Exploring the Relationship between Concrete and Mycelium Through an Integrated Design Methodology

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In 2023, the built environment sector was labelled the largest global emitter of greenhouse gases, prompting an increased effort to reduce its embodied carbon. While research in sustainable, low-carbon materials has proved an excellent method to define where we have failed in material use and what we might use in the future, a discussion blending the two is underdeveloped and worthy of further exploration. Also lacking is the number of materials that exist in the grey area between sustainable and structural, with one quality seemingly favoured over the other. It is in this area of architecture that the greatest green impact will be felt, as it then competes with the three largest carbon emitters – concrete, steel and aluminum. This thesis takes concrete, the largest emitter, and contrasts it with mycelium-based composites, an innovative biomaterial whose potential has been constrained by studying it in isolation (solely observing mycelium with its substrate). By comparing them, we stay grounded in the current state of material in architecture and its impact on the planet. By combining them, we have an opportunity to blend their individual properties to offer new applications not previously available to either material. These applications could then benefit the construction industry in a manner that might significantly impact our environment today, as the familiarity with a traditional material and its properties could lead to more trust in the new material's production and use.

In addition to providing more structure to sustainable materials, the intent of this thesis was to broaden the perception of mycelium applications in the field of architecture – to help expand the imagination, to explore the material's ability to repurpose waste and grow in conjunction with the material architecture is most familiar with. It strove to position mycelium as a material of today, not of tomorrow, and guide concrete away from its troubled relationship with the environment.

An integrated design methodology was created to guide the design process through a holistic framework, considering as many factors as possible to use concrete as a means to strengthen mycelium-based composites, and to reach a design proposal for a product that combines the materials in a way that is both practical and sustainable. This inspired a series of material experiments that explored the surface and form bonding capabilities of the materials, as well as how mycelium-based composites paired with deconstructed concrete (cement and recycled concrete aggregate). These experiments then tested for their acoustic properties and compressive strength. Throughout this process, the working methodology was constantly cross-checked with Jason F. McLennan's six principles of sustainable design as well as proposed sustainable policies to ensure the final product maintained its integrity as a sustainable material. The work culminated in a design proposal for a recycled concrete acoustic masonry unit with a mycelium-based composite infill.

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Dedication

To my family,
the ones who gave me the strength to try
and believed in me more than I believed in myself.
The ones who were always there to
make me laugh when I needed it most.
Who's unwavering support is the sole
reason I had the opportunity to be in this position.

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my brothers,
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1

Introduction

"No problem can be solved by the same manner of thinking that created it."

— Albert Einstein

Our planet is in crisis and our buildings are 37% to blame.[1] For the last two hundred years, buildings have been designed on the practical merits of tradition over innovation - we still favour the use of concrete, steel and aluminum, the three largest contributors to greenhouse gases (GHG) in the construction industry.[2] We shy away from lower carbon innovations such as recycled concrete as it is not yet classified a structural material, but let other implementations remain underexplored.[3] We have only recently introduced biomaterials to construction, an innovation so far from traditional it remains largely sequestered to the realms of experimental pavilions and insulation panels. These biomaterials are an opportunity to drastically reduce the embodied carbon present in our buildings today – but they require more research on potential applications, and their technical properties fall short of traditional materials (refer to Section 2.2). It is therefore practical that the construction industry would value tradition over innovation, but our environmental crisis requires a solution that blends the reliability of traditional materials with the sustainability of biomaterials.

It is for this reason that this thesis suggests a new approach to material. One that summarizes the state of our industry and acknowledges where we've been, while still offering a new way forward. One that stays grounded in where we are and offers applications that benefit the construction industry in a manner that might significantly impact our environment today. It is this work's hypothesis that to embrace new materials we see as radical we must combine them with materials that are traditional to then encourage their acceptance and spark a faster and more widespread adoption of these ideas. Using an integrated design methodology, it is then possible to transform this hypothetical blending of materials into a practical and sustainable product fit for construction use today.

1 United Nations Environment Programme, "Building Materials and the Climate," 1.
2 United Nations Environment Programme, xiv, xv.
3 United Nations Environment Programme, xiv, xv.



Figure 1.1: Workers in a white limestone quarry, surrounded by limestone dust. Limestone is a key ingredient for the production of cement, which has the most environmentally detrimental production process in the construction industry.

1.1 The Crisis

According to the United Nations report on Building Materials and the Climate in 2023, the built environment sector has been firmly labelled the largest global emitter of greenhouse gases (37%).[4] Studies in reducing its impact have prioritized reducing the 'operational carbon' (the amount of carbon produced from the ongoing operation) of buildings over the 'embodied carbon' (the amount of carbon emitted in the production and disposal process) of the materials they are constructed with (Figure 1.2).[5] This strategy was logical, as the lifetime energy consumption of buildings outweighs the environmental impact of their embodied carbon – only 13% of the total volume of carbon the building sector produces is embodied carbon.[6] Successful applications of research have been notable in reducing operational carbon using a variety of techniques, such as improving the quality of insulation and automating lighting.[7] However, these ideas brought additional embodied carbon to the buildings as new materials were swapped in for the old.[8]

The rising energy efficiency is lowering the operational carbon of buildings, however this has increased the relative percentage of embodied carbon within the total carbon.[9] Canada is already seeing a near 50/50 split between embodied and operational carbon within its buildings.[10] This sliding ratio illustrates that if we continue in primarily addressing operational carbon, we will no longer be addressing the primary source of carbon in our buildings, and we will ultimately fail in our goal of a more sustainable architecture.

With our global population nearing 10 billion, the global building stock is expected to double in size if left unchecked.[11] Without regulation, our consumption of raw materials will double alongside it by the year 2060.[12] Embodied carbon is not an element that can be removed from an existing building – it can only be addressed in the initial planning and design phases.[13] For this reason, we now require a thoughtful reconsideration of how we approach design buildings, and an expansion of our understanding of low-carbon materials. We need to analyse the role of material within the building industry and note where we have become stuck in routines of tradition, and where we can innovate. Embracing low-carbon materials is necessary to secure the future of both architecture and our environment.

