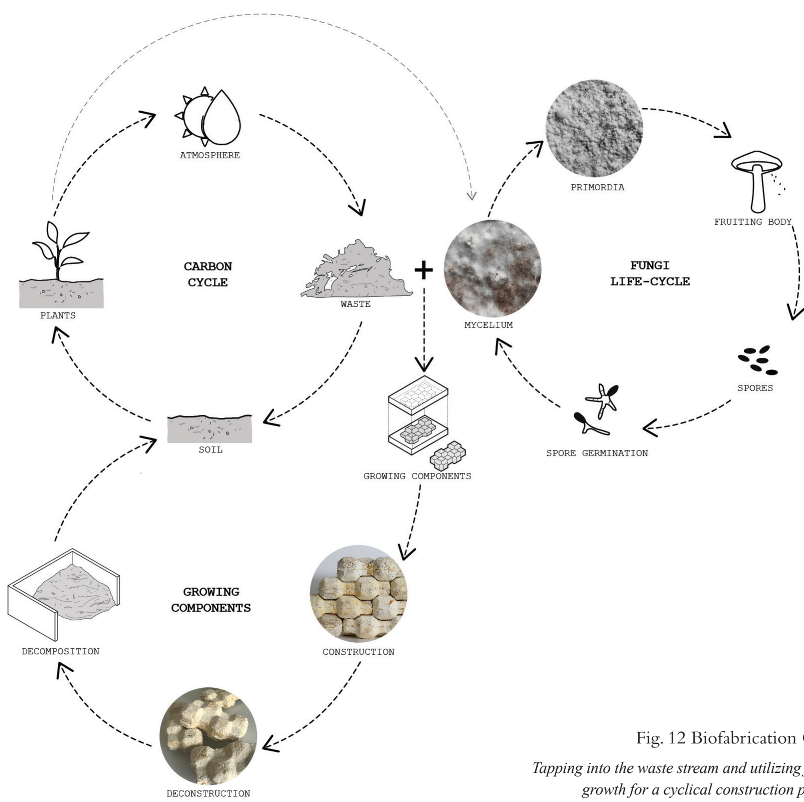


Fig. 12 Biofabrication Cycle

Tapping into the waste stream and utilizing fungal growth for a cyclical construction process

Characterized by exploratory testing of various forms and dispersed applications, this experimental design movement –although lacking a thorough understanding– encompasses a shared curiosity among designers, with an underlying admiration for fungi as biological super organisms and impressive collaborators in the design process.

Fig. 13 Phil Ross, Mycotecture
Blocks fusing to create continuous structure

Fig. 14 Phil Ross, Mycoworks Leather
Biofabricating strong flexible fabrics from mycelium

Phil Ross, artist and lecturer at Stanford University, was one of the pioneering figures of this biofabrication technique. Growing an array of artifacts such as furniture, faux-leather, and bricks, his projects Mycotecture and Mushroom Tea House were the first to introduce the idea of growing components for the purpose of architecture. In these projects, blocks were cultivated and merged together through mycelial growth, creating continuous forms and artifacts from individually grown elements. This concept, although unresolved at a functional architectural scale opened the dialogue amongst designers. Piquing the interest of architects like David Benjamin of The Living, the most notable and resolved fungal-based architectural project to date was erect in 2014 called the Hy-Fi; a

Fig. 15 David Benjamin, Hy-Fi, MoMA's Ps1 Courtyard
Exterior View of Structure

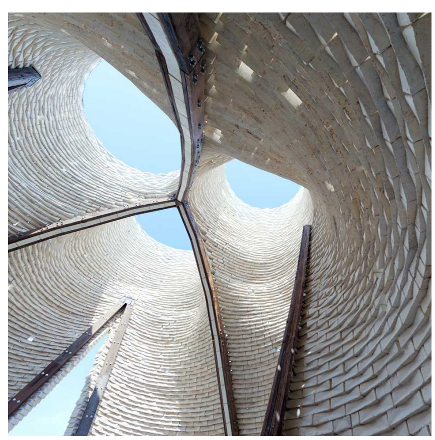


Fig. 16 David Benjamin, Hy-Fi, MoMA's Ps1 Courtyard
Interior View of Structure

temporary structure at MoMA's Ps1 Courtyard in New York. Mycelium bricks were assembled using mortar and secured using a timber form work. Following disassembly, bricks were composted and distributed to local gardens.[24]

This realized application, although unprecedented, ambitious, and highly innovative, is lacking an available source of thorough analysis in regards to material behaviour and performance. Knowledge sharing is critical in this phase of development, and information concerning how these bricks were cultivated, how they carried out during their three month lifespan, the effects of environmental stimuli, as well as load, were not explicitly discussed or accessible. This project is an incredible source of information that is yet to be unveiled; therefore uncertainties about material performance still persist.

Standing 12m tall, 10 000 bricks were grown for the Hy-Fi [25] , through a biomaterials company called Ecovative, founded by Eben Bayer and Gavin McIntyre. Ecovative specializes in growing packaging materials and foams as an alternative to petroleum-based products. With a decade of experience, this company has the most developed growth techniques at the industrial scale.

However, due to the lack of material understanding outside of this very small community, several designers and artists have adopted a Do-It-Yourself approach, in testing a medley of recipes, growth methods and applications as a means of material learning. Designing with a new materiality is an extreme challenge, therefore tactile experimentation is necessary in order to evaluate

Fig. 17 Maurizio Montalti, The Growing Lab
Growing Everyday Objects

Fig. 18 Sebastian Cox, Mycelium and Timber
Growing Everyday Objects

24 LafargeHolcim Foundation for Sustainable Construction, "Hy-Fi: Zero Carbon Emissions Compostable Structure, New York, NY," LafargeHolcim Foundation Website, accessed April 24, 2017, https://www.lafargeholcim-foundation.org/projects/hy-fi
25 Ibid.

this material in any sense. Nevertheless, the amount of uncertainty circulating this practice due to varying and undocumented knowledge has resulted in a spectrum of ventures in the design world. This realm ranges from familiar applications, such as brick assemblies, or Maurizio Montalti's collection of everyday objects, to more complex or romanticized applications that perhaps do not fully consider the current realities of the material practice– its limitations and capabilities; projects that focus on: form over matter or biological traits that are meant to contribute specifically to formal language or means of assembly.

Project Modular Mycelia, by Sean Campbell et al, is an example of a project that focuses on the biological trait of hyphal bonding as a means of architectural assembly.[26] Spherical units of 40 mm in diameter are grown and assembled in varied configurations, allowing the units to merge together via mycelial growth.[27] This concept is similar to Philip Ross' block projects, where continuous or larger assemblies are created from individual parts. This implies that the spheres are kept alive in order for individual units to fuse into larger assemblies, like walls for example.[28] At an exploratory phase of research, the purpose is " not to produce functional architecture made from fungus.. [but] instead to demonstrate the strengths of a multi-scalar assembly system, while outlining the technical challenges of using fungal growth as a means of architectural assembly."[29] The findings of this research show that contamination is a reoccurring and continual challenge when assembling live units in a final prototype.[30] This raises important concerns in regards to the concept of keeping assemblies alive, not only in the phase of construction, but also in the phase of use, as environmental

Fig. 19 Sean Campbell et al., Modular Mycelia
Spherical elements fusing

Fig. 20 Sean Campbell et al., Modular Mycelia
Elements fusing to create a larger assembly

26 Sean Campbell et al., "Modular Mycelia: Scaling Fungal Growth for Architectural Assembly." In The Virtual and the Physical, 125-134. Proceedings of 5th ECAADe Regional International Symposium 2017, Cardiff University, Cardiff, Wales, UK.
27 Ibid., 128-129
28 Ibid., 130-132
29 Ibid., 128
30 Ibid., 132

stimuli can trigger physiological changes and growth of competing organisms.

At an emergent level, there are still many basic factors that have yet been addressed by this biomaterials community, such as: the notion of upscaling and the implications of growth for an architectural use, methods of production, and variances in recipe impacting final material composition. The technical and aesthetic qualities are still in an exploratory phase, hence gauging a functional architectural application is a great challenge.

Fig. 21 Eric Klarenbeek, 3D Printing with Fungi
Complex forms and techniques result in nonfunctional objects

Fig. 22 Gianluca Tabellini, Mycelium Tectonics
350 mm high, growth guided on hemp structure, testing morphological uses

Therefore, projects that are form-oriented in this phase of knowledge, such as Eric Klarenbeek's 3D printed chairs or Gianluca Tabellini's Mycelium Tectonics for example, are somewhat premature, and require a better understanding of the material complexities before assigning complex morphological possibilities.

The significance of exploring familiar uses can allow for a focus and attentiveness towards material learning, while creating artifacts that can physically be experienced in pursuit of material acceptance. The adoption of new materials can typically have a long period of gestation– 20 years or more between innovation, first application, and its widespread use. [31]

An example of this can be seen in history, with the first use of cast-iron for a structural purpose; The Iron-Bridge at Coalbrookdale (1777–1779).[32] This bridge represents the beginnings of a very important material development, and is the symbol of process in the material's evolution. Without the comprehensive understanding of the remarkable properties, potentials, and great spans of iron,

31 Elicia Maine, David Probert, and Mike Ashby, "Investing in New Materials: A Tool for Technology Managers," Technovation 25, no. 1 (2005) 16
32 David J. Brown, Bridges Three Thousand Years of Defying Nature (London: Mitchell Beazley, 2005),46

the techniques implemented in the construction of this bridge were derived from pre-existing construction knowledge– short spans, dovetails, and mortises, emulating methods of a timber assembly. [33] The redundancies of this technique were yet to be discovered, as iron could reach far greater spans, with much less use of material. However, the familiarity of application allowed for the material to prove its capacities during a period of gestation leading up to its widespread use. Surviving the great flood of 1795, while other bridges did not, the possibilities of this new material were revealed, gaining material understanding and acceptance, and inspiring further development and use. [34]

Fig. 23 The Iron-Bridge at Coalbrookdale
Abraham Darby III, Built in 1777–1779

Fig. 24 The Iron-Bridge at Coalbrookdale
Mortise joints and pegged dovetails emulating wood construction

Similarly, with the collective knowledge gained through architectural and product-oriented applications, the appealing qualities of this fungal-based material practice are beginning to surface, not only as an ecologically responsible fabrication process, but through suggested capabilities of fire resistance, insulation, lightweight composition, and durability. [35, 36]

In the early stages of gestation, this research aims to: offer insight into designing with fungi as living collaborators, learn and document the characteristics of the material, and recognize the challenges and potentialities of material implementation for the purpose of architecture. Through a series of hands-on, material-driven investigations, this work contributes to questions of aesthetic, scale, recipe, growth environment, growth technique, performance and application. The intent is knowledge acquisition through an instinctual and tactile engagement – by cultivating artifacts and material experiences.

33 Ibid.
34 "English Heritage," History of Iron Bridge | English Heritage, , accessed April 26, 2017, http://www.english-heritage.org.uk/visit/places/iron-bridge/history/.
35 Ecovative. "How It Works." Ecovative Mycelium Biomaterials, Green Island, New York. Accessed Jan 25, 2017. https://ecovativedesign.com/how-it-works
36 Phil Ross, "Mycoworks Technology," MycoWorks, , accessed April 26, 2018, http://www.mycoworks.com/.

EXPERIMENTATION

Fig.25 Lingzhi Block Initial Prototype
Testing growth method and casting techniques

3. Experimentation

In finding architectural value in biologically grown mycelium composites, this research documents the outcomes of a multi-stage experimentation process. Every step is directly impacted by the observations of the preceding. The first is the initial interaction with the organism: testing a variety of substrates and growth techniques for basic form creation and evaluation. This interaction aims to grasp an overall sense of the material practice, in learning the organism's growth: processes, conditions, and characteristics. The next phase focuses on optimizing the means of growth for biofabrication, with the intent of reaching an accurate representation of the material's technical and experiential qualities for further evaluation. This includes the improvement of growth environment, material preparation, and formulating a productive recipe. Subsequently, a series of artifacts are grown as a means of developing technique and material learning through active prototyping. Intriguing capacities of fungi are revealed during this process, while tangible results allow for a sensorial interpretation of the material. Additionally, questions of scale are addressed through a dimensional study, with the objective of determining a correlation between the growth time, drying time, and size of specimens. Samples grown in this phase are subjected to compression testing to better contextualize the technical properties of the material, and to further define the challenges and opportunities of a fungal-based future in design. The intent is to collect documented knowledge and experience through an active material engagement. The emphasis is not a final design resolution, but rather the understanding of the material's capacity through growing material experiences. This approach is addressed with a pragmatic curiosity, similar to the rigors of a science experiment.

"We do not always create 'works of art', but rather experiments; it is not our ambition to fill museums: we are gathering experiences" [37] *-Josef Albers*

37 Barry Bergdoll and Leah Dickerman, Bauhaus 1919-1933 Workshops for Modernity (New York: Museum of Modern Art, 2009), 17.

Engaging Mycelium

a process of "tinkering"

3.1 Engaging Mycelium

a process of "tinkering"

In this introductory phase, I establish a dialogue with the living organism. In Karana et al.'s Material-Driven Design (MDD) approach , the first encounter with an exploratory material is described as material tinkering, an "explorative process of creation and evaluation".[38] Taking influence from the theoretical foundations of Johannes Itten of the Bauhaus and his educational beliefs of material understanding through direct engagement, the intention of tinkering is to encourage material learning and ultimately to obtain insight and knowledge to further guide experimentation and development. [39, 40] This type of practice promotes iterative research, which can foster quicker feedback for evaluation. In this phase, I conduct a series of rapid and instinctual exploratory studies. My broad goal is to assess the process of a mycelium-based fabrication and therefore tinkering is meant to ease and guide this unversed material practice. Mitchel Resnick from the MIT Media Lab believes the value and validity in this style of working, where a tentative or a general goal can continually be "adapted and renegotiated" based on the feedback of the interactions. He believes that a playful spirit underlies this entire learning process, and states that by adapting, iterating, and refining, we can reach new opportunities. This process does not follow rigorous rules, but rather reacts to specific details in a particular experiment by rigorous means.[41] Resnick defines material tinkering as "a playful, experimental, and iterative style of engagement, in which makers are continually reassessing their goals, exploring new paths, and imagining new possibilities." [42] I implement this style of learning during the first phase of my research.

38 Elvin Karana et al., "Material Driven Design (MDD): A Method to Design for Material Experiences," International Journal of Design Vol. 9 (November 2, 2015) 37

39 Magdalena Droste, Bauhaus: 1919-1933 (Köln: Taschen, 2006). 25-26

40 Mitchel Resnick and Eric Rosenbaum, "Designing for Tinkerability," in Design, Make, Play: Growing the Next Generation of STEM Innovators, ed. Margaret Honey and David E. Kanter (New York: Routledge, 2013) 163-166

41 Ibid., 165

42 Ibid., 164

Fig. 27 Mycelium Growing on Sawdust Substrate
4 days of growth

3.1.1 substrate test

To grasp the processes of fungal growth, a series of experiments are conducted using Pleurotus ostreatus, the common oyster mushroom. This specific variety is recommended for beginner cultivators during a consultation with a local spawn production company, due to its rapidity of growth, resilience to contaminants, and its ability to grow under various conditions and substrates. The colonization patterns of the Pleurotus ostreatus are tested with different sources of nutrients derived from organic waste such as: straw, wood shavings, sawdust, coffee grinds, and leaves. The substrate nutrients are all pasteurized to prevent the growth of competing organisms and inoculated with Pleurotus ostreatus grain spawn, purchased locally. Spawn is a substance that has already been introduced to mycelium and therefore functions as a carrier of the vegetative fungi used to inoculate substrates for cultivation. A sterile work environment is crucial in preventing contamination in this process.

The inoculated substrates are packed into 2" silicon cubic moulds and placed in a dark environment at room temperature. The test cubes are monitored during a one week span to observe growth behaviour in relation to substrate variables. In less than 24 hours, traces of growth are already visible. Samples are removed from the moulds for initial observation. Upon removal, samples are placed in the oven to terminate growth of fungi.

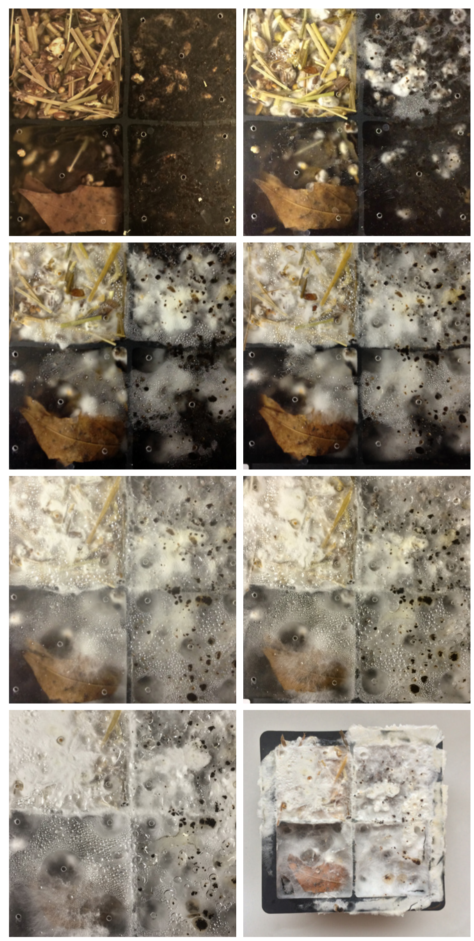


Fig. 28 Sequence of Growth
Pleurotus ostreatus growing on various substrates.
Documenting 8 days of growth

Fig. 29 Mycelium Colonizing Straw
Sample removed from mould 8 days after inoculation.

observations:

The specimens release from the cubic moulds with difficulty, suggesting a high level of adhesion. This must be taken into consideration when conceiving future moulds and formworks. Once removed, it is apparent that samples are not fully colonized, although substantial growth can be seen. Notably, the top surface of the cubes have much denser mycelial growth. Once samples dry and loose water content, a lightweight compact material remains.