The most effective low-carbon materials must be considered from a 'whole life-cycle approach,' a holistic view on the impact of the material on the ecosystem it will be removed from, the method of extraction, its installation and its end of life processing.[14] Existing low-carbon materials include timber, wood and bamboo, but these are imperfect candidates as they must all be sustainably resourced – they are often harvested at a greater rate than they can be replenished, placing a firm limit on supply.[15] Many have begun to look instead towards the development of biomaterials as the future of construction due to their ability to excel in every category of the whole life-cycle approach.

4 United Nations Environment Programme, "Building Materials and the Climate," 1.
5 United Nations Environment Programme, vi
6 Carroll, "Embodied Carbon vs. Operational Carbon."
7 Engel, "Embodied Carbon vs Operational Carbon."
8 Engel.
9 Carroll, "Embodied Carbon vs. Operational Carbon."
10 Carroll.
11 United Nations Environment Programme, "Building Materials and the Climate." xviii
12 World Green Building Council, "Bringing Embodied Carbon Upfront," 22.
13 Engel, "Embodied Carbon vs Operational Carbon."
14 United Nations Environment Programme, "Building Materials and the Climate." xiv
15 United Nations Environment Programme. xiii

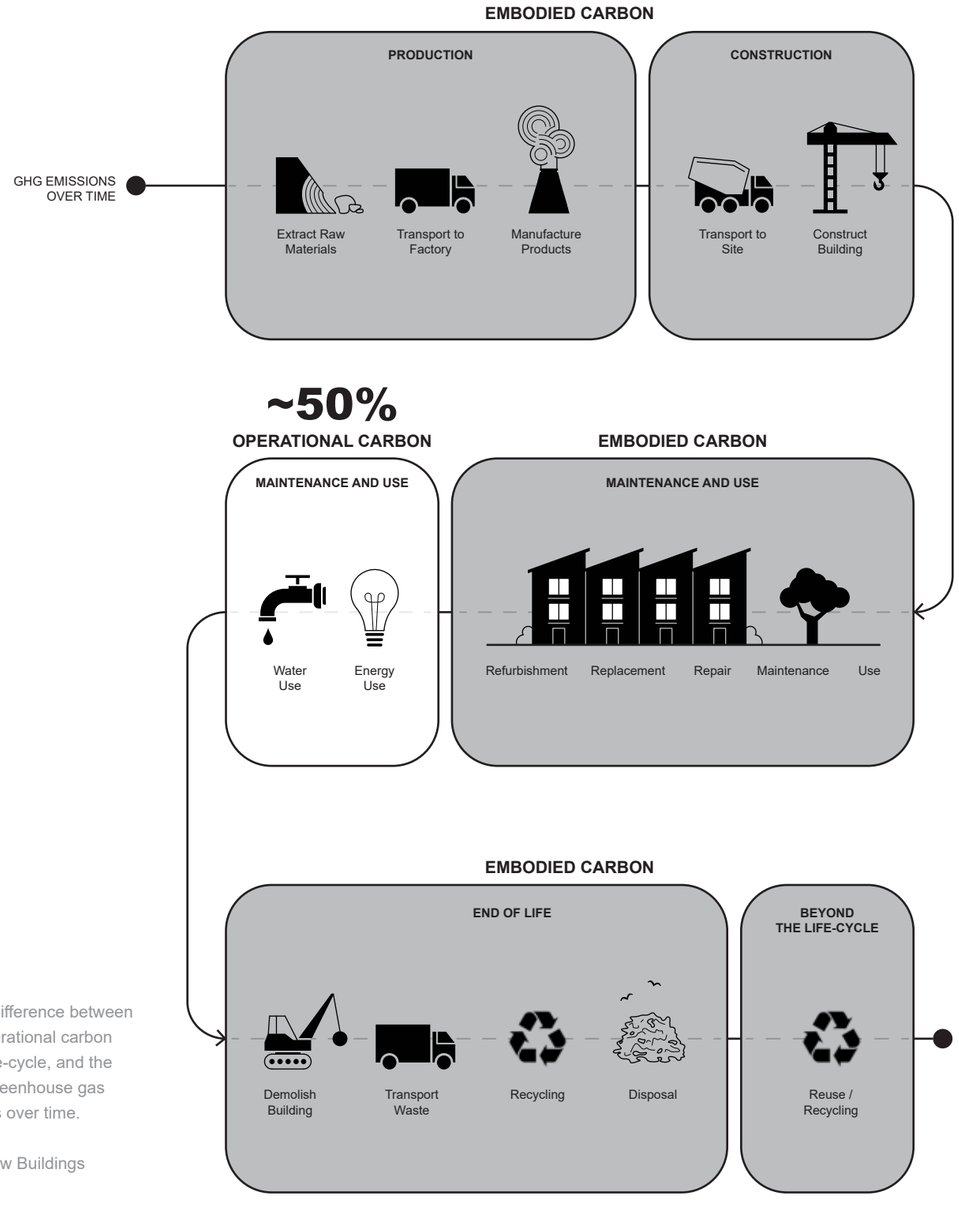


Figure 1.2: The difference between embodied vs operational carbon in the building life-cycle, and the source of their greenhouse gas (GHG) emissions over time.

Adapted from New Buildings Institute (2025)

Biomaterials are materials derived from living organisms like plants, animals and fungi[16] – their scope often expands to include materials derived from agricultural by-products and waste materials.[17] Some examples include hempcrete, algae and mycelium-based composites (Figure 1.3). According to a review on *Biomaterials Technology and Policies in the Building Sector* done in 2023, "Bio-based materials have the potential to reduce over 320,000 tons of carbon dioxide emissions by 2050. They also exhibit advantages like decreasing water absorption by 40%, reducing energy consumption by 8.7%, enhancing acoustic absorption by 6.7%, and improving mechanical properties."[18] The potential of biomaterials represents an opportunity to completely reshape our approach to architecture and the urban environment. Put another way, biomaterials have been positioned to represent the future.

As of today, biomaterials have been used to create products such as insulation, acoustic panels, experimental cladding and sculptures. While these outputs are currently viable within construction, they do little to challenge the reliable versatility of construction's worst offenders of embodied carbon – concrete, steel and aluminum. (Figure 1.4).[19] They lack the strength and load baring capacity those materials provide.[20] Biomaterials have tremendous potential, but neither the construction industry nor the research and technology behind them are prepared for such a thorough integration.

16 Ghisleni, "What Are Biomaterials in Architecture?"
17 Chen et al., "Biomaterials Technology and Policies in the Building Sector," 716.
18 Chen et al., 715.
19 United Nations Environment Programme, "Building Materials and the Climate." xiv, xv
20 Alemu, Tafesse, and Mondal, "Mycelium-Based Composite," 9.



Mycelium-Based Composite (MBC)



Algae

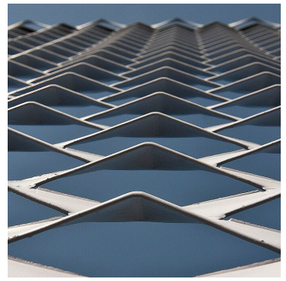


Hempcrete

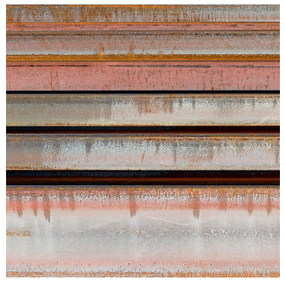
Figure 1.3: Examples of low carbon materials.

We now find ourselves at a crucial intersection for our planet – one in which drastic decisions must be made and quickly implemented concerning the embodied energy of our materials. It is impossible to continue down our current path, but the proposed path of biomaterials is at this stage too experimental and limiting to meaningfully offset where we've been. What is required then, is a radical approach to material. While research has proved an excellent tool to define where we have failed in material use and what we might use in the future, a discussion blending the two seems underdeveloped and worth further exploration. Also lacking is the number of materials that exist in the grey area between sustainable and structural, with one quality seemingly favoured over the other. It is in this area of architecture that the greatest green impact will be felt, as it then competes with the big three carbon emitters.

This thesis looks to explore the use of traditional materials in architecture, specifically concrete, the largest emitter of carbon, and contrast it with mycelium-based composites, an innovative biomaterial whose potential has been constrained by largely studying it in isolation. By comparing these materials, we stay grounded in the current state of materiality in architecture and its role in the carbon cycle, and thus its impact on the planet. By combining them, we have an opportunity to analyse their individual properties, then blend them to offer new applications not previously available to either material. These applications may then benefit the construction industry in a manner that might significantly impact our environment today, as the familiarity with the traditional material and its properties may lead to more trust in its production and use.



Aluminum



Steel



Concrete

Figure 1.4: Examples of high carbon materials.

1.2 The Tradition of Concrete

The Industrial Revolution marks the beginning of modern pollution.[21] While previous generations were content to build in harmony with the elements, a combination of mass migrations of people to cities and the rise of new technologies made it possible to transform buildings into machines for living in.[22] These new technologies fed into man's blind faith that it is their right to shape the Earth as they see fit, creating an environment where there was no problem that could not be solved with a man-made, technological fix.[23] This confidence bolstered us to design microclimates within buildings, using air conditioning and heating systems to separate us from the need to consider our local climates.[24] Eventually technology allowed us to build higher, far beyond our previous limitations with elevators and steel beams that erected skyscrapers lit with electric light, further severing our connection to the earth. It was during this phase of architectural history that innovation was prized over tradition, and that philosophy extended from the large scope of buildings down to the materials they were constructed out of.

It was during this Revolution that we were introduced to modern Portland Cement, first patented by Joseph Aspdin in 1824.[25] While concrete had been used in architecture for the past 12,000 years,[26] this new cement was capable of creating a concrete twice as strong as any that had ever been used before.[27] Concrete was already a material with a high compressive strength and a low tensile strength, but with the further invention of reinforced concrete in 1854 (perfected in 1892 by French Engineer Francois Hennebique) its tensile strength was substantially improved – its range of uses could be expanded to construct entire multi-storey buildings with the one material.[28] Weaver's Mill (1898) was the first building to utilize Hennebique's reinforced concrete technique, and in the ten years following 40,000 more structures were constructed using the same method (Figure 1.5).[29]

In his article published in *Concrete & Constructional Engineering* in 1906, J. Winn noted, "We've had the Stone Age, the Bronze Age and the Iron Age. From the dawn of the twentieth century... is the Concrete Age."[30] Concrete quickly spread across the globe, establishing itself as capable of several styles and functions of building. It became the cheap material of choice to rebuild after the second world war, a bold expression of brutalism, the core of skyscrapers – it was increasingly interwoven into a culture that was gradually being claimed by every country around the world until, inevitably, it was hardly conceivable to plan a building without it. Its widespread use transformed the material from innovative to a material so traditional within construction that it has become one of the most consumed materials in the world, second only to water.[31]

Today, concrete represents approximately 25% of the carbon emitted by the entire building sector, which is 7% the global total.[32] Over the past 65 years its production has grown 10-fold, while steel and timber production has only grown 3-fold.[33] Its production consumes almost 10% of the world's water supplies, 75% of which are in drought and water-stressed regions.[34] According to some calculations, concrete may even have already surpassed the total volume of all the plants and shrubbery currently on Earth – only rather than degrading as the next step in the natural carbon cycle it hardens and remains for centuries.[35] Now understanding how

21 McLennan, The Philosophy of Sustainable Design, 22.
22 McLennan, 22.
23 McLennan, 22.
24 McLennan, 22.
25 The Science Museum Group, "Building the Modern World."
26 Nobis, "History of Cement."
27 Rinde, "Hard-Headed Man."
28 The Science Museum Group, "Building the Modern World."
29 The Science Museum Group.
30 The Science Museum Group.
31 Gagg, "Cement and Concrete as an Engineering Material."
32 United Nations Environment Programme, "Building Materials and the Climate." xiv
33 United Nations Environment Programme. xiv
34 Watts, "Concrete: The Most Destructive Material."
35 Watts.