Fig. 30 Sawdust

Fig. 31 Coffee Grinds

The straw appears to be the preferred source of nutrients in my experiments, as it shows the most breadth of colonization. The wood shavings appear to have the least nutritional value and growth. The wood shavings were acquired from a local farm and most probably used for animal bedding, therefore may have been treated with anti-fungal, or antibacterial chemicals rendering them deficient for nutritional purposes.

Fig. 32 Wood Shavings

The assortment of substrates tested result in a notable variation in material composition– the straw is relatively elastic, whereas the coffee grinds and sawdust result in a much stiffer material

Fig. 33 Leaves

The most significant observation from this initial experiment is that depending on the characteristics of the nutrient substrate, the resulting material can have a completely varied physical structure– strengths, load capacities, weaknesses and therefore uses. This implies that the particle size and compactness of substrates can also influence the final material form.


Fig. 34 Various Substrates Inoculated


Fig. 35 Packed Moulds

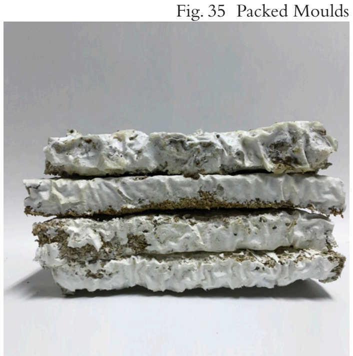


Fig. 36 Resulting Specimens


Fig. 37 Resulting Specimens

3.1.2 thickness test

Parallel to test 3.1.1, variations in thickness are grown to consider how results differentiate based on depth. These tests are conducted using the same variety of substrates and methods as the previous set, each grown in forms of 3.5"x7.5", ranging from 0.25" to 2.5" in depth. Samples are monitored for a 14-day period.

observations:

These set of tests are conducted before receiving feedback from the previous, therefore much of the observations remain the same. However, with the increase in scale, samples begin to produce fruitbodies before fully colonizing the substrate. The fungi go from a vegetative state to a generative one, and eventually growth comes to a halt. This results in a fragile object with uncolonized areas completely crumbling and falling apart. The thinner the sample, the weaker it appears to be. Collectively, an even distribution of growth is not achieved.

3.1.3 form test

Simultaneously, a series of experiments are conducted with an additional variable of formwork, i.e. moulds and methods for setting up growth. Templates of different shapes, sizes, and materials are tested in growing a variety of formations. Through these miscellaneous forms, the intent is to establish a correlation between the type of formwork, the quality and potential of growth, and the integrity of the specimen.These tests are meant to identify any boundaries in growth technique, to inform the architectural applicability. I attempt to grow samples that are solid, curved, perforated, and flexible.All substrates are pasteurized, inoculated, grown at room temperature, and dehydrated as the final step.

Fig. 38 Curved Sample

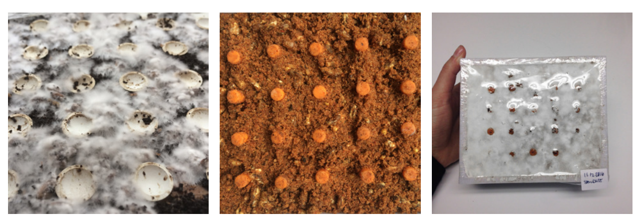


Fig. 39 Growing Perforated Samples

observations:

Although samples have an uneven distribution of mycelium growth, the various formworks can indicate a good sense of the boundaries and opportunities of this material system, which informs the next series of experiments.

Hollow moulds appear to be the most effective type of formwork in achieving a variety of desired formations, resulting in specimens that are solid and durable masses. The most important consideration is the process of removing samples from their formwork, as they are still delicate in their living state and therefore susceptible to damage.

Fig. 40 Cardboard Waffle Structure
Internal Scaffolding

A series of perforated samples are grown at different thicknesses. Removal from formwork is merely impossible without damaging the specimens. The mycelium is fully bound to the elements that perforate. To avoid cracks or breakage, samples can be removed from their formwork after they have dried and strengthened. This study suggests that less intricate forms are more suitable at this stage of material practice. It also emphasizes the importance in the design and functionality of the actual formwork, requiring careful consideration for the process of packing, growing, and removing.

Integration with natural fabrics and netting is also tested. In theory, soft templates fuse with the mycelium, creating a material that can be formed and dried to create more complex geometries. However, during its hydrated state, the material is very soft and susceptible to breakage, and in its dehydrated state, it is incredibly delicate and brittle. Perhaps if the resulting material could remain flexible, a tensile-type application could be considered. In attempting to maintain material flexibility, a transparent mycelium sheet is conceived.

A cardboard waffle structure is created as internal scaffolding. In speculation, the cardboard skeleton will integrate with the inoculated substrate, eventually becoming a single entity. Difficulties with this technique include the warping of the cardboard structure due to the moisture content of the inoculated substrate; the cardboard absorbs much of the moisture dehydrating fungal growth. Additionally, fruitbodies are eventually formed, and the scaffold never reaches full colonization.

The testing of soft templates and internal scaffoldings are suggestive of a means of construction based on the idea of a whole or continuous architecture, rather than that of assemblies of discrete parts; shifting away from the idea of assemblage towards an architecture based on growth.

Fig. 41 Fabric Formwork

Fig. 42 Fabric Formwork

Fig. 43 Transparent Mycelium

However, upscaling this concept to an architectural scale brings forth many reservations.

The more I interact with this organism, the more I realize how pernickety and sensitive it actually is, and that a controlled environment is absolutely necessary to establish healthy growth. Consequently, on-site applications become far-fetched speculations, as contamination and inconsistencies in growth are the reality of this material practice– hindering concepts of large-scale cultivation.

At this stage of research, this material practice appears to be more suited to a contained growth, leading towards pre-cultivated individual units of construction that make up a greater whole.

The implications of large-scale growth requires further testing to determine a relationship between growth time, drying time, and size of specimens. However, through these experiments, it is evident that the process of growth and dehydration require a controlled and allocated environment, which may further limit the size of growth, due to space availability.

3.1.4 grain size test

Various grain sizes are tested to determine if there is a relationship between substrate size, material composition, and rate of colonization. All samples are grown under the same environmental conditions and processes. Coarse, medium, and fine grains of straw are pasteurized, inoculated, and packed into cubic moulds to grow for an 8 day period. This time, the moulds are lined with plastic wrap to facilitate with the removal of forms in avoiding adhesion.

Fig.45 Preparing Various Grain Sizes for Pasteurization

Fig.46 Coarse Grain

Fig.47 Fine Grain

observations:

Upon successful removal, there does appear to be a strong correlation between the grade of the substrate and the time it takes for the mycelium to fully colonize the form. [Fig. 46 & 47] are a direct comparison of growth in relation to particle size. As a result, the finer substrate colonizes quicker, and by fully binding the substrate particles, the subsequent sample is more dense and less elastic in composition.

This test verifies that by altering substrate nutrients, the resulting material can vary dramatically. Therefore depending on application, specific recipes can be formulated to achieve specific results.

"If you want the organism to do something in the way that you want them to do it... it means understanding the subtle factors that go into growing them" 43   Phil Ross

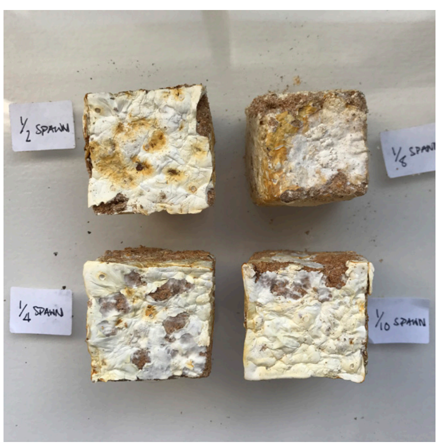


Fig.48 Spawn Ratio Results

3.1.5 spawn ratio test

Through these initial experiments, sawdust nutrients has produced the most durable samples. However, in an attempt to have a more homogenous mycelial growth, spawn to substrate ratios are tested to verify if this ratio has an influence on the density of colonization.

observations:

At the scale of 2-inch cubes, variances in ratio do not appear to make a difference. All specimens grow relatively equal to one another, although collectively inconsistent in texture and growth. This may suggest several considerations:

43 Phil Ross, "Mycotecture: Architecture Grown out of Mushroom" (lecture, Parsons The New School for Design, New York), April 11, 2014, accessed March 2016, https://www.youtube.com/watch?v=7q5i9poYc3w.

i) the Pleurotus ostreatus is not receiving enough nutrients from the sawdust; additional sources can be added during the inoculation processes, or different varieties of fungi can be tested which have a natural inclination towards hard-wood nutrients

ii) the growth environment may be optimal for fruit production, however it does not seem ideal for an exclusive and homogeneous mycelial growth. Conditions can be tested in finding the optimal growth environment (temperature & humidity).

3.1.6 nutrient test

Flour, bran and sugar are all tested individually with sawdust and Pleurotus ostreatus during the inoculation process. The attempt is to add nutrients to the recipe to encourage productive mycelial growth.

Fig.49 Contamination from Nutrient Test

observations:

This resulted in full contamination, as ingredients were most likely not sufficiently sterilized prior to inoculation. Working in a kitchen-lab setting has its challenges in terms of providing controlled conditions for sanitation.

Reflection

Through the process of tinkering, I have rapidly developed a basic understanding of fungal growth, and the potential ways in which mycelium can be guided to create desirable formations. Although preliminary, these studies have put into perspective the limitations and boundaries of this material practice within the architectural realm, and reiterate that before a form and application can be firmly determined, there needs to be a more thorough understanding of the material system.

Based on this initial encounter, the most important observation is the significance of the substrate, and the impact it has on the final composition of the material, ranging from dense to elastic in nature. The substrate seems to be a determining factor in the physical and mechanical characteristics of the resulting samples, significantly influencing the use and application of the material. Therefore, it appears that recipes can be altered and formulated to achieve desirable characteristics for use. This however requires further experimentation and materials research.

For the purpose of this study and projecting for an architectural use, sawdust has produced the most promising and durable results, and will be the substrate of choice for the experiments to follow. A recipe will be formulated, and a series of artifacts grown as a means of materials research.

Based on my perception and understanding of the growth patterns and tendencies of mycelium, I can make an informed hypothesis that growth will be most effective in contained and individualized units of construction that are parts of an assemblage. This takes into consideration that this organism is spontaneous and sensitive, reacting to environmental conditions and extremely susceptible to competing organisms. Therefore, a modular assembly of parts can allow for a controlled and compartmentalized growth, which can reduce growth time, while preventing the spread of contamination.

Reflecting on the realities of fungal growth, it is essential to develop a cultivation method, which includes the optimization of growth environment, material preparation, and recipe.


1/10 SPAWN

Developing Foundation for Growth

3.2 Developing Foundation for Growth

The next phase of experimentation will focus on improving growth conditions, simplifying material preparation, and conceiving a promising recipe; hence setting up the stage for future experiments. Improving growth will grant a more accurate representation of this material's capabilities, allowing for better evaluation of the material practice, particularly for the realm of architecture. A variety of fungi will be tested with sawdust substrate, as sawdust cultivates the most durable samples, as recognized in the previous study. Ganoderma lucidum (lingzhi), Hypsizygus ulmarius (elm), and a new variety of Pleurotus ostreatus (oyster), are recommended by a local spawn production company, as appropriate species for consuming sawdust– particularly the Lingzhi and its inclination towards hardwoods. This is the same species that Phil Ross utilizes in the cultivation of bricks and furniture. In realizing a more efficient material preparation method, specimens will be grown at a larger scale in this segment of research. Starting with a modular brick size, a variety of fungal samples will be scaled up laterally and vertically in order to observe the implications of growth and material performance at more architecturally applied scales. In this section, I am confronted with the challenges of bulk pasteurization and material preparation for larger scale experimentation. Additionally, and perhaps most importantly, in pursuit of optimal growth, I design and build a grow chamber.


Halwell Mutual
PROUD
TO BE
Pellets
PREMIUM

3.2.1 optimizing growth conditions

By acknowledging the importance of environmental stimuli, and understanding that a clean, and stable environment can promote healthy mycelium growth, the next challenge is to gain control of temperature, humidity, and sanitation. I build an enclosure with 2 x 4 lumber and polyethylene vapour barrier. Occupying the only available space in my basement, which happens to be the darkest space in the house, I construct a 1.4m x 1m space dedicated to cultivation. Tightly wrapped in vapour barrier, with a zipper door for access, this small space contains shelving racks, a humidifier, heater, and a thermometer so I can continually control and keep track of the internal conditions. The construction of this chamber is a fundamental piece of this entire exploratory process, as this is where I create an alternate environment for the organism to flourish. The collaboration with this living organism requires a special nurturing, which the grow chamber can provide. This space significantly impacts and advances the quality of growth for the remainder of the experiments, and is a pivotal step in this thesis.

Fig.52 Experiencing Contamination

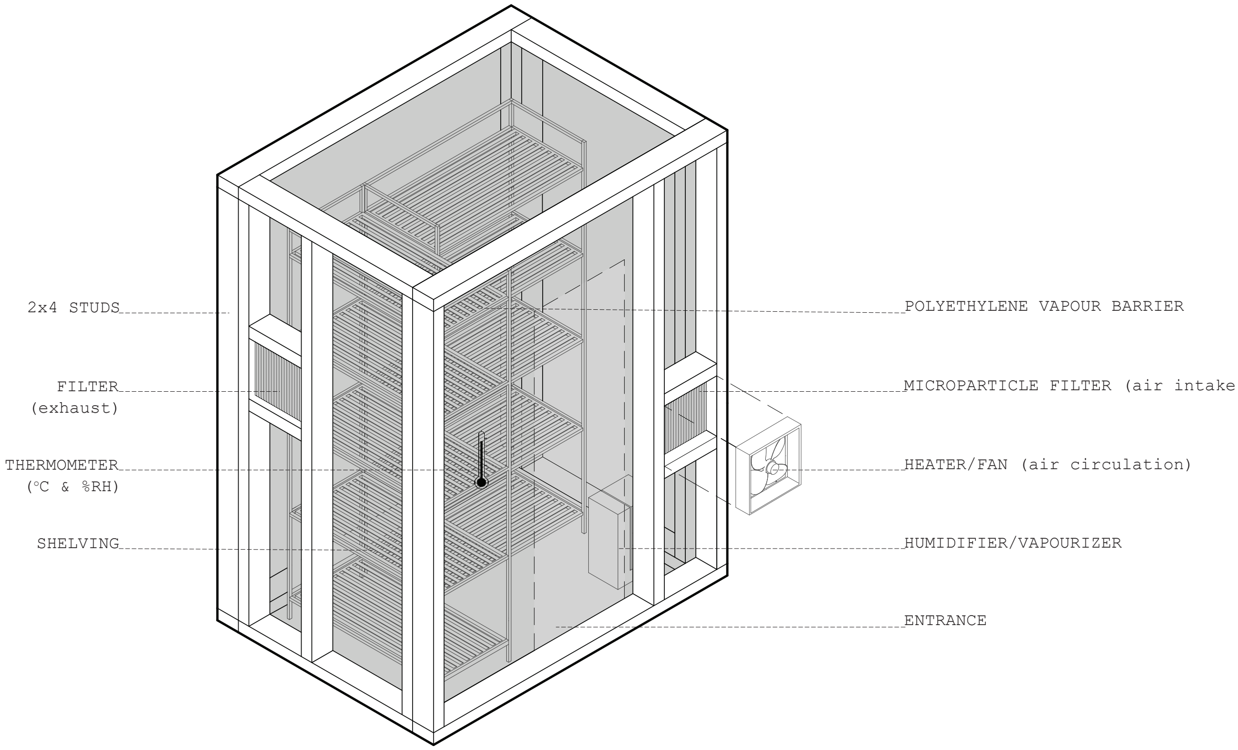


Fig.53 Designing a Grow Chamber

Fig.54 Building a Grow Chamber

Fig.55 Completed Grow Chamber

Fig.56 Entrance

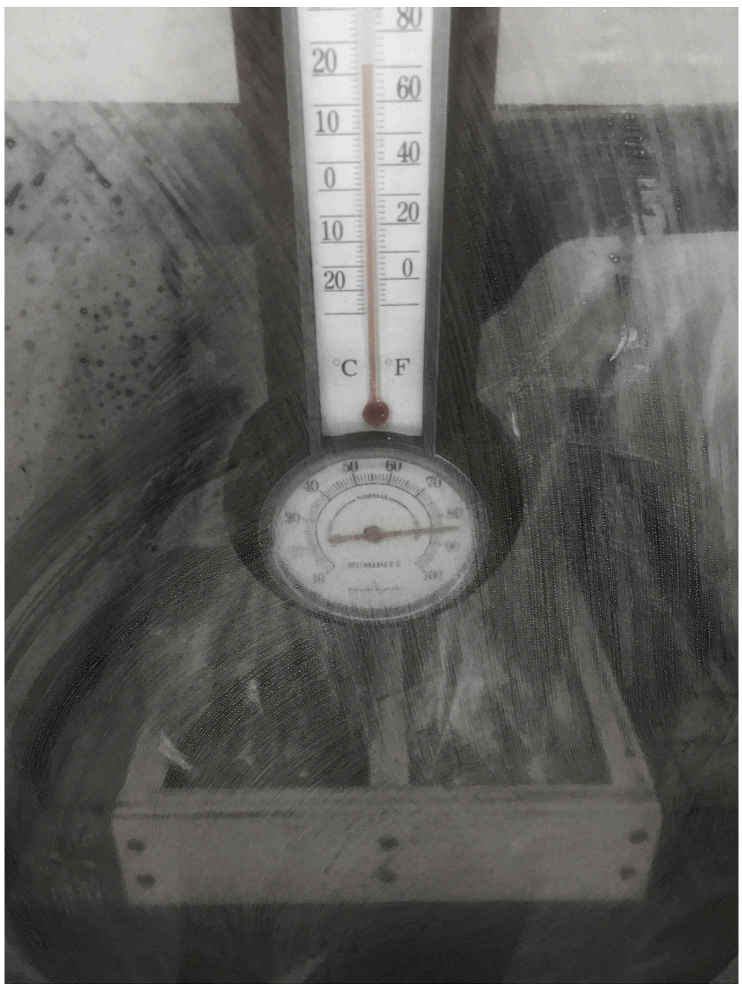


Fig.57 Reaching Ideal Growth Conditions
Very important moment in experimentation-
significantly impacting growth for the remainder of
the research


FSSC 22000 Certified

3.2.2 optimizing material preparation

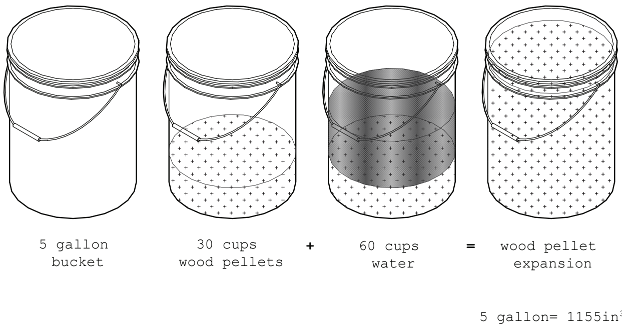


Fig.59 Sawdust Substrate Preparation

Fig.60 Fuel Pellets

Fig.61 Fuel Pellet Expansion

The pasteurization of substrate was previously conducted in small batches in a kitchen-lab setting, using readily available cookware. However, this method was rather repetitive and labour intensive, and only allowing for small-scale pasteurizing, resulting in the growth of small-scale samples. Without access to a laboratory, or industrial size equipment, this process is in need of optimization for the purpose of this study. Hardwood fuel pellets are tested for sawdust preparation. Fuel pellets are commercially used as renewable, clean burning fuel for woodstoves. These biofuels are made of compressed organic matter, generally industrial wood waste and by-products. Exposed to great temperatures in manufacturing, I predict these pellets are sufficiently pasteurized in their phase of production. Comprised of 100% hardwood with no additives, pellets can be rehydrated with boiling water, additionally pasteurizing and transforming into sawdust at the same time. This method can potentially eliminate the need for heavy equipment, and can accelerate preparation time tremendously, all needed is a bucket and boiling water.