Figure 1.5: Weaver's Mill, the first building to be constructed with reinforced concrete.

Source: The Science Museum Group

concrete became inextricable from our process of planning and constructing buildings, along with our understanding of concrete's impact on vulnerable, water-stressed regions and the environment, it is our responsibility to work towards making a change. "Innocence can be rightfully claimed with ignorance, but once informed, lack of action can only be regarded as irresponsibility."[36] The problem of concrete should be approached from both ends, meaning at the beginning of production and at the end of its life. Cement production produces the most carbon in comparison to every other stage of concrete's life-cycle. This process and the methods of reducing carbon at this stage will be discussed more in the *Literature Review* section. The focus of this thesis is in addressing concrete at the demolition phase and beyond.

It is estimated that concrete and other materials from construction, renovation and demolition waste occupy approximately 45% of Canada's landfills.[37] Coarse aggregates make up most of concrete's volume. Conflating these two facts has given rise to recycled concrete, which crushes concrete at the end of its life to turn it into aggregate to be used in a new batch of concrete.[38] This method of reusing existing concrete works well in theory, the greatest challenge in using it thus far has been the variability in aggregate size, and how this might affect the strength, stiffness and durability of reinforced concrete. This thesis will adapt this method of reuse to explore if a living biomaterial might create a practical bond between itself and recycled concrete or ordinary Portland cement (OPC) concrete. It will further explore if a combination of cement and a living biomaterial can create a strong and durable product. In exploring these relationships through an integrated design methodology, we may more easily provide ourselves a platform to discuss the diverse role both traditional and innovative materials might play in architecture today, and more practically, ask ourselves if continued experimentation with these two materials is viable in the development of new products.

36 McLennan, The Philosophy of Sustainable Design, 211.
37 United Nations Environment Programme, "Building Materials and the Climate," 102.
38 University of Notre Dame, "Why Not Recycled Concrete?"

1.3 The Innovation of Mycelium

Even during the Industrial Revolution, the increase in pollution was noticeable to the average person – not only from concrete production but from the rising expansion of new industries. Large numbers took notice as industrialized cities were overcome with poor air quality, with a majority of those living there suffering from upper respiratory diseases.[39] Efforts were made in cities such as St. Louis in the United States to switch from coal to oil in the 1930s,[40] while others invested in the 'City Beautiful Movement' between the 1890s and 1920s in an effort to bring nature back into the built environment.[41]

Calls for introspection concerning our pollution were not properly addressed again until 1962, when Rachel Carson published *Silent Spring*.[42] For many this was the first true revelation at the drastic impact humans can have on the environment, and the consequences that come with that sobering responsibility. Yet it was only in 1992 that we held the Rio Earth Summit as a global call for awareness, and then even later in the mid-1990s that green committees began to form to do something about it.[43] Those in the construction industry took an inclusive approach to these meetings, involving architects, engineers, builders, and industry representatives to discuss solutions to advance the industry toward sustainability.[44] It was clearly understood that a solution to our impact would require coordination across all disciplines, but the specific direction remained unclear.

In 2004, Jason F. McLennan published *The Philosophy of Sustainable Design* as a compendium to gather the leading ideas at the time and encompass them under an umbrella of six guiding principles that emphasized respect for our planet (refer to Sections 1.6 and 2.3.2).While these principles were intended to guide the design of sustainable buildings, they are also easily transferrable to the field of material design, specifically in the development of biomaterials. These materials (in the order of principles); embody the wisdom of natural systems within their make-up and natural material properties, strive to define healthy and engaging spaces for humans to thrive in, are locally sourced, are completely biodegradable, have minimal to no embodied carbon and take into consideration all of these principles at once in addition to consideration for how they might find their own place within our existing system, and where they might innovate. In short, biomaterials neatly slot into McLennan's definition of the philosophy of sustainable design:

"Sustainable Design is a design philosophy that seeks to maximize the quality of the built environment, while minimizing or eliminating negative impact to the natural environment."[45]

39 McLennan, The Philosophy of Sustainable Design, 24.
40 Missouri Department of Natural Resources, "Missouri Skies Now and Then."
41 Britannica, "City Beautiful Movement."
42 Carson, Silent Spring.
43 McLennan, The Philosophy of Sustainable Design, 31.
44 McLennan, 30.
45 McLennan, 4.

The material chosen for study in this thesis is mycelium-based composites (MBC). Mycelium (Figure 1.6) is the root-like structure of a fungus composed of branching hyphae (hyphal structure).[46] It has been observed that a combination of the proper strain of mycelium and a corresponding substrate (e.g. hardwood sawdust, agricultural waste) from which the hyphal structure would gain nutrients through decomposition can, when given the proper time to inoculate, combine to form a composite of the two biomaterials.[47] The resultant material can be molded into various shapes, making them versatile for applications such as biodegradable and compostable packaging.[48] Due to their porous structure, some MBCs have proven themselves to be 30% more thermally conductive than common insulation materials commonly used in the market.[49] There have also been promising studies documenting the fireproofing properties of the material[50] in addition to the application of MBCs as acoustic panels.[51]

So far, experimentation with this novel material has been limited to the formation of panels, bricks, or a combination of the two to create experimental pavilions and sculptures. But these promising applications have their limitations. Findings have shown that MBCs are negatively impacted by humidity, rain and severe temperature fluctuations[52] – all signs that this material would be unsuitable for an exterior Canadian climate. While the compressive strength of the material is impressive for its weight, it is still only comparable to that of polystyrene, and is therefore not reliable for construction purposes.[53] Furthermore, in the production process, the formwork required to create the finished product is often discarded, creating additional waste that must be considered part of the material's embodied carbon if not properly accounted for.[54] A further analysis of the material properties of mycelium and methods of strengthening them will be included in the *Literature Review*.