3.2.3 optimizing formula

Fig.62 Samples Growing in Micro-filter Polybags
Inside the grow chamber

In optimizing a recipe, the fuel pellet substrate is tested with 3 new species of fungi, Ganoderma lucidum (lingzhi), Hypsizygus ulmarius (elm) , and a new variety of Pleurotus ostreatus (oyster). The samples are grown at various sizes, starting with the modular brick size, and scaled-up vertically and horizontally, in order to observe implications at various scales. 5 different sizes of moulds are created. The 3 varieties of spawn are introduced to the substrate and packed inside polybags with home-made microparticle filters. I decide to grow this batch inside prepared polybags to allow gas exchange but prevent the passage of contaminants.

In theory, once the blocks have grown sufficiently, they can be removed from the wooden frames to further colonize inside the chamber while another batch takes their place. Additionally, in the case of contamination, bags can easily be discarded without disrupting the templates or other samples. This is meant to accelerate the growth process. Upon inoculation with hard wood fuel pellets, the samples are bagged, placed inside moulds, and grown inside the chamber.

observations:

Results indicate that fuel pellets are a successful source of nutrients for the organism, and that the means of pasteurization is sufficient for healthy growth. The Ganoderma lucidum (Lingzhi) is the most compatible with the hardwood fuel pellets, resulting in the strongest and fastest colonizing combination. The Lingzhi mycelium is incredibly tough on its own in comparison to the oyster and elm, with mycelium a similar consistency to leather. This suggests that not only is the substrate important in determining the final material composition, but the fungal variety is also a differentiating factor.

All future experiments will be conducted with this promising combination of Ganoderma lucidum and sawdust.

It is important to note that as the scale of the blocks increase, the samples are still consistently forming fruitbodies before reaching full colonization. An uneven distribution of spawn throughout the substrate can lead to such inconsistencies in growth, therefore the next series of experiments will consider how to achieve a uniform spawn distribution.

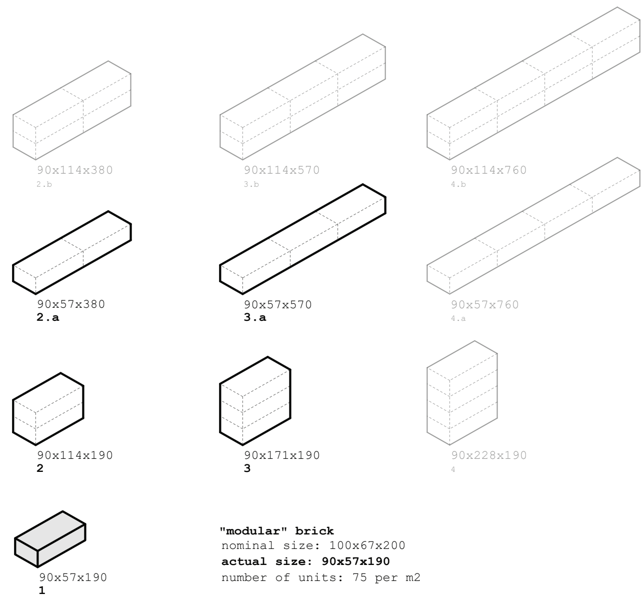


Fig.63 Sizing the Samples
Scaling up the Modular Brick

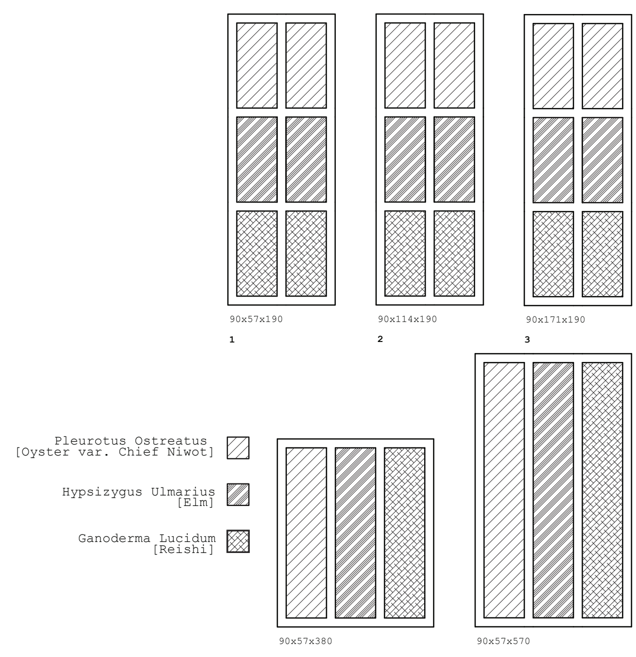


Fig.64 Testing a Variety of Fungal Species with Sawdust Substrate
Moulds of different sizes

Fig.65 Ganoderma Lucidum (Lingzhi)
Variety chosen for remainder of experiments

Fig.66 Lingzhi Bricks
Recipe chosen for remainder of experiments

Reflection

Through experiments conducted in this phase, variables have narrowed to a single fungal specie and substrate. Ganoderma lucidum and sawdust are chosen, as this combination produces a material far more durable and promising in comparison to other variables tested. By optimizing material preparation, creating a controlled environment, and conceiving a promising recipe, the next phase of this research is well equipped for:

i) conceiving a growth methodology through prototyping
ii) conducting technical assessments

Additionally, here are some images of blocks that never reach full colonization, and instead fruit and spoil. These are the results of some overgrown specimens.

Fig.67 Lingzhi Bricks
Overgrown Samples

Fig.68 Lingzhi Bricks
Overgrown Samples

Fig.69 Lingzhi Bricks
Overgrown Samples

Material Learning Through Prototyping

3.3 Material Learning Through Prototyping

By developing a strong foundation for growth in the previous section, this next phase focuses on the cultivation of various artifacts and prototypes as a means of further material learning and improving growth methodology.

Fig.70 Lingzhi Block Initial Prototype
Testing growth method and casting techniques

3.3.1 Developing Method for Homogeneous Growth

In achieving an even distribution of mycelium growth, I develop a system for mass inoculation and incubation so the substrate is fully colonized prior to the packing of moulds. The colonized substrate is then cast, removed, cured, and dried to terminate growth. Every step takes place inside the grow chamber, except dehydration. The process of inoculation involves growing the mycelium in large containers so the sawdust particles are coated in mycelium. Moulds are cast with pre-colonized substrate, and therefore require minimal time inside the casts. Once consolidated and removed, a process of curing allows for samples to develop a thick chitinous external skin, functioning as a protective barrier. The following time-line illustrates the process of growth, tracking day-by-day observations.

This method is conceived through rapid prototyping, where silicone mould making and casting techniques are implemented, and a modular unit of construction is grown as a result. As previously noted, growth is most effective in contained and individualized units of construction. Therefore, a modular assembly has been designed allowing for a controlled and compartmentalized growth. 3D printed samples are used to facilitate the process of mould making.

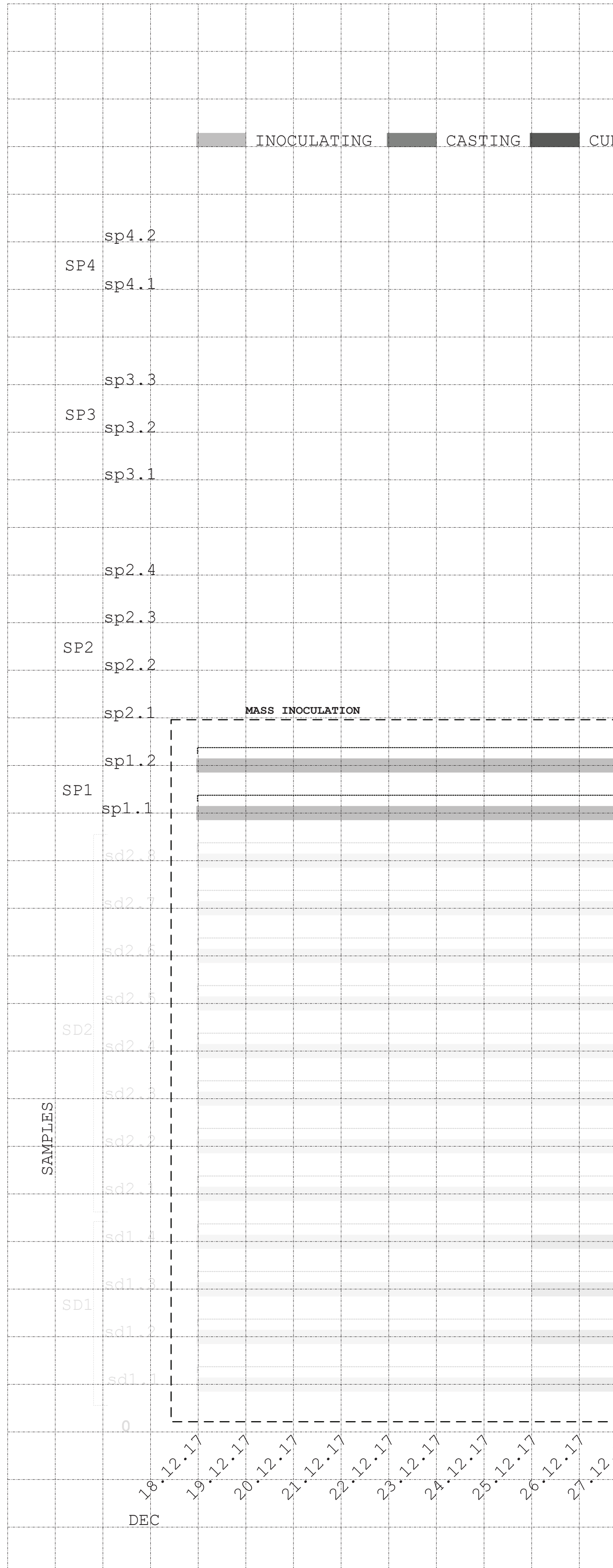
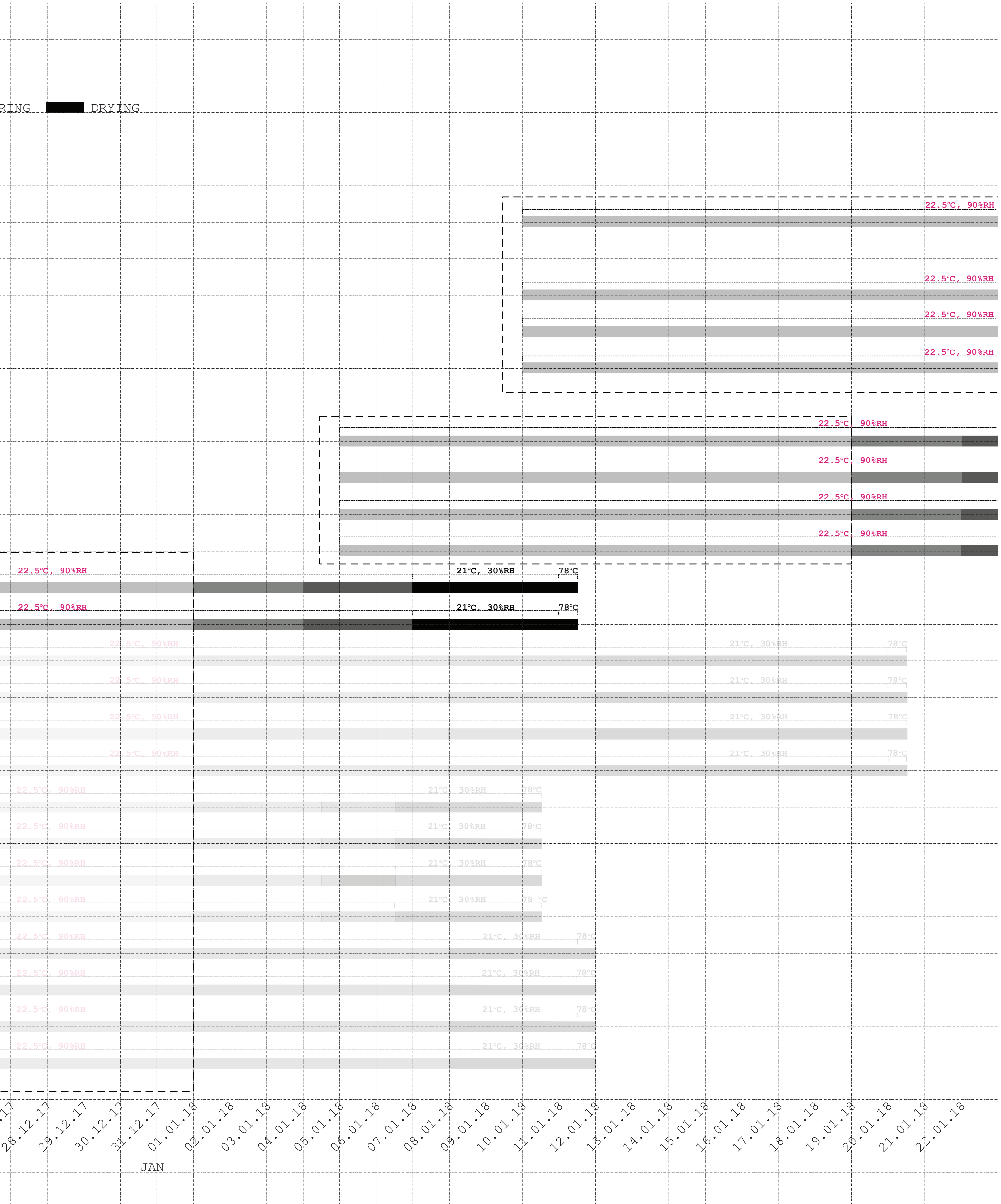


Fig.71 Time-Line of Growth, Lingzhi Blocks
Documenting day-by-day growth processes from inoculation to termination of growth.


RING
DRYING
22.5°C, 90%RH
21°C, 30%RH
78°C
28.12.17
29.12.17
30.12.17
31.12.17
01.01.18
02.01.18
03.01.18
04.01.18
05.01.18
06.01.18
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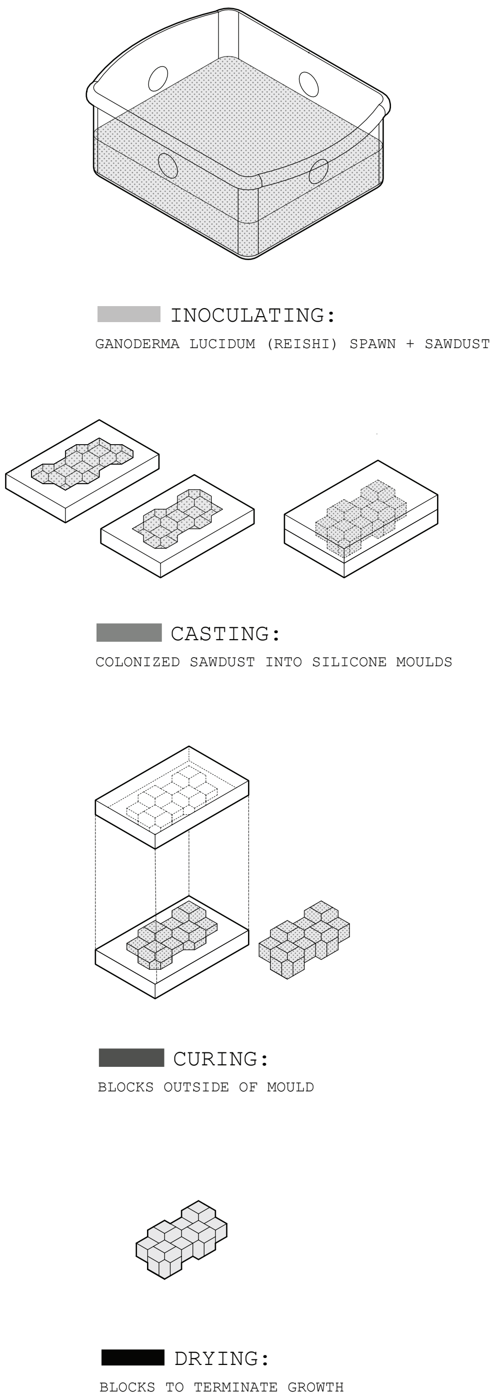


Fig.72 Determining a Growth Method

Process includes: mass inoculation of substrate, casting moulds with pre-colonized substrate, removal from cast, curing of objects, and termination of growth via dehydration

3.3.2 Material Learning Through Prototyping: Lingzhi Blocks

Through cultivating Lingzhi Blocks, I develop a successful growth model, while nurturing a set of modular, multi-configurational building units at the same time. The intension of the design is primarily to develop growth techniques, and as a result promote material interaction and user experience through tangible interlocking; a playful attempt at getting acquainted with the resulting material.

The Lingzhi Blocks are designed to be stacked, in constructing an endless array of configurations. This self-aligning, mortarless system relies on its shape for stability. It is a space-filling geometry, meaning it can tessellate and fill 3-dimensional space, with the ability to configure a mass from an aggregation of parts. The scale of these blocks are addressed through a dimensional study in the next segment of the research.
The objective is to showcase a speculative range of uses and configurations while getting to know the material practice.

Additionally, blocks can adhere to one another when kept alive, creating larger pieces from single units of construction. This is a material trait that can open some intriguing design possibilities, however depending on scale, termination of growth via dehydration may become a challenge.

From walls, to surfaces, to screens, and structures, configurations are meant to open a dialogue for contemplating applications rather than specifying definite uses. Extensive testing is required to comment on the applicability of the system for an exterior application, therefore interior uses are more feasible at this stage.

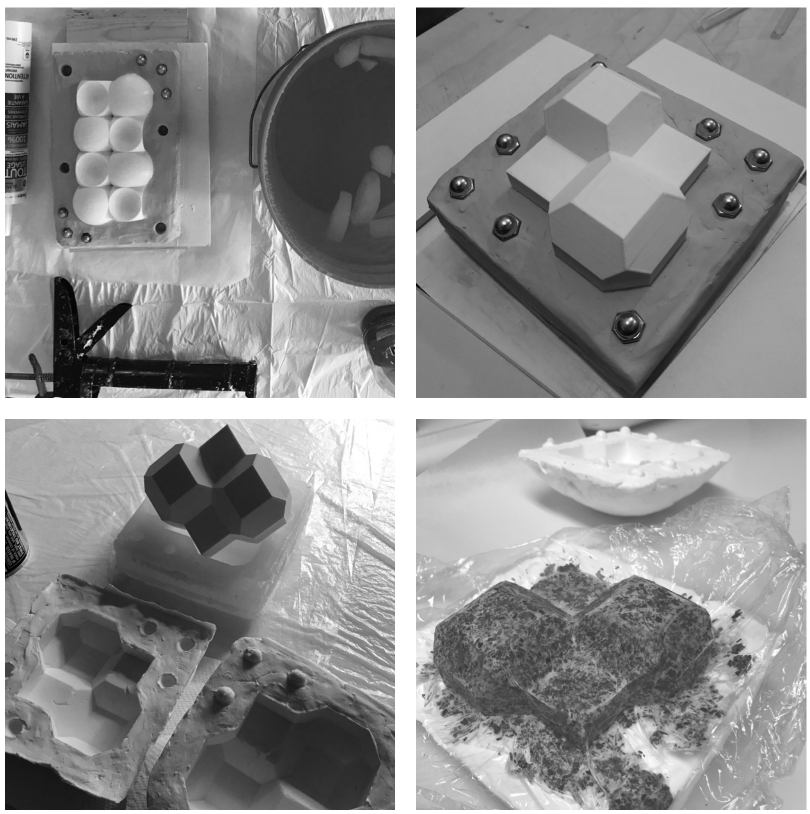
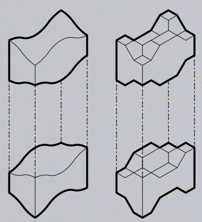


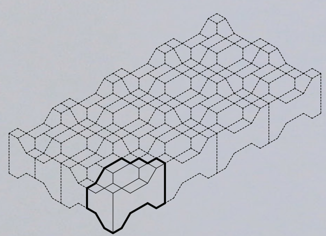
Fig.74 Silicone Mould Making
Growing Initial Prototype

Fig.75 Process Images
Material Learning Through Prototyping

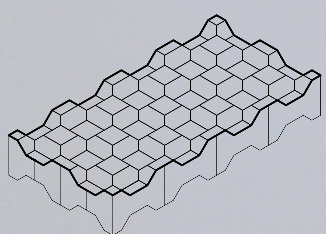
Block Evolution
Towards a Space Filling Logic



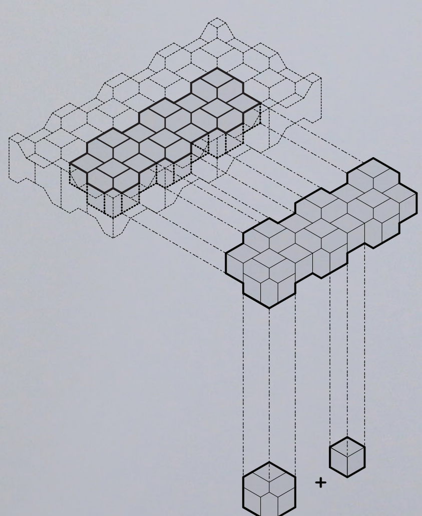
Derived from the osteomorphic block

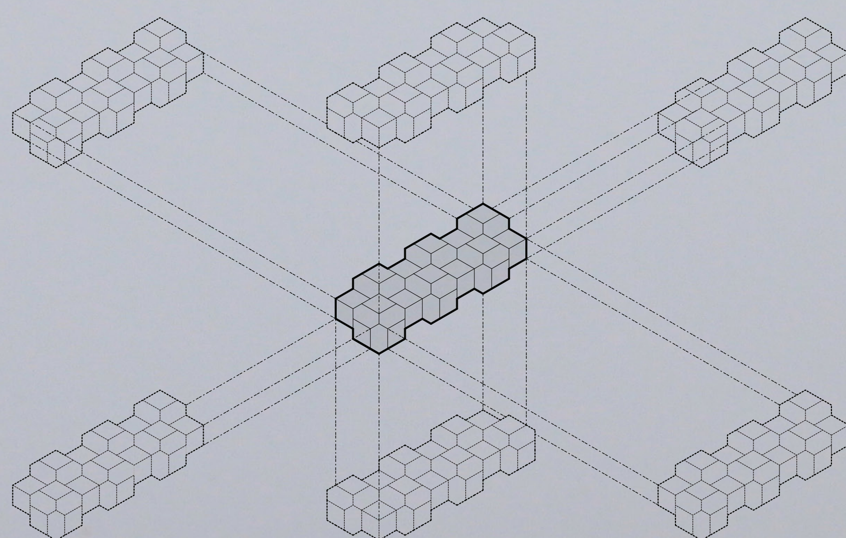


Tiling block



Conception of new form





Lingzhi Block 1.0

Chamfered Cube (Truncated Rhombic Dodecahedron) + Cube
Space filling polyhedra combination

Fig.76 Lingzhi Block Evolution
Logic of Block and Assembly

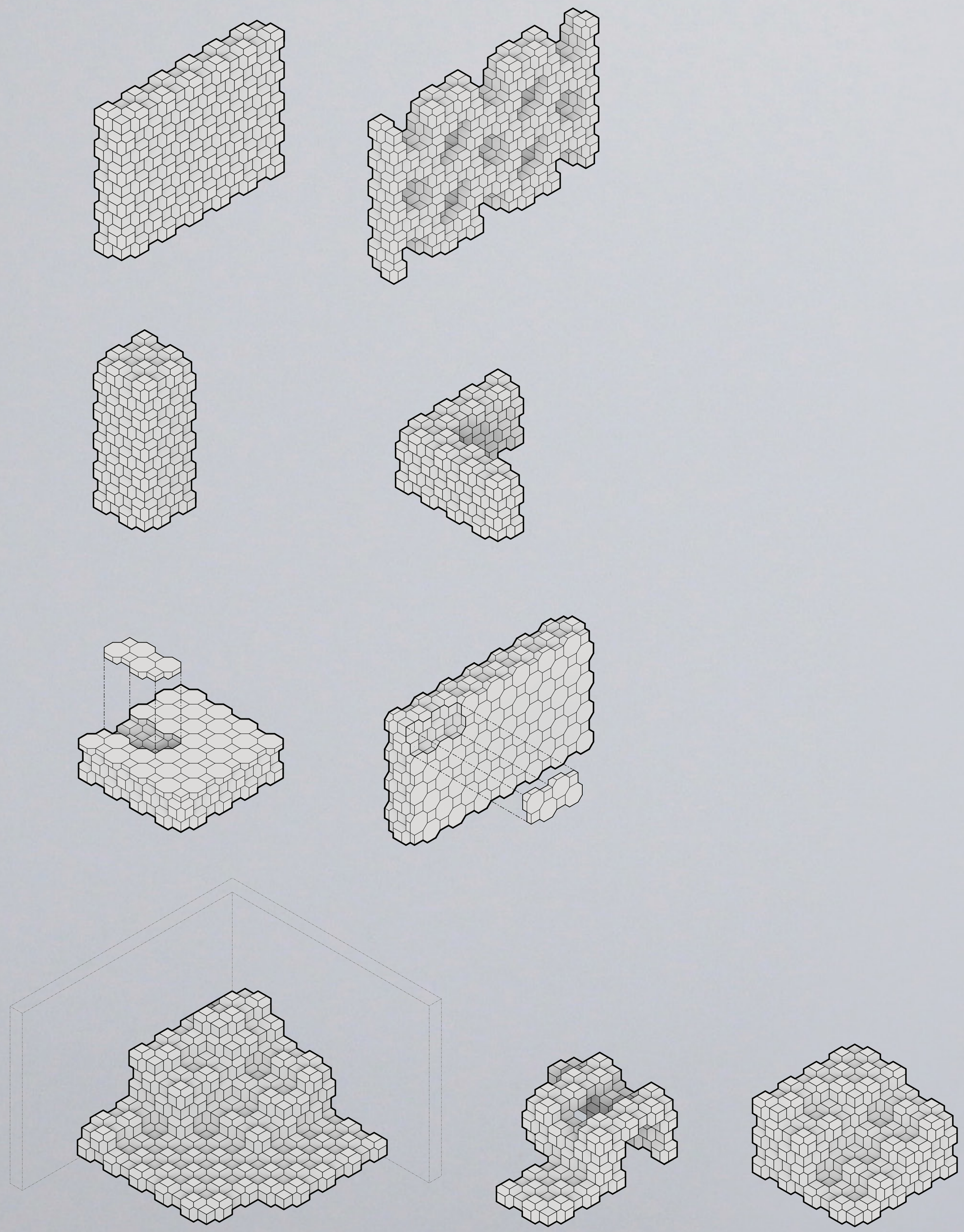
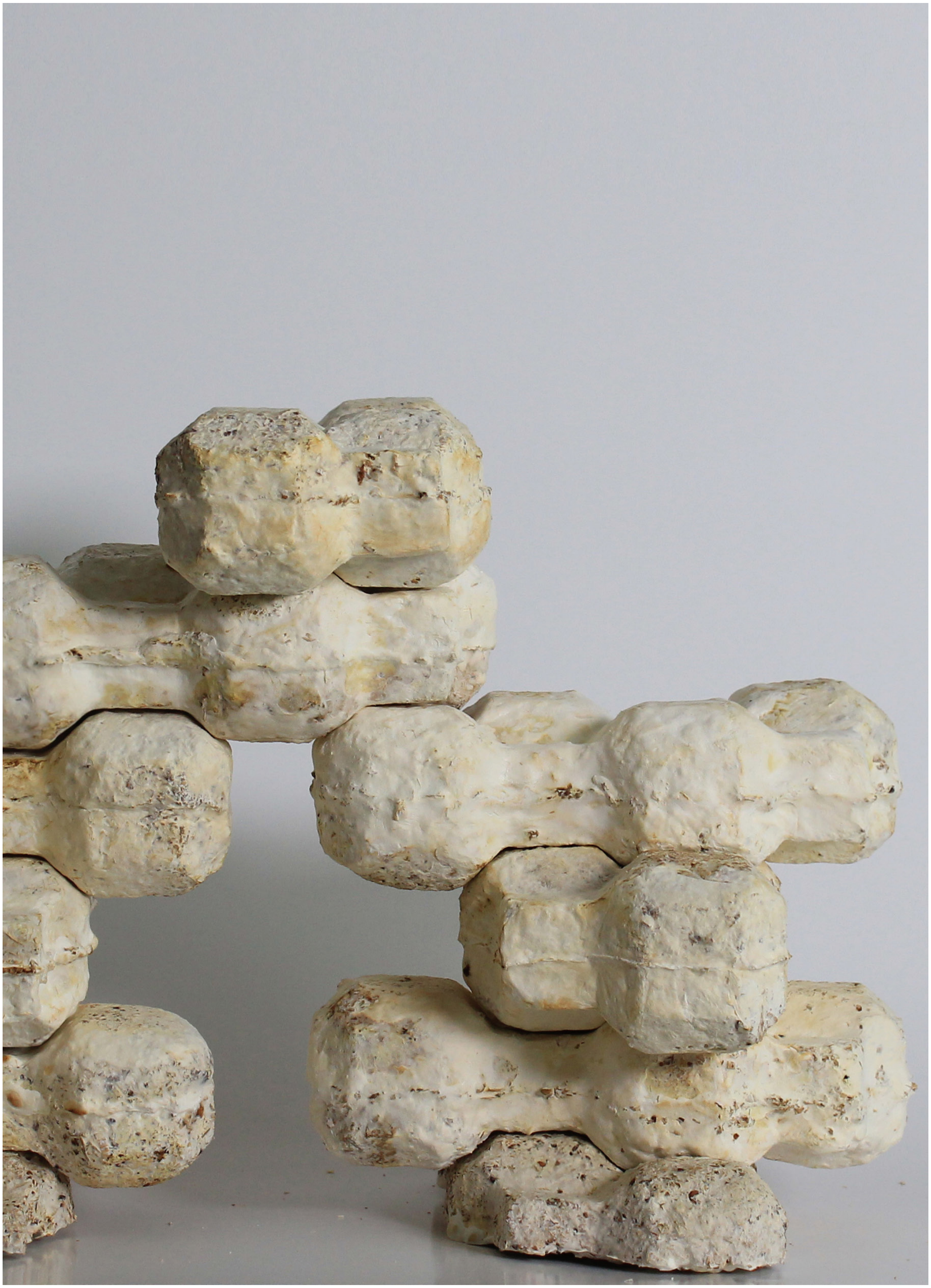


Fig.80 Configurations
Flexibilities in Form and Function



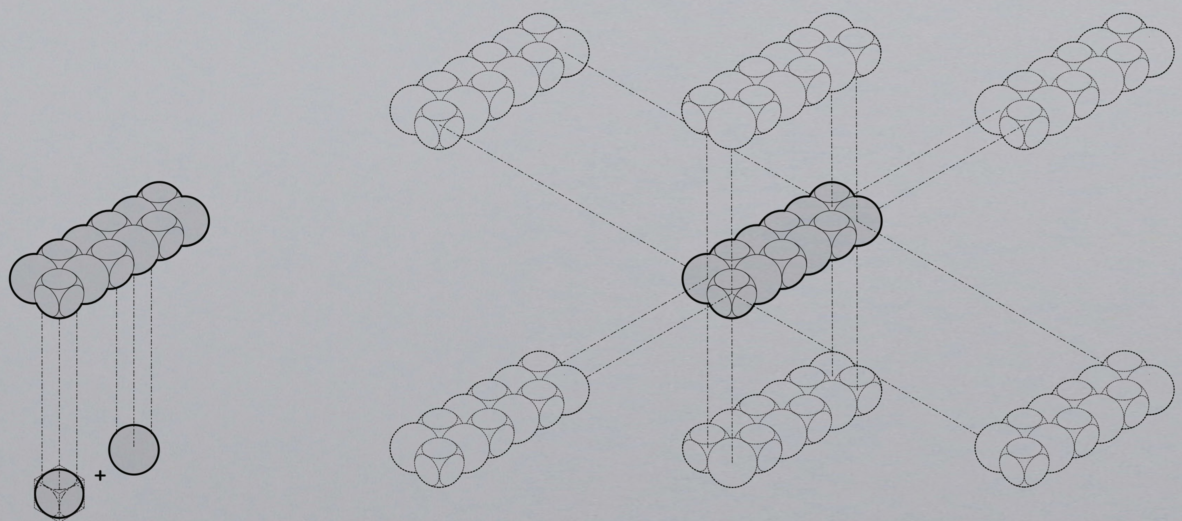


Fig.95 Lingzhi Block 2.0
Same configuration logic, spherical in form

Fig.96 Hyphal Bonding as Joinery
Fusing as means of assembly. Same logic as projects:
Mycotexture and Modular Mycelia

Fig.97 Hyphal Bonding as Joinery
Fusing as means of assembly

3.3.3 Material Handling

Additionally, observations indicate that grown objects cannot be cut, heavily sanded, or altered for use, as material composition changes. For this reason, the design of a specific modular assembly unit was conceived for this study.

The interior composition of grown objects differ drastically from the exterior. Although internally fused together through hyphal bonding, the outer layer is a much thicker chitinous skin acting as a protective shield. Once penetrated, the shield is broken, and the interior is susceptible to crumbling and damage. The rigid structure of the chitinous cell walls function as protection against hostile conditions encountered by fungi.[44] This protective layer acts as a shield against environmental stresses and foreign substances such as competing organisms, "while allowing for the fungal cell to interact with its environment".[45] The chitin also behaves as a "specialized support system" for the fungal network, preserving moisture and nutrients within the organism.[46] Thus, fungal cell walls are dynamic structures that are essential for the viability of the organism. As a result, the exterior casing of grown objects differ substantially in material property, which signifies that carving down biofabricated objects will alter and compromise the structure of the specimen. Therefore, conceiving a final form prior to cultivation would be suggested.