For the past several years, there has been an influx of new studies involving mycelium that propose it having a viable future in building construction. However, when considering this material as an opportunity to offset to the behemoths of concrete, steel and aluminum, it is overpromising on what it can deliver. With such limited applications, it is not yet practical to implement a shift in the industry that would warrant creating and investing in new facilities to support this material's production and development. This leaves us stuck between continuing to pursue the traditional materials of the past (which are devastating to our environment) or pushing unrealistic expectations of a green future. This thesis frames itself as a proposal on how to best mitigate the two extremes.

46 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 38.
47 Ghazvinian and Gürsoy, 38.
48 Ghazvinian and Gürsoy, 39.
49 Ghazvinian and Gürsoy, 56.
50 Ghazvinian and Gürsoy, 56.
51 Walter and Gürsoy, "Sound Absorption Properties of Mycelium-Based Composites."
52 Patel and Sharma, "The Possible Applications of Mycelium-Based Bio-Composites in Architecture."
53 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 59.
54 Patel and Sharma, "The Possible Applications of Mycelium-Based Bio-Composites in Architecture."



Figure 1.6: Mycelium of the common button mushroom (*Agaricus bisporous*).

1.4 Designing for the Present

We require new, sustainable materials and a heightened awareness of the carbon cycle in construction. While the development of mycelium blocks and panels is a step in the right direction, it is a limiting one. By solely exploring how organic materials can be used in isolation (solely combinations of mycelium and substrate), they will continue to be relegated to the realms of interior decoration, insulation, acoustics and experimental pavilions.[55]

The proposed solution of this thesis is to combine mycelium-based composites (MBCs) with concrete to achieve the following:

1. Represent a bridge between the past and future of the construction industry and serve as a platform for further discussion on the role of embodied carbon in the climate crisis.
2. Determine if this combination can blend the strongest technical properties of both materials and provide more structural integrity to MBCs.
3. Introduce an integrated design methodology to develop a product design based on the discoveries in goal (2) that is both practical and sustainable.

The hypothesis of this material experiment is that the combination of concrete and mycelium-based composites (two materials on the opposite ends of the sustainability spectrum) will broaden the scope of applications of biomaterials. By proposing a product based on this expansion, low carbon materials might then have a greater advantage when competing for construction applications against high-carbon structural materials, thus lowering the embodied carbon of a newly constructed building. By framing this study through an integrated design methodology, the research and development of this product will be balanced between its functionality, aesthetics and sustainability.

The intent is to broaden the perception of MBCs (and biomaterials in general) in the field of architecture – to help expand the imagination and to explore the material's ability to grow in conjunction with the material architecture is most familiar with. It strives to position mycelium as a material of today, not of tomorrow, and guide concrete away from its troubled relationship with the environment. This thesis also looks to popularize a more holistic approach to designing and selecting materials that values sustainability without overtly compromising cost or function. This thesis has been written and formatted for the use of architects, engineers, manufacturers, builders, policy makers, and anyone who might find an interest in the studied relationship between these opposing materials and the effect they might have on material practices in the construction industry.

55 Patel and Sharma, "The Possible Applications of Mycelium-Based Bio-Composites in Architecture."

1.5 Scope and Limitations

The material scope is limited to one strain of mushroom (blue oyster mushrooms). Oyster mushrooms are the fastest growing species, and their easy availability and simple care requirements make them a popular choice for rapid mycelium experimentation.[56] These mushrooms grow best in hardwood supplemented with nutrients, therefore the consistent substrate chosen for all experiments was hardwood sawdust with wheat bran. They were grown at room temperature, which ranged from 20-28°C (ideal for oyster mushrooms).[57] Only one type of cement (Original Portland) was used to in combination with pea gravel and sand to make concrete, as this would combine mycelium-based composites with the most traditional and abundant form of concrete. Recycled concrete aggregate was also chosen to explore how mycelium might affect concrete beyond its life cycle.

The equipment was limited to mushroom grow bags for inoculation, a pot for tyndallisation, and an oven for heat ceasing. Specialized machinery was used to produce some of the formwork (3D printing). Only one CAD software was used to model the exploratory formwork and proposed design (Rhinoceros).

The scale of the material samples was limited to allow for rapid iteration with a limited supply of materials. Surface and form bonding explorations were limited to the dimensions of the mushroom grow bags (refer to Section 3.2.1). The scale was also limited by the size of the oven and the load capacity of its rack. Deconstructed bonding did not range beyond 100 x 100 x 38mm[58] (refer to Section 3.2.2), and the scale of physical testing was defined by ASTM C109 (refer to Section 3.2.3).

All planning and execution of the material experimentation took place over the course of nine months. Stages of material experimentation were limited to 3-weeks for consistent mycelium growth, with short exceptions of a few days if it benefitted the material.

56 Aditya et al., "Comprehensive Review on Oyster Mushroom Species (Agaricomycetes)," 2.
57 Hoa and Wang, "Effects of Temperature and Nutritional Conditions on Mycelium Growth," 17.
58 Walter and Gürsoy, "Sound Absorption Properties of Mycelium-Based Composites," 8.

1.6 Methodology

One of the primary goals of this thesis was to produce a product that is both functional and sustainable, and capable of being tested to prove both claims. While it is simple to research and physically test this material combination's 'functionality', it is less simple to define what makes a product sustainable in the first place, and even less to prove this demonstrably. The book *The Philosophy of Sustainable Design* by Jason F. McLennan was studied to better understand the philosophy behind sustainable design and in what ways it can practically be applied to architecture. Through these readings it was determined that a holistic framework was imperative for the development of a design methodology. This strategy was then compared with the traditional reductionist method for design (narrowed to Material Driven Design) to see in what ways it intersected with sustainable holistic thinking for the development of a new Integrated Design Methodology. This new approach to design development was then expanded to include experimentation with these materials to create an ideal methodology for a product that is both sustainable and functional.

Integrated Design Methodology

If the sustainable design process had a single name, it would be **holistic thinking**.[59] Broadly speaking, it considers how things are gathered, put together, operated and maintained. Holistic thinking is not easily defined – it naturally encompasses more than words can describe.[60] Put simply, holistic thinking is a way of thinking that attempts to widen the circle of understanding in order to comprehend the connections that exist between all things and, more specifically to this thesis, connections between the design process and the built environment.[61]

Holistic thinking stands in contrast to the traditional western **reductionist scientific process**.[62] This method 'draws circles' around things in order to define problems and eliminate variables[63] – it draws a straight line from the problem to the solution. This method misses things because it does not first attempt to widen the sphere of the known.[64] Holistic thinking shows the limits of the reductionist method by acknowledging its boundary and attempting to expand it until it can no longer, and then and only then does it zoom in on its potential in the form of a final design.[65] Put another way, the reductionist method problem solves from the bottom up, examining parts until they coalesce into a whole. The holistic method problem solves from the top down, viewing the problem in the context of its environment, and then it whittles down these widely considered factors until it reaches the core of the issue (Figure 1.7).

Integrated design occurs at the intersection of holistic and reductionist thinking. Integrated designs simultaneously solve several problems within one solution and embody the work and requirements of multiple disciplines.[66] It protects against value engineering, the process of removing elements of projects that are deemed superfluous, which is often the sustainable design features.[67] Performance features that simultaneously serve several other critical needs are difficult to remove, which is why truly sustainable buildings/products are only achieved through the integrated design process.[68] In order to create an integrated design methodology

59 McLennan, The Philosophy of Sustainable Design, 218.
60 McLennan, 218.
61 McLennan, 218.
62 McLennan, 219.
63 McLennan, 219.
64 McLennan, 219.
65 McLennan, 219.
66 McLennan, 222.
67 McLennan, 223.
68 McLennan, 223.

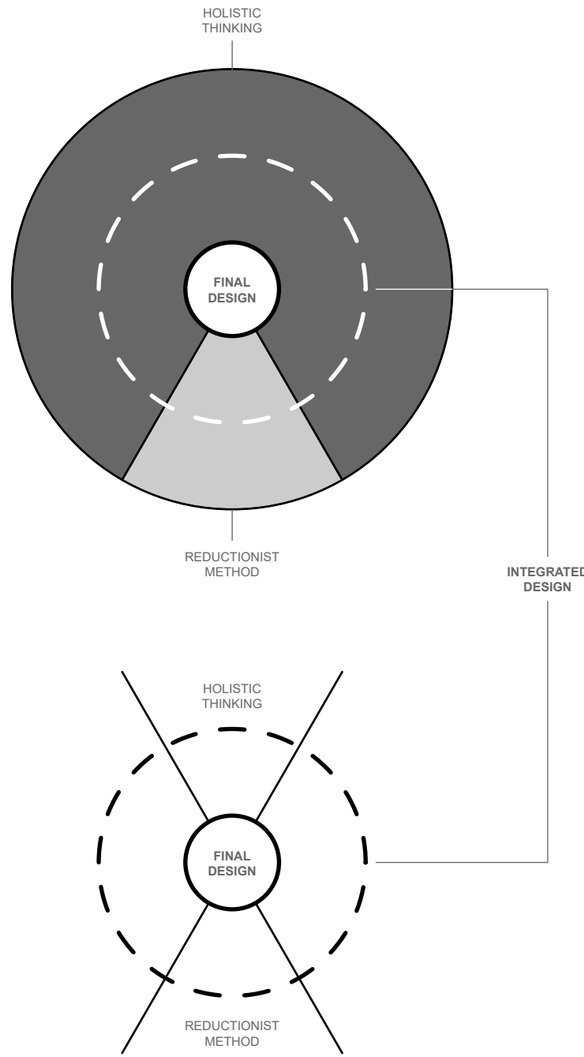


Figure 1.7: Holistic Thinking vs the Reductionist Method, and the Integrated Design that occurs at their intersection.

that suits this thesis, it is necessary to first define the direction and scope of holistic and reductionist thinking.

McLennan notes that since sustainable design is a philosophical approach to design, it can be used on any building type at any scale, or transcend buildings to be used on any object or project under design.[69] One of the major goals of the movement is to enhance quality – by this he means creating "better buildings for people, better products for our use and better places to inhabit."[70] He went on to note that unlike many philosophies, sustainable design principles are not invented but discovered by individuals or groups. The true principles have existed in some form in nature already.[71] At the time the book was written (2004), six major principles had emerged. Many overlap and reference each other, as it is difficult to separate them fully since they all encompass the values of sustainable design. The word 'respect' was used as a framework for all the principles to emphasize the general attitude of reverence for the planet the principles describe.[72]

Arranged around their goal of a producing a well-rounded sustainable design, these principles act as an excellent guide and pseudo checklist of six different perspectives that require consideration (Figure 1.8). Its holistic framework begins from a large, interconnected scope and narrows itself down to a final product.

The reductionist method discovers a final design from the bottom up, beginning with a large range of parts that can be individually selected due to their relevance to the project, then combining and refining them to create a final design. This process has defined traditional design, and while it is not an incorrect approach, its narrow scope is not sustainable. Without it however, sustainable design lacks a clear direction.