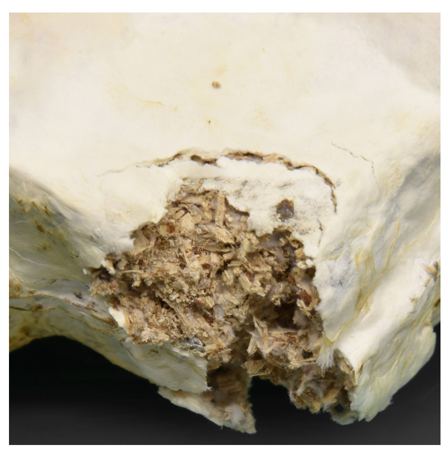


Fig.98 Material Handling
Differentiation between interior and exterior

44 Jean-Paul Latgé, "The Cell Wall: A Carbohydrate Armour for the Fungal Cell," Molecular Microbiology 66, no. 2 (2007), 279
45 Shaun M. Bowman and Stephen J. Free, "The Structure and Synthesis of the Fungal Cell Wall," BioEssays 28, no. 8 (2006), 799
46 Gina Hamilton, "Chapter 1: What Are Fungi?" in Kingdoms of Life-Fungi (Lorenz Educational Press, Milliken Publishing Company, 2006), 6.

This was one of the greatest challenges during the design process of David Benjamin's Hy-fi.[47] The standard brick can be cut to create desired formations, however the structural integrity of the mycelium block alters and weakens if cut, as the interior and exterior have different characteristic.[48] Therefore, 3 modules of bricks had to be designed and grown (quarter brick, half brick , and full brick), as cutting was unviable.[49] The distribution of these modules for a complex double curve structure was another challenge, which was assigned through means of computation; the form was meticulously designed and resolved prior to the growth of bricks.

3.3.4 Material Learning Through Prototyping: Everyday Objects

Using the growth methods conceived through the development of the Lingzhi Blocks, I grow a series of everyday-objects using more intricate moulding techniques. A fascinating observation is learned through this process of prototyping; the self-healing capacities of mycelium are revealed. In removing objects from moulds, almost every sample is damaged or cracked. As forms are still alive and soft in this state, the curing process gives the opportunity for the mycelium to self-repair. By bandaging damaged areas, and placing back inside the grow chamber, the cracks are fully mended in less than a day.

Fig.99 Cracks
Object in process of curing and self-repair

47 David Benjamin, "Adaptation" (lecture), 57:50-59:56, January 21, 2015, accessed May 08, 2018, https://vimeo.com/117833339.
48 Ibid.
49 Ibid.

Fig.101 Material Learning Through Prototyping
Artifact was able to self-heal, leaving no trace of damage

Fig.102 Material Learning Through Prototyping
Creating user experience and material familiarity

Fig.103 Testing Intricate Moulds
Bandaging damage for self-repair

Fig.105 Material Learning Through Prototyping
Creating user experience and material familiarity

Fig.106 Lamp Prototype
Creating user experience and material familiarity

Dimensional Study

3.4 Dimensional Study

As scale is a re-occurring topic of discussion, a dimensional study is conducted to determine a correlation between growth time, drying time, and size of specimens. Using the growth techniques developed in the previous experiments, 1" to 8" cubes are successfully grown. Samples are cast at two different times during their incubation process, precisely 7 and 14 days after inoculation, to determine if any differences occur in surface texture or mechanical performance based on the time of casting. Visually, samples cast at 7 days (SD1) do not reach the level of textural uniformity as the ones cast at 14 days (SD2), and maintain a woody finish. Upon drying, the mycelium colour slightly alters from white to beige, with a chalky finish. Both set of samples feel rigid to the touch, however compression testing can help differentiate their mechanical performances.

Fig.108 Cultivated Cubes 1-8 Inch

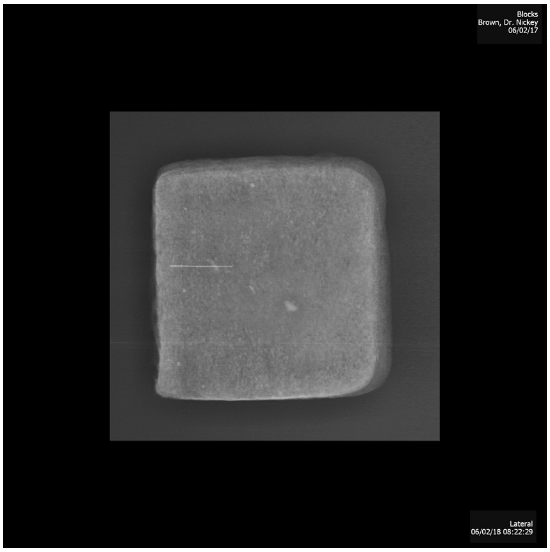


Fig.109 X-Ray of 7 Inch Cube
Uniform appearance

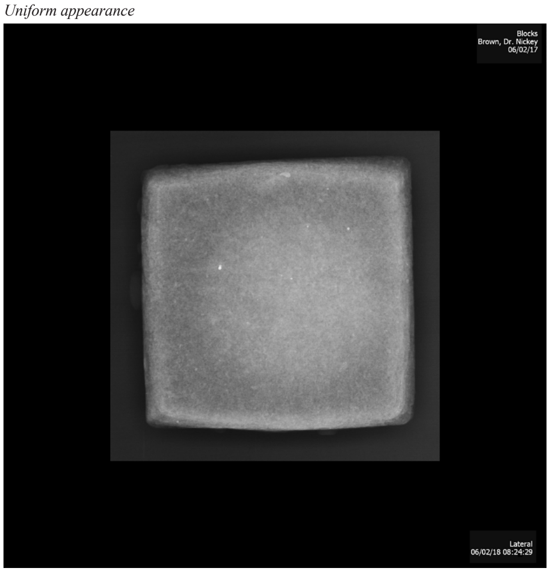


Fig.110 X-Ray of 8 Inch Cube
Radian marking suggesting residual moisture

The time of growth is recorded in a time-line.
1" - 4" samples took exactly half the time to cast and cure in comparison to the 5"- 8" cubes.

This can suggest that by doing a bulk inoculation and compacting pre-colonized substrate inside moulds, greater scales become more easily attainable, taking far less time to grow. The limitations and implications that would hinder the successful growth of larger scale samples are no longer uniformity of growth or concerns of time, but rather the implications of contamination and moisture as depths increase.

To address concerns of drying, samples are X-rayed with the objective of having an internal view of the specimens. Although most of the resulting X-rays are uniform internally, the 8" cube has a radial marking in the center, which can suggest residual moisture. This marking is not apparent in any other sample. This observation can suggest that moisture can potentially become an issue at larger scales, and that drying techniques must be further investigated. However, creating perforated or hollowed forms to reduce thickness and volume can address this preoccupation as larger objects are grown.

This study suggests that Lingzhi blocks can be grown at larger scales, however extra caution must be taken in the drying process to ensure no residual moisture.

Fig.111 Sample SDI (left) Sample SD2 (right)
SD1- 7 day incubation period
SD2- 14 day incubation period

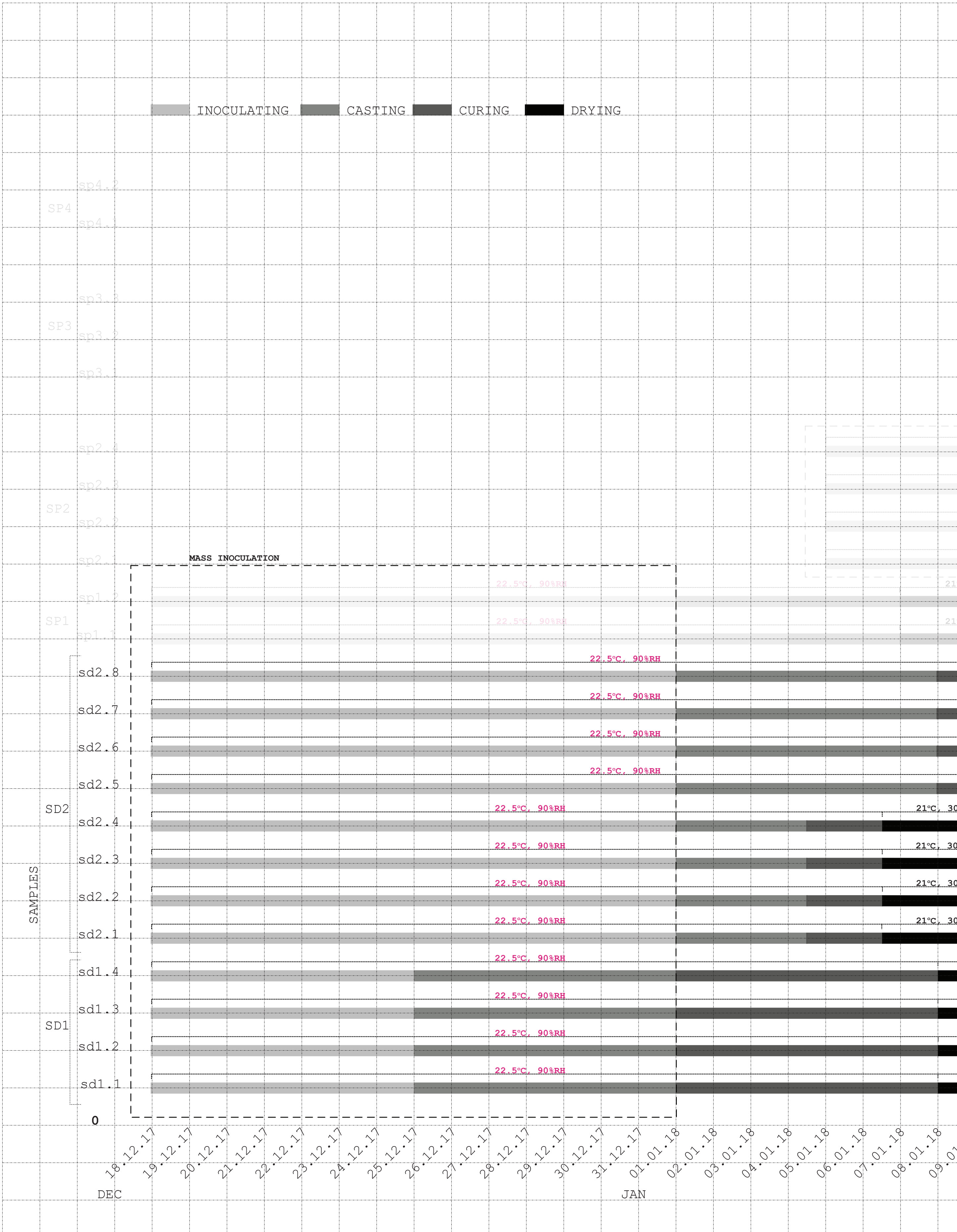

INOCULATING
CASTING
CURING
DRYING
MASS INOCULATION
SAMPLES
SD2
SD1
sd2.8
sd2.7
sd2.6
sd2.5
sd2.4
sd2.3
sd2.2
sd2.1
sd1.4
sd1.3
sd1.2
sd1.1
22.5°C, 90%RH
0
18.12.17
19.12.17
20.12.17
21.12.17
22.12.17
23.12.17
24.12.17
25.12.17
26.12.17
27.12.17
28.12.17
29.12.17
30.12.17
31.12.17
01.01.18
02.01.18
03.01.18
04.01.18
05.01.18
06.01.18
07.01.18
08.01.18
DEC
JAN

Fig.112 Tracking Growth of Dimensional Samples
Daily documentation of growth process

Fig.113 Process Images of Cubic Growth
Incubating, Casting, Curing

Aesthetic Qualities

Fig.114 Achieving Good Representation of Growth
Seamless Surface Texture

3.5 Aesthetic Qualities

In growing samples for the dimensional study I was able to achieve seamless surface texture, with the occasional fruitbody.These imperfections were a personal preference, as I consciously decided when to terminate growth.

These next series of photos are intended to express the experiential qualities of a fungal-based material practice:

3.5.1 Material Texture

In achieving seamless growth, many different surface textures have been conceived along the way. Through extensive experimentation, it is clear that timing is crucial in this material practice, and that understanding and working within the life-cycle of fungi allows for a variety of textures and finishes. It is however, entirely possible to achieve a perfect uniformity by terminating growth at a very specific time

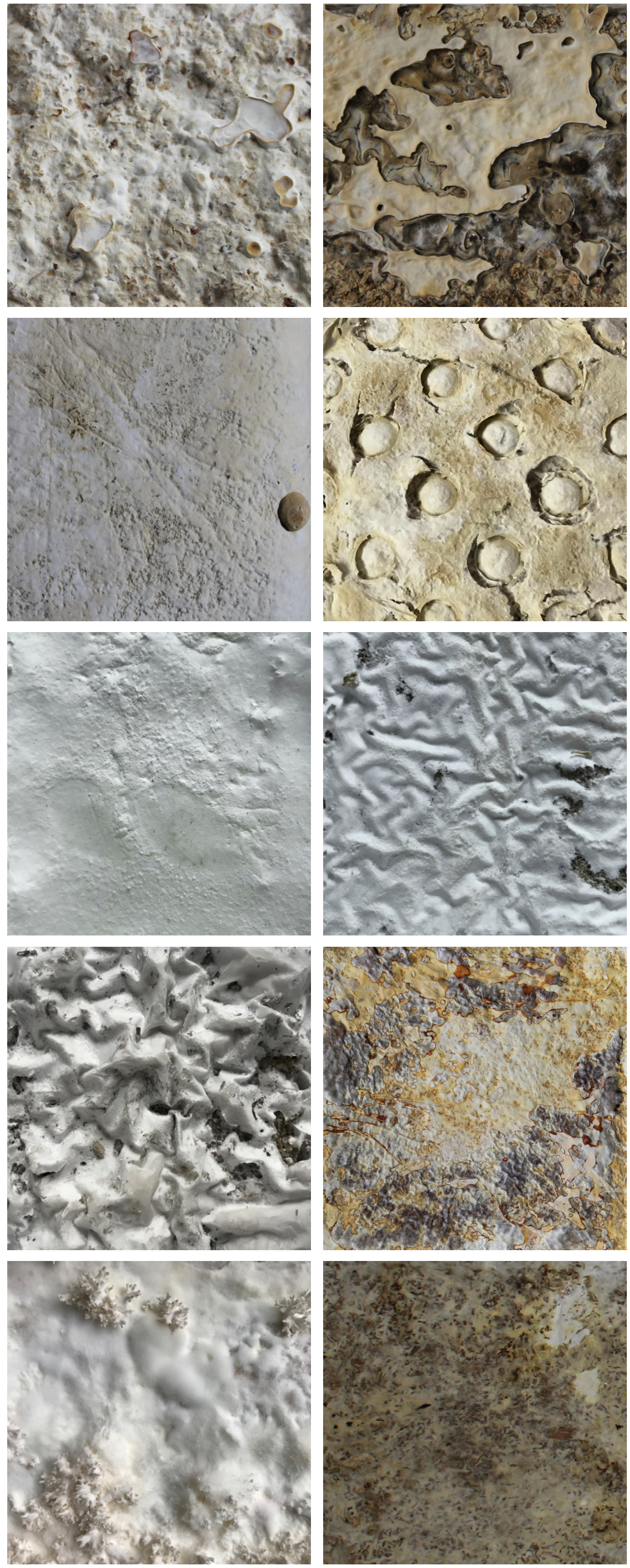


Fig.127 Surface Textures
Variety of textures achieved throughout study

Fig.128 Surface Texture
Homogeneous Skin

Fig.129 Compression Testing
University of Waterloo, Department of Civil Engineering

Technical Qualities

3.6 Technical Qualities

Using the samples grown for the dimensional study, a series of compression tests are conducted at the University of Waterloo, Department of Civil and Environmental Engineering. Both SD1 and SD2 samples are subjected to testing. SD1 samples experience more permanent damage with a lower peak strength, suggesting that a 14 day incubation period is beneficial in achieving a better performance.

Interestingly, many samples flatten instead of break, suggesting a level of elasticity in material behaviour.

Data is plotted on a stress-strain graph. SD2 samples are recorded, with a curve of best fit for all specimens tested. The slope of the blue line is the elastic limit; the extent to which the material can take force without permanent deformation and return to its original state. The peak strength is also noted; the maximum stress the material can withstand before failing completely.