The method chosen for use this material relationship study was Material Driven Design (MDD) to ensure the qualities of material are first and foremost in its functionality (Figure 1.9). This method was borrowed from *A review of Recent Advances in Fungal Mycelium Based Composites*, a study published in May 2024. It highlights a new research path for mycelium-based materials that eliminates manufacturing restrictions previously placed on product design development and emphasizes instead the qualities of the materials first to define the end result.[73] This occurs in four stages, each building off the knowledge gained from the previous step to reach a final design. The definitions of the stages have been adjusted to be neutral to the material being considered. By using this method to consider the properties of both mycelium and concrete, the final product then maximizes the functionality of its end use.

69 McLennan, The Philosophy of Sustainable Design, 5.
70 McLennan, 5.
71 McLennan, 37.
72 McLennan, 38.
73 Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites."

I RESPECT FOR THE WISDOM OF NATURAL SYSTEMS
The Biomimicry Principle
II RESPECT FOR PEOPLE
The Human Vitality Principle
III RESPECT FOR PLACE
The Economic Principle
IV RESPECT FOR THE CYCLE OF LIFE
The "Seven Generations" Principle
V RESPECT FOR ENERGY AND NATURAL RESOURCES
The Conservation Principle
VI RESPECT FOR PROCESS
The Holistic Thinking Principle

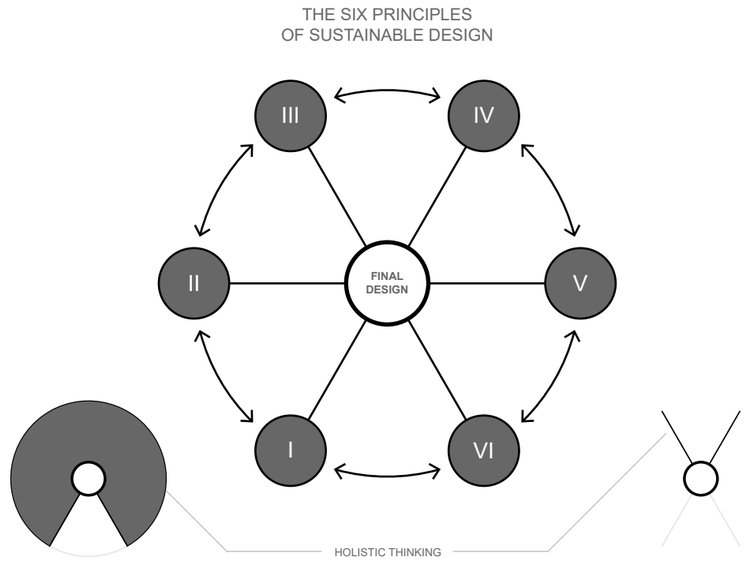


Figure 1.8: Holistic Thinking demonstrated through the Six Principles of Sustainable Design.

1 UNDERSTANDING MATERIAL
Cultivation, production and its outcome on the final result
2 TECHNICAL PROPERTIES
Material experience based on references and studying the value of manipulating its properties
3 VISUAL PROPERTIES
Theory of Diffusion of Innovations and the value of aesthetics and attraction
4 PRODUCT CONCEPTS
New product based on the results of the previous stages

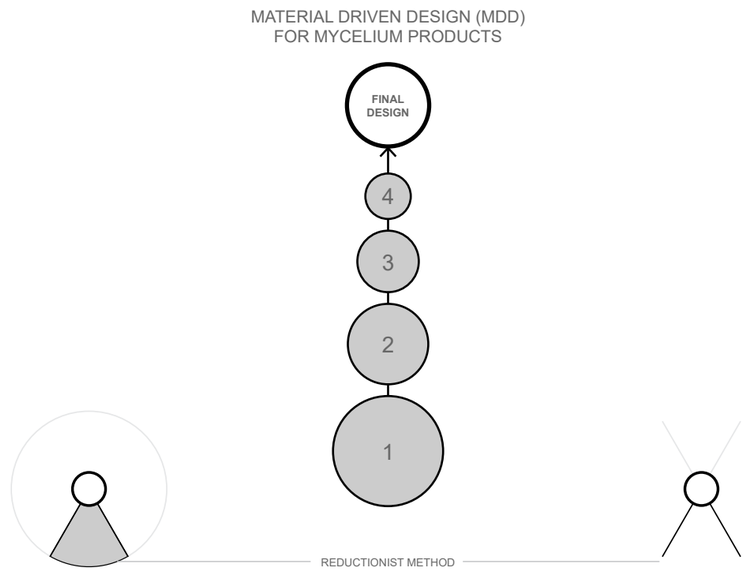


Figure 1.9: The Reductionist Method demonstrated through Material Driven Design (MDD) for Mycelium Products.

When combining the Six Principles of Sustainable Design with MDD (Figure 1.10), it was essential that they reached the same design solution from different directions, as is the nature of their approach: the holistic top-down vs the reductionist bottom-up. Once combined, the dashed line represents where the two modes of thinking intersect for the creation of an integrated design methodology. The scope of holistic thinking was narrowed to focus purely on how it effected to study of concrete and mycelium in relation to the steps of MDD. This is represented with lower case roman numerals of the equivalent principle. The MDD was also redefined, but through a different method. It was noted that steps one and two (understanding material and its technical properties) represented the research and review phase of product development, while steps three and four (visual properties and product concepts) represented the design phase.

By dividing MDD into two distinct phases, there is then an opportunity to introduce two checkpoints (Figure 1.11). At each of these, the forward momentum of the reductionist method must pause to consider the sustainability of the design thus far. The designer should not only consider the six principles that encourage holistic thinking but also consider existing and proposed policies for sustainable materials and products. Material properties must be refined through this filter of sustainability early in the design process, otherwise the project runs the risk of overextending itself into environmentally detrimental design directions, leading to unnecessary work and greater chances for mistakes when deciding on a final design. A second holistic checkpoint ensures that beyond the materials, the product and the methods used to produce, distribute and build it adhere to sustainable principles.