A similar experiment is conducted at the University of Anchorage, Alaska, where the physical and mechanical

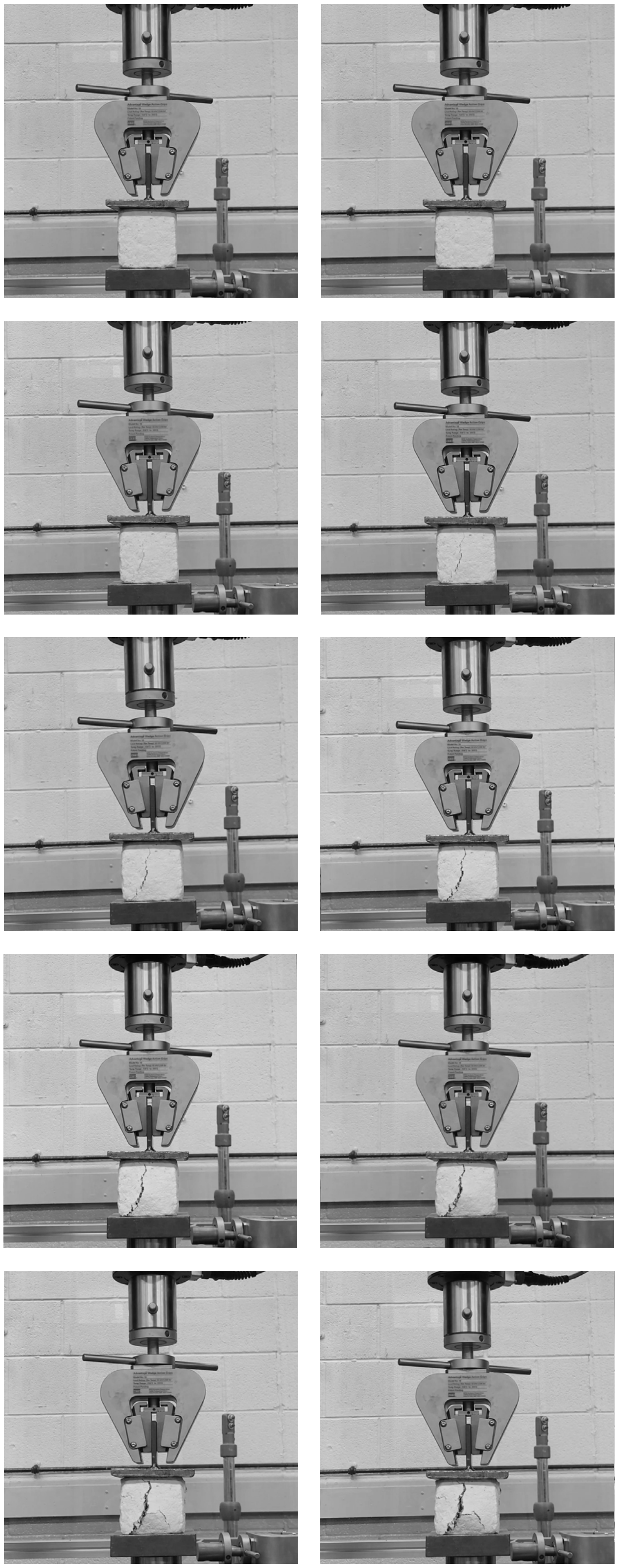


Fig.130 Sequence of Compression Test
SD2 Samples

Fig.131 SD1 Samples

Fig.132 SD2 Samples

Fig.133 SD1 Failure

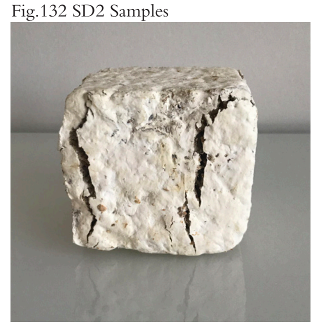


Fig.134 SD2 Failure

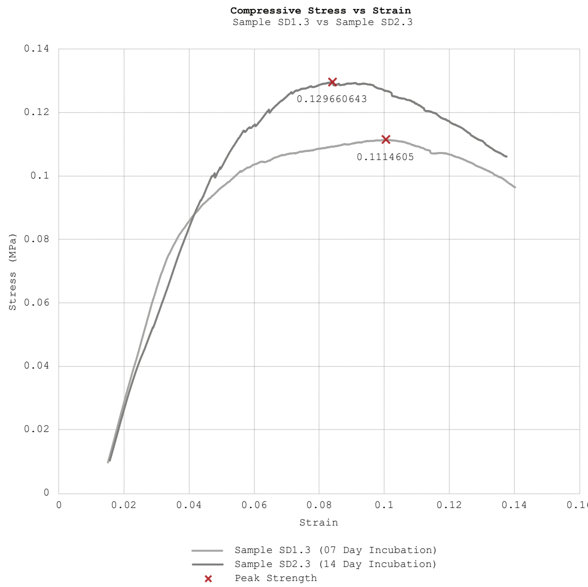


Fig.135 Stress-Strain Graph
Comparing SD1 and SD2 Samples

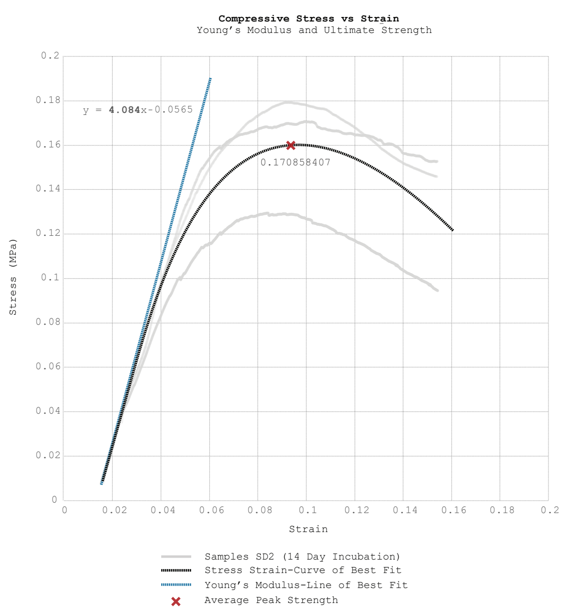


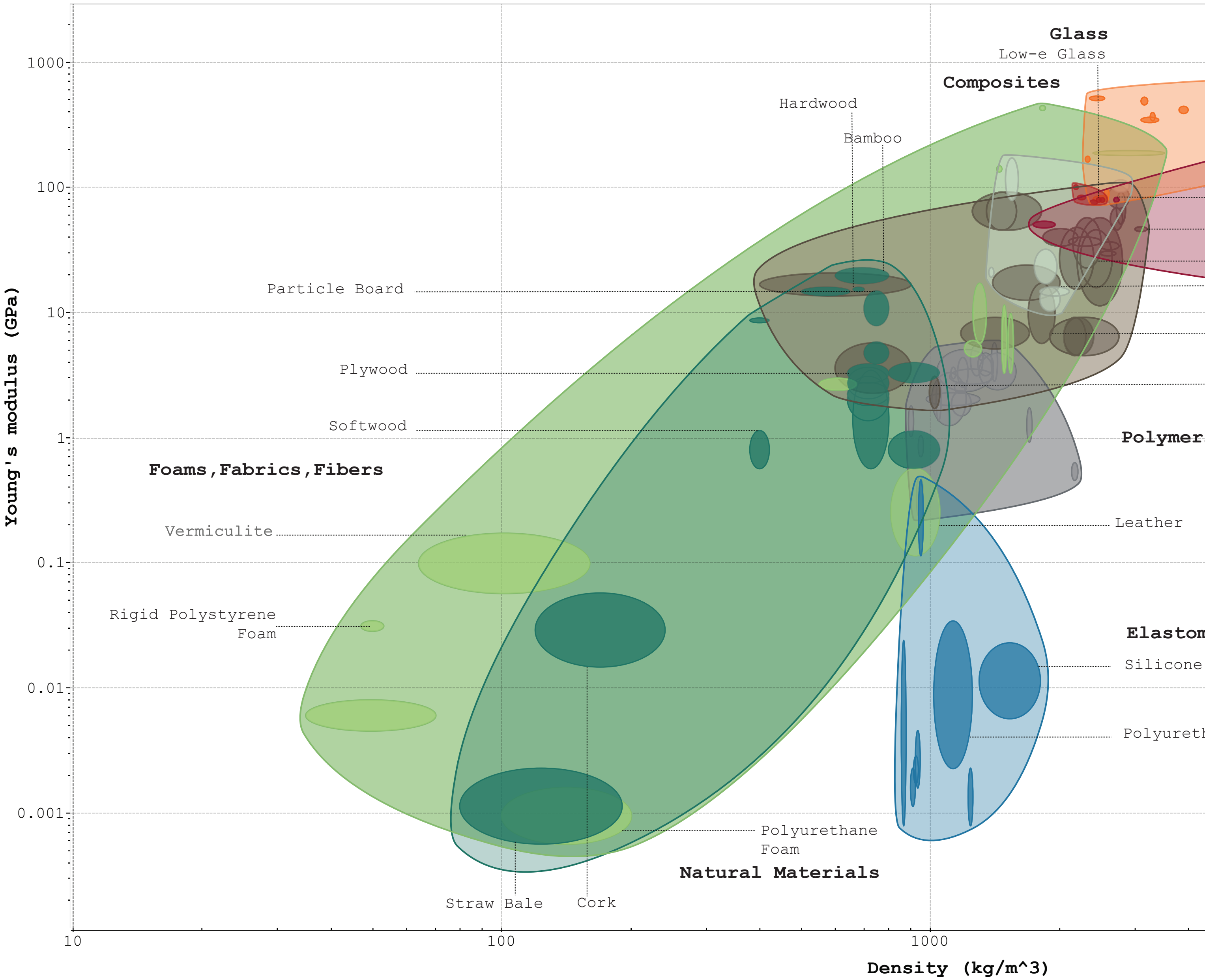
Fig.136 Stress-Strain Graph
Young's Modulus and Peak Strength

properties of a fungal-based biofoam are tested under compression.[50] I extrapolate this data as a comparison point to my own, but also to increase my data range to have more extensive information when comparing fungal-based materials to other architectural materials.

In pursuit of this comparison, I use a software called CES eduPack developed by Mike Ashby of Cambridge University, known for his contributions in Materials Science. The software is essentially a comprehensive database of materials information used to understand classes of materials, their properties, environmental impacts, and even costs. Materials comparison is at the core of this software, allowing users to explore and graph any material property against any other material property.[51]

50 Zhaohui (Joey) Yang et al., "Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam," Journal of Materials in Civil Engineering 29, no. 7 (2017)

51 CES EduPack," Granta Design, , accessed March 02, 2018, http://www.grantadesign.com/education/edupack/.



Glass
Low-e Glass
Composites
Hardwood
Bamboo
Particle Board
Plywood
Softwood
Foams,Fabrics,Fibers
Vermiculite
Rigid Polystyrene Foam
Polymer
Leather
Elastom
Silicone
Polyureth
Polyurethane Foam
Natural Materials
Straw Bale
Cork
Young's modulus (GPa)
Density (kg/m^3)
1000
100
10
1
0.1
0.01
0.001
10
100
1000

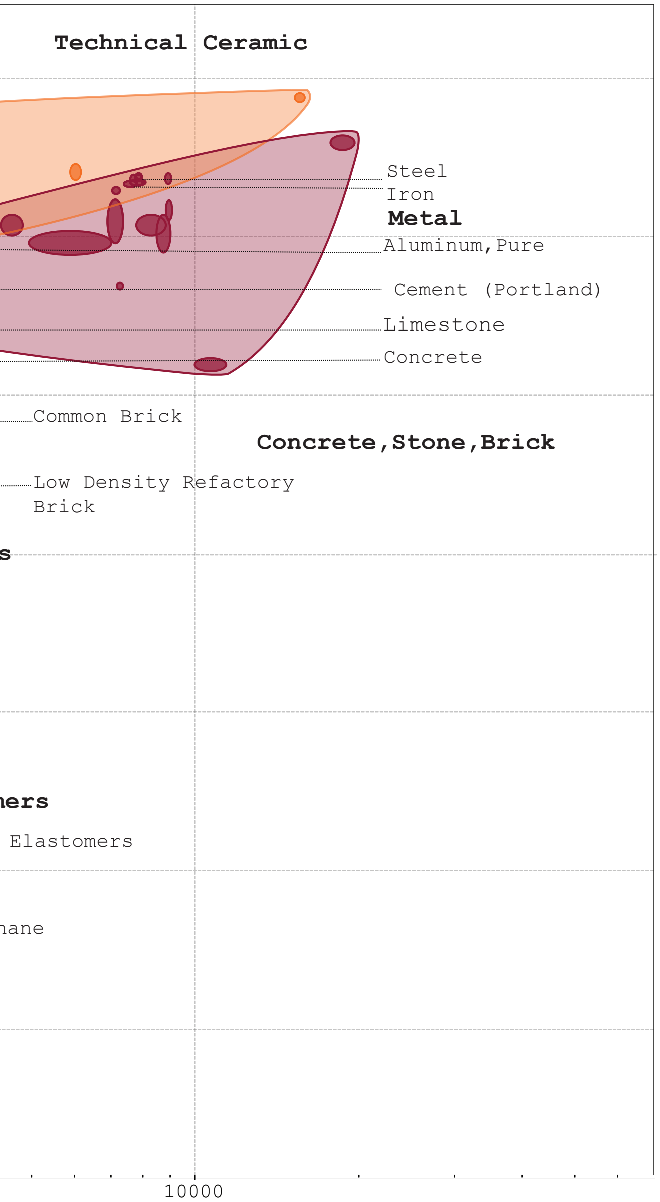


Fig.137 CES eduPack Material Comparison
Ashby Chart: Young's Modulus vs Density
Architectural materials family database

Most interestingly, users can input their own data to have a direct visual comparison to other materials. This Materials Comparison Chart shows the existing material families within the Architectural database of the software. [Fig. 137]

Young's Modulus (GPa) vs Density (kg/m3):

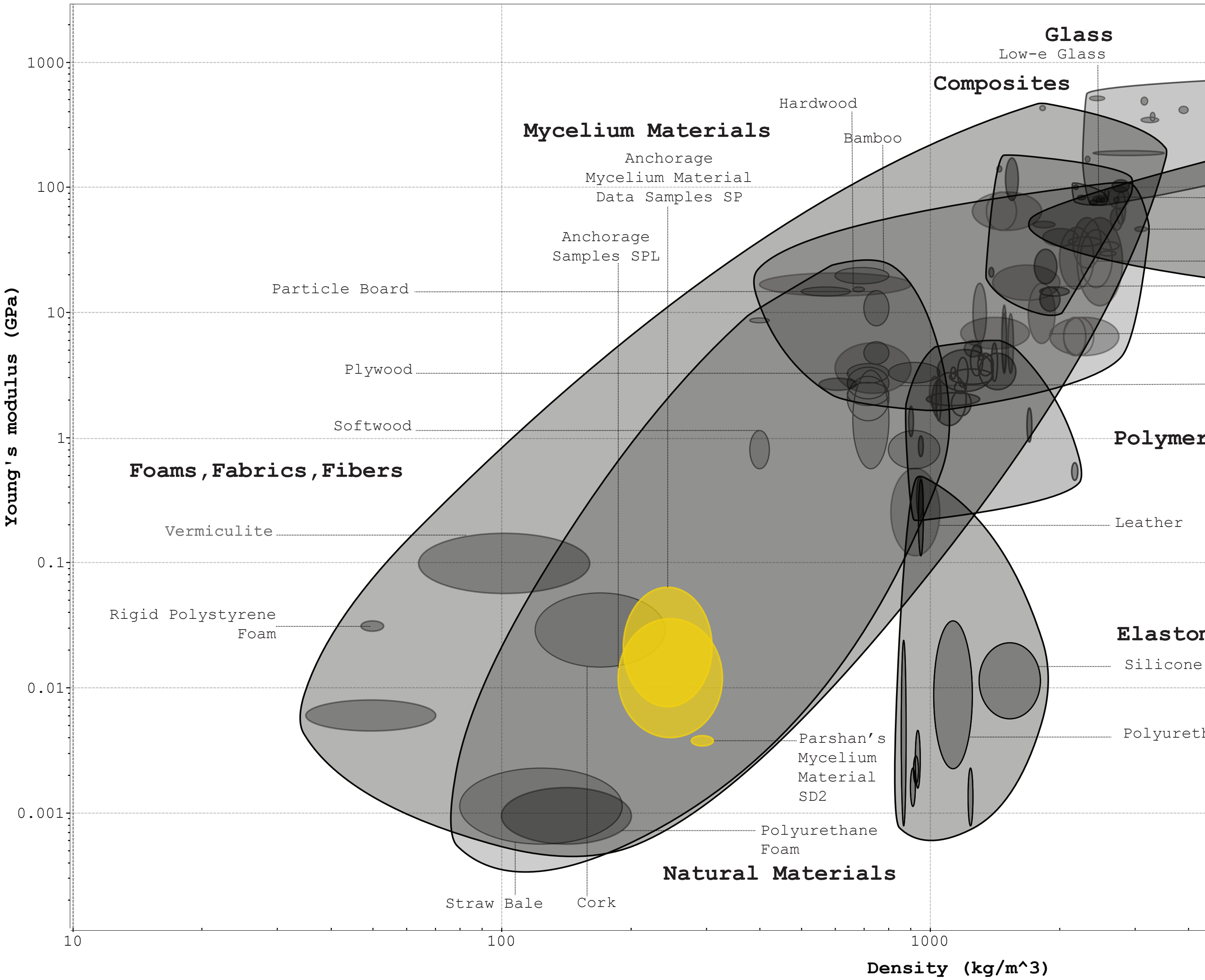
This chart is meant to guide selection for light, stiff material components.[52]

I input 2 sets of data- my own, and the data collected from the University of Anchorage biofoam study. In comparing Young's Modulus to Density, it is apparent that all data lands within the Natural Materials and Foams families, in relatively close proximity. In this comparison chart, mycelium based-materials are most comparable to cork and are in the same vicinity as polyurethane foam and straw bale construction, although more stiff and dense than both. [Fig. 139]

Compressive Strength (MPa) vs Density (kg/m3):

Compressive Strength (MPa) vs Density (kg/m3) are also plotted. The mycelium-based materials achieve ratios comparable to those of cork, polyurethane foam, straw bale, and metal foam, with also a similar compressive strength to asphalt concrete, bitumen, autoclaved aerated concrete (AAC), and ceramic foam, although much lower in densities. [Fig. 140]

52 Michael Ashby, "CES EduPack 2010 Guide: Material and Process Selection Charts," Granta Design, January 2010, 5



Data Range, Parshan's Compression Tests							
Description	Batch Name	E (GPa) (min)	E (GPa) (max)	Density (Kg/m3) (min)	Density (Kg/m3) (Max)	Compressive Strength (MPa) (Min)	Compressive Strength (MPa) (Max)
2 week incubation	SD2	0.00334	0.00408	237.3	266.97	0.1296606	0.17947

Data Range, University of Alaska Anchorage									
Description	Batch Name	E (GPa) (Min)	E (GPa) (Max)	Density (Kg/m3) (Min)	Density (Kg/m3) (Max)	Poisson's Ratio (min)	Poisson's Ratio (max)	Compressive Strength (MPa) (Min)	Compressive Strength (MPa) (Max)
2 week incubation	SP	0.007	0.060	165	265	0.15	0.45	0.02	0.375
4 week incubation	SPL	0.004	0.034	160	280	0.25	0.5	0.05	0.7

Fig.138 Data Collection
Parshan's Data
University of Alaska Anchorage, Data Retrieved From: Zhaohui (Joey) Yang et al., "Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam," Journal of Materials in Civil Engineering 29, no. 7 (2017

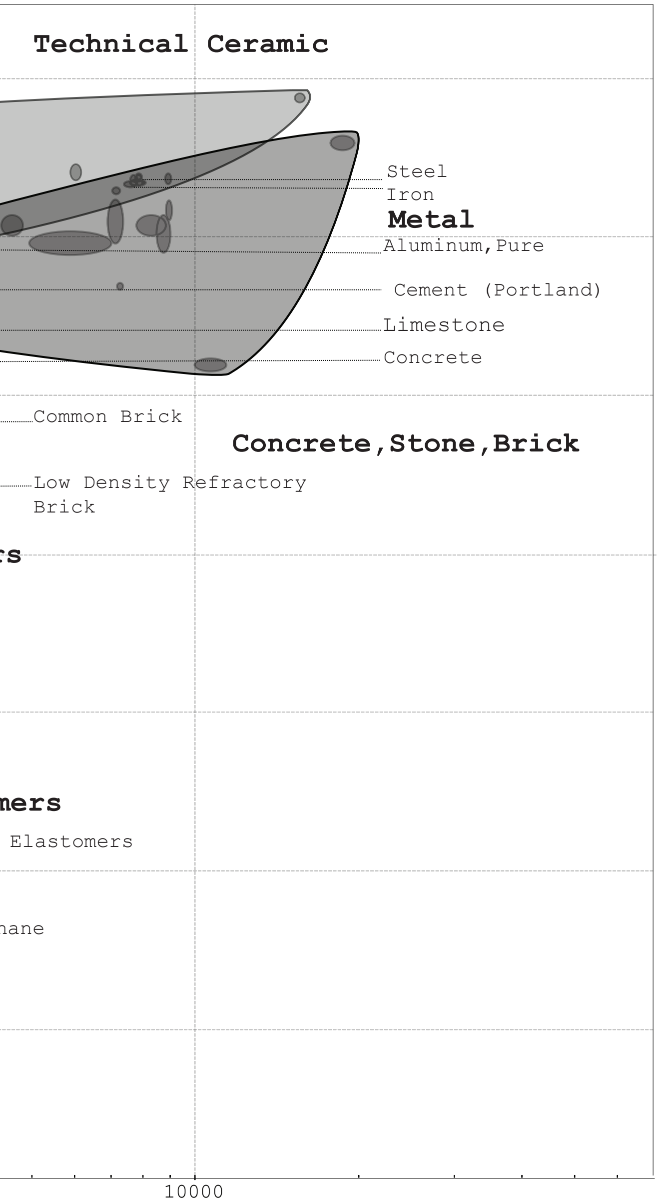
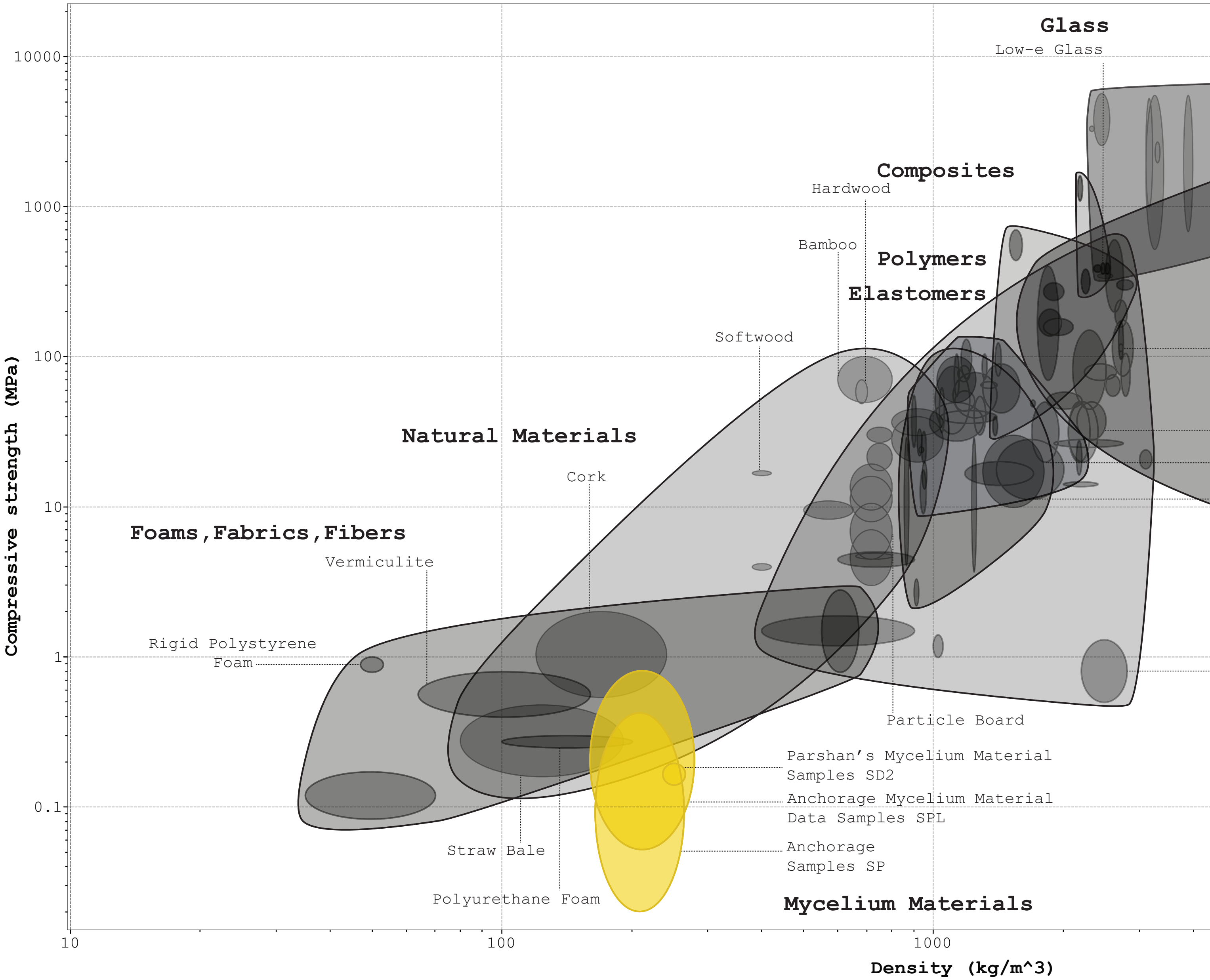


Fig.139 Young's Modulus vs Density
Ashby Chart: Highlighting mycelium-materials based on data collected


Glass
Low-e Glass
Composites
Hardwood
Bamboo
Polymers
Elastomers
Softwood
Natural Materials
Cork
Foams,Fabrics,Fibers
Vermiculite
Rigid Polystyrene Foam
Particle Board
Parshan's Mycelium Material Samples SD2
Anchorage Mycelium Material Data Samples SPL
Anchorage Samples SP
Straw Bale
Polyurethane Foam
Mycelium Materials
Compressive strength (MPa)
10000
1000
100
10
1
0.1
10
100
1000
Density (kg/m^3)

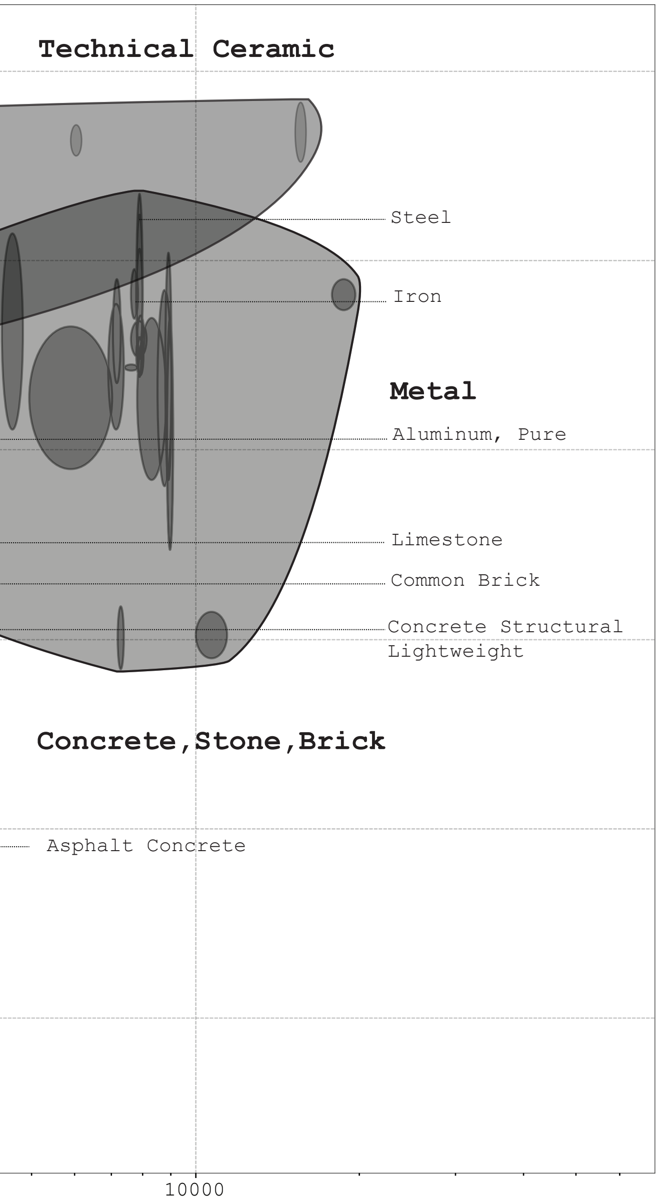
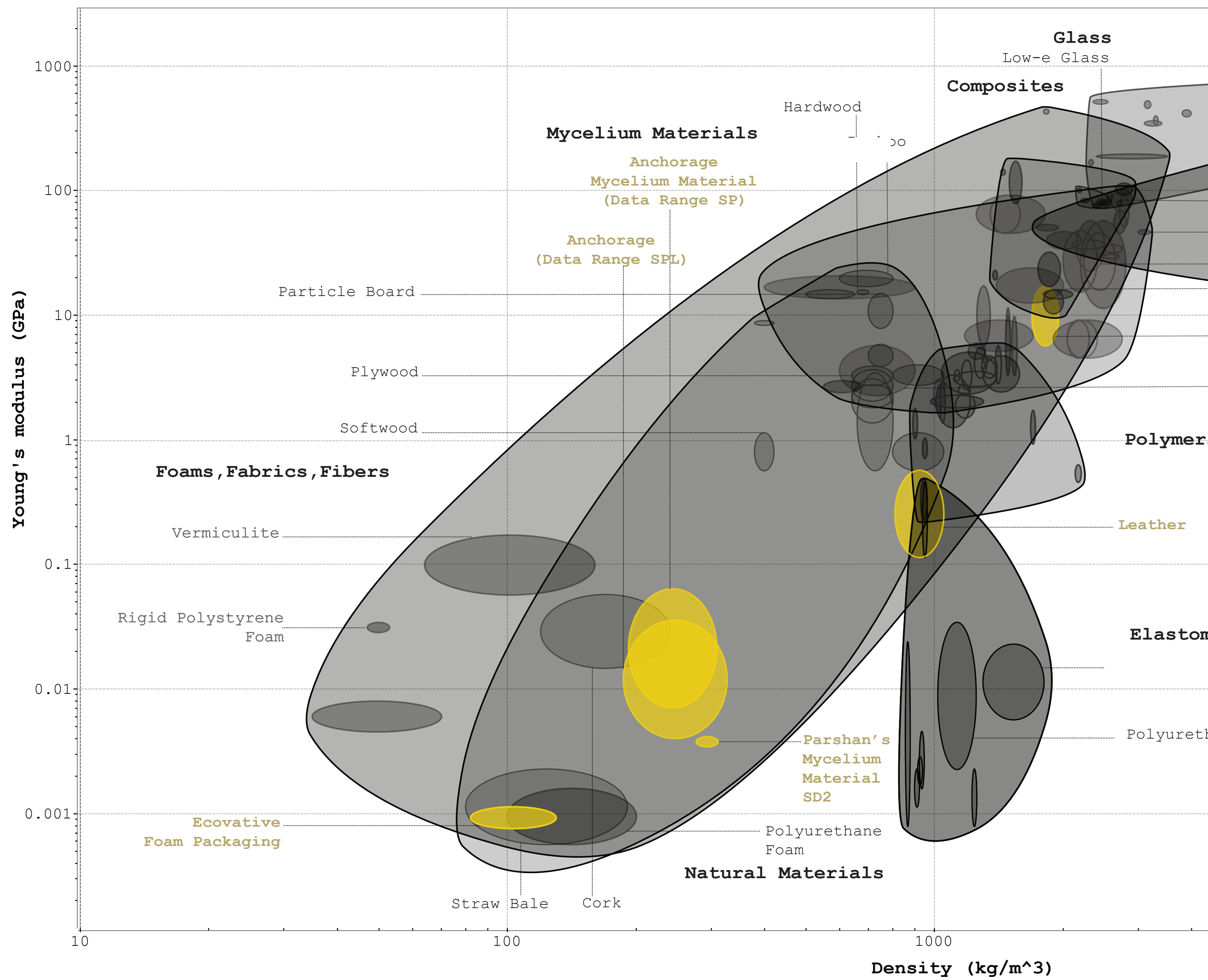


Fig.140 Compressive Strength vs Density
Ashby Chart: Highlighting mycelium-materials based on data collected



Data Range, Ecovative							
Description	**Batch Name**	**E (GPa) (min)**	**E (GPa) (max)**	**Density (Kg/m3) (min)**	**Density (Kg/m3) (Max)**	**Compressive Strength (MPa) (Min)**	**Compressive Strength (MPa) (Max)**
-	-	0.00069	0.001034	80	130	0.055	0.01

Fig.141 Data Collection

Ecovative, Data Retrieved From: "Material Specifications," Ecovative GIY, , accessed April 10, 2018, https://giy.ecovativedesign.com/material-specifications/.

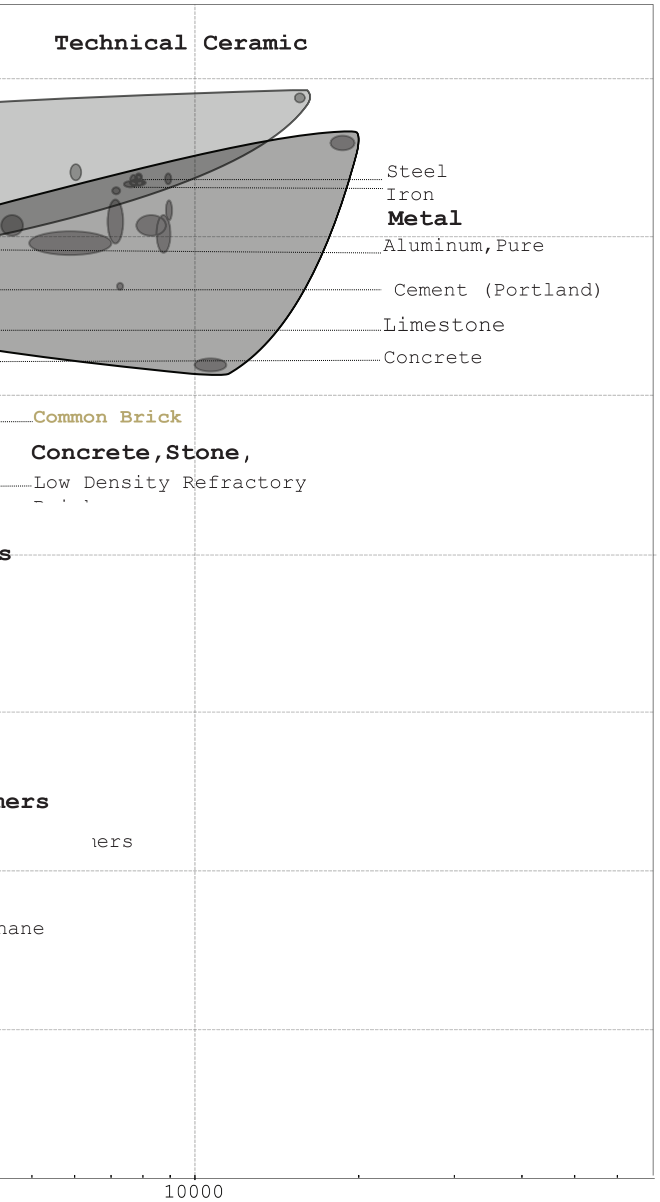
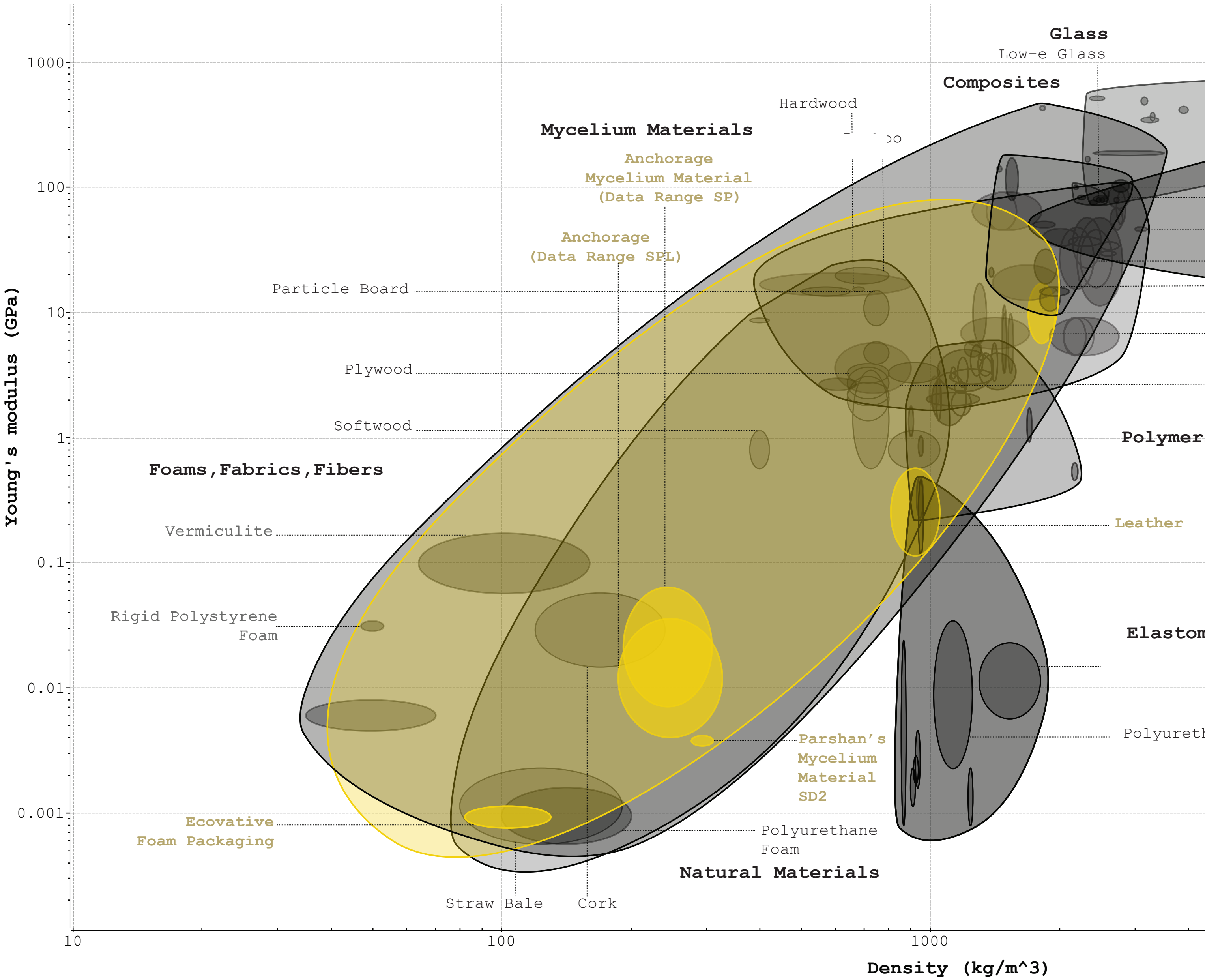


Fig.142 Young's Modulus vs Density
Speculative Ashby Chart: Highlighting the EXISTING spectrum of mycelium-based applications within design community

Reflection:

With the data collected, it appears that mycelium-based materials are most relatable to the Foams, and on the lower spectrum of the Natural Materials family in relation to both compressive strength and young's modulus (stiffness) vs density, therefore with the current properties achieved, applications are clearly not well suited as structural load-bearing members such as concrete or steel, but are relatable to straw bale construction where load-bearing walls can have a limit of single or double story assembly used for structural elements and insulation for example. Additionally, interior applications could be well suited such as, partitioning walls, screen walls, acoustic panels, and decorative elements.

Throughout this research, it has also become evident that the properties of mycelium-based materials can vary depending on recipes grown. Through hands-on experimentation and the testing of variables, diverse results are presented in my research alone. Considering the state of the art, Phil Ross is thriving for material



Glass
Low-e Glass
Composites
Hardwood
Mycelium Materials
Anchorage Mycelium Material (Data Range SP)
Anchorage (Data Range SPL)
Particle Board
Plywood
Softwood
Foams,Fabrics,Fibers
Vermiculite
Rigid Polystyrene Foam
Ecovative Foam Packaging
Straw Bale
Cork
Natural Materials
Polyurethane Foam
Parshan's Mycelium Material SD2
Leather
Elastom
Polyreth
Polymer
Young's modulus (GPa)
1000
100
10
1
0.1
0.01
0.001
10
100
1000
Density (kg/m^3)

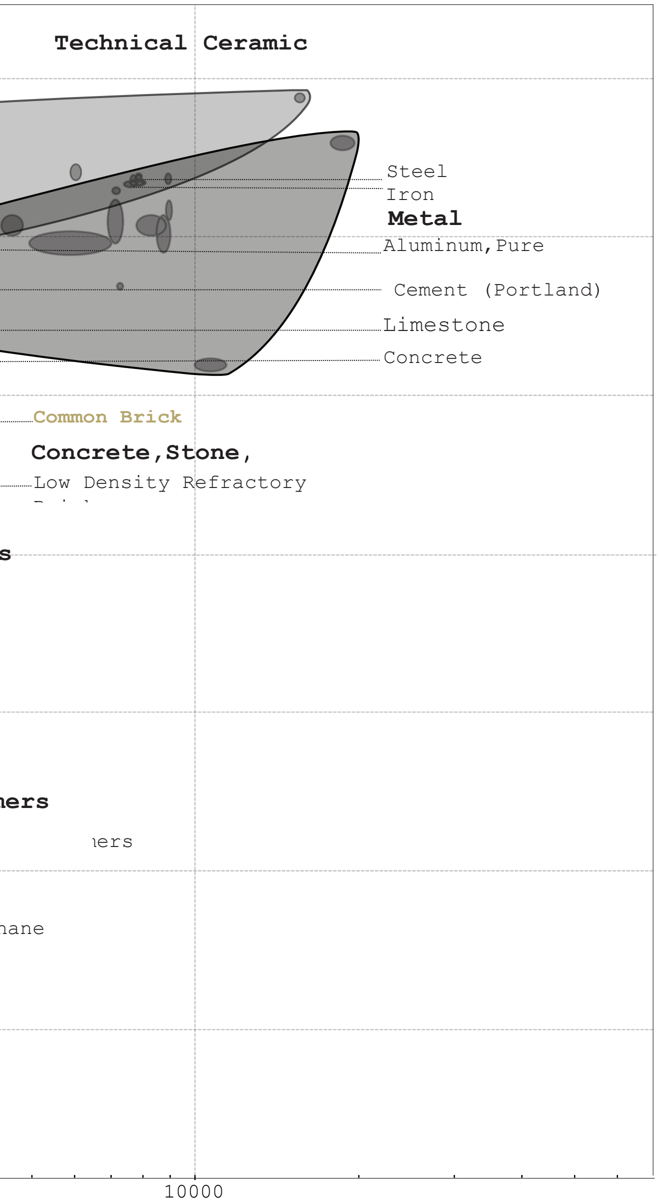


Fig.143 Young's Modulus vs Density
Speculative Ashby Chart: Highlighting the FUTURE spectrum of a mycelium-based material family

properties close to leather, and Ecovative is aiming for properties comparable to foam packaging. Therefore, varied qualities are attainable, and the spectrum within this small community is already expanding.

However, I believe we have reached a position where an interdisciplinary approach is critical in moving forward, particularly for an architectural applicability, as this requires an extensive and integrated knowledge in achieving and understanding material processes and performances.

Through experts such as biologists, mycologists, architects, engineers, and materials scientists, there is great potential in achieving favorable properties for a specific use, however, this requires a shift in materials research from a Do-It-Yourself approach towards an integration, where collective knowledge will lead to an effectiveness in materials innovation, perhaps even on the level of industry.

DISCUSSION

I believe that gaining material understanding on a technical level is fundamentally important for new materials research. Simultaneously, I consider the aesthetics and the experiential qualities vital in the material's acceptance and user receptivity. With this research, the intention was to gain a balanced understanding of this spectrum, through a multi-stage material investigation that acquired technical knowledge by growing material experiences. A series of artifacts were grown as a means of material learning. Through an in-depth study of fungal-mycelium, methods of production were conceived which resulted in artifacts that were physically presented to colleagues and classmates during the presentation of this research; allowing the material to be shared and experienced on a sensory level. The importance of having physical representation was not only to evaluate technical performance, but to promote awareness of the material practice, and to open the dialogue to this new materials study on a very direct and tactical level.

Fig.144 Presentation of Research
Sharing Material Experience
University of Waterloo

Through documenting this investigation, I cover the progression of a materials study: from a brief introduction to fungi, to developing a production methodology through the cultivation of artifacts. Through this process, I learn valuable information about what it means to design with fungi as living collaborators, and how to improve growth conditions to accommodate the challenges and sensitivities of the organism. Through exploring variables of growth, I realize the importance of recipe, and how material properties can change depending on substrate and specie. Through a dimensional study, I comment on the notion of scale, and the potential limitations in large-scale growth due to issues of dehydration and residual moisture. I also comment on material texture through understanding the life-cycle of fungi, and touch base on the technical qualities of the material through compression testing, and comparing data to other materials in the architectural world. Results suggest that both the compressive strength to density ratios and young's modulus (stiffness) to density ratios of fungal-based materials are similar to that of foam or natural materials such as cork or straw bale.

Notable through research and observation, it is indicative that material properties can be altered through varied recipes in achieving desirable results. This opens opportunities for diverse functionalities and future applications. However, further material consideration requires rigorous investigation through an interdisciplinary approach, as the junction of specialized knowledge can promote an efficient design process, in better guiding the organism to achieve specific results.

OUTLOOK

At the current level of mycelium-based material knowledge, there are many reservations in regards to material lifespan and the consequences of stresses such as temperature, humidity, moisture, etc. The dimensional stability of this material practice is still undocumented or unknown. For example, what transpires when material is loaded for a long period of time under environmental stresses? Does stability get disrupted? What changes in shape and size may occur? Does the material expand and contract upon installation? These are just a few of the many factors that influence the application and lifespan of such material; therefore, it is elemental to understand the consequences of time, and whether the lifespan is weeks, months, or years. Finally, when the material is ready for decomposition, what does this process entail, and how long does biodegradation take?

These unknowns are the logical next steps of this research which must be acknowledged in order to move forward. A starting point is to analyze the samples grown for this thesis under various stresses and document the impacts over time. The Lingzhi Blocks can be arranged in different environmental conditions to analyze changes in material behaviour. Perhaps different finishes can also be tested to add a protective layer to the material. Additionally, the remainder of the samples can be subjected to more rigorous mechanical testing in learning further about material performance. Creep tests can be conducted for example, subjecting specimens to prolonged constant stresses such as tension or compression at a constant temperature. This is a time-dependent deformation that occurs under constant applied loads, which can inform the dimensional stability of the material. Architectural applications and functional uses require this knowledge, as it is essential to know material behaviour and its consequences through time. As successful samples were grown for the purpose of this research, the evaluation process can continue beyond this thesis– gaining further knowledge and material awareness.

Material applications are gravitating towards enclosed or temporary uses at this stage of research, as further testing is required to grasp the continuing impacts of various environmental stresses on the material. Additionally, comparisons to straw bale, insulation, and cork have been drawn upon compression testing, implying that the recipe conceived in my investigation may be suitable for similar uses. Like straw bale construction, perhaps a single or double story assembly can be achieved as structural elements and insulation. Or comparable to cork, applications such as wall tiles, ceiling tiles, flooring, and acoustic paneling can be implemented. Other possibilities could include partition walls, screen walls, and decorative elements; the Lingzhi Blocks can potentially be utilized for such applications. Further experimentation can more precisely determine interior uses of the material, as relative humidity and interior temperatures may also impact installation; if material significantly expands or contracts for example, assembly could result uneven. This is primary knowledge to be determined.

The potential for design and construction remains strong; qualities of biodegradation make this material particularly suitable for temporary uses and applications, where materials would typically and rapidly end up in landfills at the end of their useful life, in contrast, can be biodegraded becoming nutrients for more growth. Furthermore, the lightweight composition of the material eases transportation and assembly, and the low input, low impact biofabrication process makes this an economical and ecological material practice. As seen in David Benjamin's Hy-Fi, ephemeral architecture such as pavilions or installations can also be a good use of the material, as elements can be composted at the end of their short-lived purpose. This type of application is also an effective means of material learning. Installations are a great means of gauging user receptivity and encouraging material familiarity while learning the technicalities and material realities at the same time. Towards a new paradigm of fabrication, this biological integration of growth and cultivation is in need of an interdisciplinary approach, in combining specialized knowledge to create material experience. During this period of gestation, I believe that material application should have the dual functionality of understanding technical behaviour, while simultaneously creating user experience– an effective means of exploring a new materiality.

BIBLIOGRAPHY

Addington, D. Michelle., and Daniel L. Schodek. Smart Materials and New Technologies: For the Architecture and Design Professions. Oxford: Architectural Press, 2006.

Ashby, Michael. "CES EduPack 2010 Guide: Material and Process Selection Charts." Granta Design, January 2010, 5

Ashby, Michael. "CES EduPack." Granta Design. Accessed March 02, 2018. http://www.grantadesign.com/education/edupack/.

Benjamin, David. "Adaptation." Lecture. January 21, 2015. Accessed May 08, 2018. https://vimeo.com/117833339.

Bergdoll, Barry, and Leah Dickerman. Bauhaus 1919-1933 Workshops for Modernity. New York: Museum of Modern Art, 2009.

Borden, Gail Peter. Material Precedent: The Typology of Modern Tectonics. Hoboken, NJ: John Wiley & Sons, 2010, 7-10

Bowman, Shaun M., and Stephen J. Free. "Structure of the Fungal Cell Wall." BioEssays 28, no. 8 (2006): 799-808

Brown, David J. Bridges Three Thousand Years of Defying Nature. London: Mitchell Beazley, 2005, 46-48

Brownell, Blaine. Material Strategies Innovative Applications in Architecture. New York: Princeton Architectural Press, 2012, 9

Campbell, Sean, David Correa, Achim Menges, and Dylan Wood. "Modular Mycelia: Scaling Fungal Growth for Architectural Assembly." In The Virtual and the Physical, 125-34. Proceedings of 5th ECAADe Regional International Symposium 2017, Cardiff University, Cardiff, Wales, UK.

"Chitin: Structure, Function, and Uses." BiologyWise. Accessed May 7, 2018. https://biologywise.com/chitin-structure-function-uses.

Droste, Magdalena. Bauhaus: 1919-1933. Köln: Taschen, 1994, 22-26

Ecovative Design "How It Works." Mycelium Biofabrication Platform, Green Island, New York. Accessed January 25, 2017. https://ecovativedesign.com/how-it-works

"English Heritage." History of Hadrian's Wall | English Heritage. Accessed April 26, 2017. http://www.english-heritage.org.uk/visit/places/iron-bridge/history/.

Gilman, Michelle Rose., Brian Peterson, and Peter Mikulecky. AP Biology For Dummies. John Wiley & Sons, 2008, 185-195

Hamilton, Gina. "Chapter 1: What Are Fungi?" In Kingdoms of Life-Fungi, 6. Lorenz Educational Press, Milliken Publishing Company, 2006.

Karana, Elvin, Bahareh Barati, Valentina Rognoli, and Anouk Zeeuw Van Der Laan. "Material Driven Design (MDD): A Method to Design for Material Experiences "International Journal of Design Vol. 9 (November 2, 2015) 35-54.

Kieran, Stephen, and James Timberlake. Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction. New York: McGraw-Hill, 2004, 27-45

LafargeHolcim Foundation for Sustainable Construction. "Hy-Fi: Zero Carbon Emissions Compostable Structure, New York, NY." LafargeHolcim Foundation Website. Accessed March 10, 2018. https://www.lafargeholcim-foundation.org/projects/hy-fi.

Latgé, Jean-Paul. "The Cell Wall: A Carbohydrate Armour for the Fungal Cell." Molecular Microbiology 66, no. 2 (2007): 279-90

Maine, Elicia, David Probert, and Mike Ashby. "Investing in New Materials: A Tool for Technology Managers." Technovation 25, no. 1 (2005), 16

"Material Specifications." Ecovative GIY. Accessed May 10, 2018. https://giy.ecovativedesign.com/material-specifications/.

Menges, Achim. "Chapter 2: Material Systems, Computational Morphogenesis and Performative Capacity." In Emergent Technologies and Design: Towards a Biological Paradigm for Architecture. Oxon, U.K Routledge, 2010, 44

Oxman, Neri. "Material-based Design Computation." Doctor of Philosophy in Architecture: Design and Computation. Massachusetts Institute of Technology, June 2010, 27-30

Peters, Sascha. Material Revolution Sustainable and Multi-purpose Materials for Design and Architecture. Basel: Birkhauser, 2011.

Resnick, Mitchel, and Eric Rosenbaum. "Designing for Tinkerability." In Design, Make, Play: Growing the Next Generation of STEM Innovator, edited by Margaret Honey and David E. Kanter, 163-81. New York: Routledge, 2013, 163-166

Ross, Phil. "Mycoworks Technology." MycoWorks. Accessed April 26, 2018. http://www.mycoworks.com/.

Ross, Phil. "Mycotecture: Architecture Grown out of Mushroom." Lecture, Parsons The New School for Design, New York. April 11, 2014. Accessed March 2016. https://www.youtube.com/watch?v=7q5i9poYc3w.

Schröpfer, Thomas, Material Design: Informing Architecture by Materiality. Basel: Birkhäuser, 2011.

Simard, Suzanne. "How Trees Talk to Each Other." TED, Ideas Worth Spreading. June 2016. Accessed September 2016. https://www.ted.com/talks/suzanne_simard_how_trees_talk_to_each_other/transcript.

Stamets, Paul. Mycelium Running: How Mushrooms Can Help save the World. Berkeley: Ten Speed Press, 2005.

Stamets, Paul, and J. S. Chilton. The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home. Olympia, WA: Agarikon, 1983.

"Sustainable Buildings and Construction Programme | UN Environment." United Nations Environmental Programme. Accessed November 21, 2016.http://web.unep.org/10yfp/programmes/sustainable-buildings-and-construction-programme.

Viray, Erwin. "Why Material Design?" in Material Design: Informing Architecture by Materiality, by Thomas Schröpfer. Basel: Birkhäuser, 2011, 8-9

Yang, Zhaohui (Joey), Feng Zhang, Benjamin Still, Maria White, and Philippe Amstislavski. "Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam." Journal of Materials in Civil Engineering 29, no. 7 (2017)