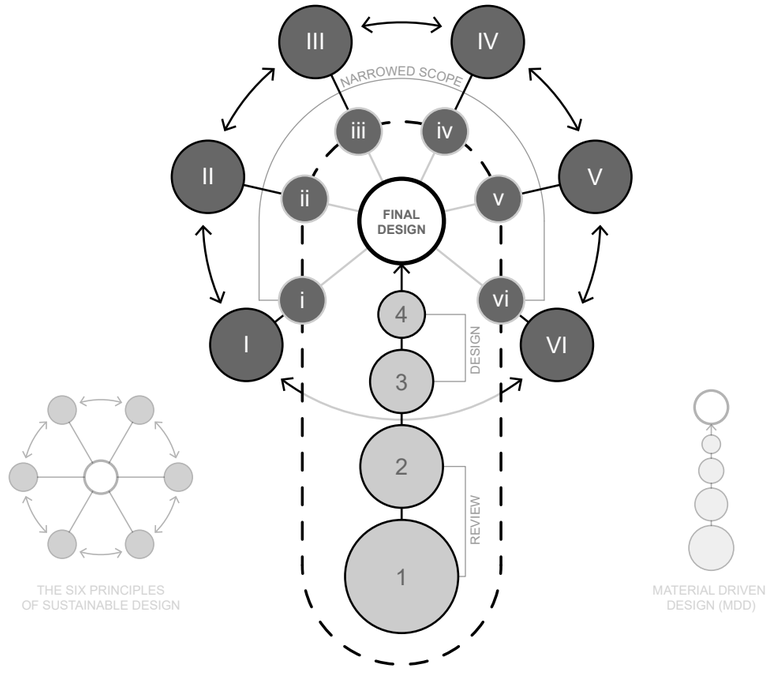


Figure 1.10: Integrated Design Methodology - Stage One.

CHECKPOINT
Stop and filter information through both philosophy and policy to ensure a sustainable approach to design

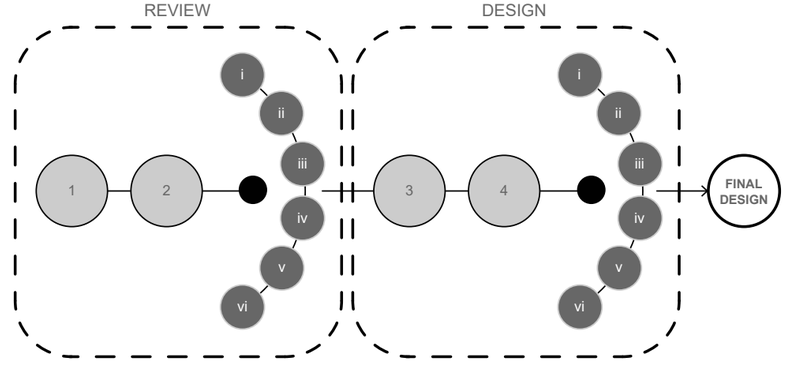


Figure 1.11: Integrated Design Methodology - Stage Two.

Apart from the integrated methodology derived from combining holistic thinking and the reductionist method, the final integrated design strategy should also include a physical exploration of the two studied materials (Figure 1.12). If an understanding of how the materials are produced and their individual properties is required to better predict how they might behave when combined, then this thinking should be furthered into a hands-on testing of these predictions. Crafting physical studies can help confirm how the materials might bond through surface, form or deconstructed connections. This exploratory methodology should include: defined material goals, well-documented material experimentation and testing, and defined design goals. Without this added exploration and experimentation, the design stage would be rooted in conjecture, as there are limited precedents that showcase the relationship between concrete and mycelium-based composites.

The final integrated design methodology places this experimentation stage between the review and design stages (Figure 1.13). A study of the production and properties of concrete and mycelium is made a part of steps one and two in the analysis stage, before a checkpoint is required to determine the environmental impact of these materials and their use through a holistic filter of sustainable policies and philosophies. Following this is the experimentation stage of the combined materials which help determine new design goals. From here the methodology can transition into the design stage to explore ideas of product aesthetic and integration as well as product concepts. A final holistic checkpoint ensures the final design meets sustainability standards. A thorough breakdown of the methodology for each stage is provided in Figure 1.13 as well as in Section 1.7.

Through the intersection of holistic thinking and the reductionist method, the final concrete-MBC product has done the work to prove its validity as both a sustainable and functional product. Its environmental impact has been both researched and forecast. Its properties have been carefully selected and maximized through this research and physical testing to determine its compressive strength and acoustic properties. These studies ensured the final use case and design of the material is perfectly suited to its task without fear of it being damaging to the environment should the product eventually be mass produced.

A MATERIAL GOALS
Desired properties of combined materials

B MATERIAL EXPERIMENTATION
Physical experimentation and testing to achieve material goals

C DESIGN GOALS
Highlights the results of experimentation and the properties that should transition into the final design.

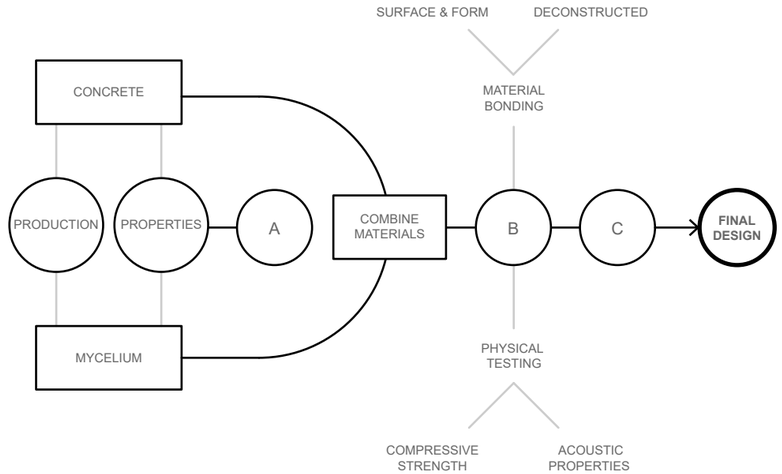
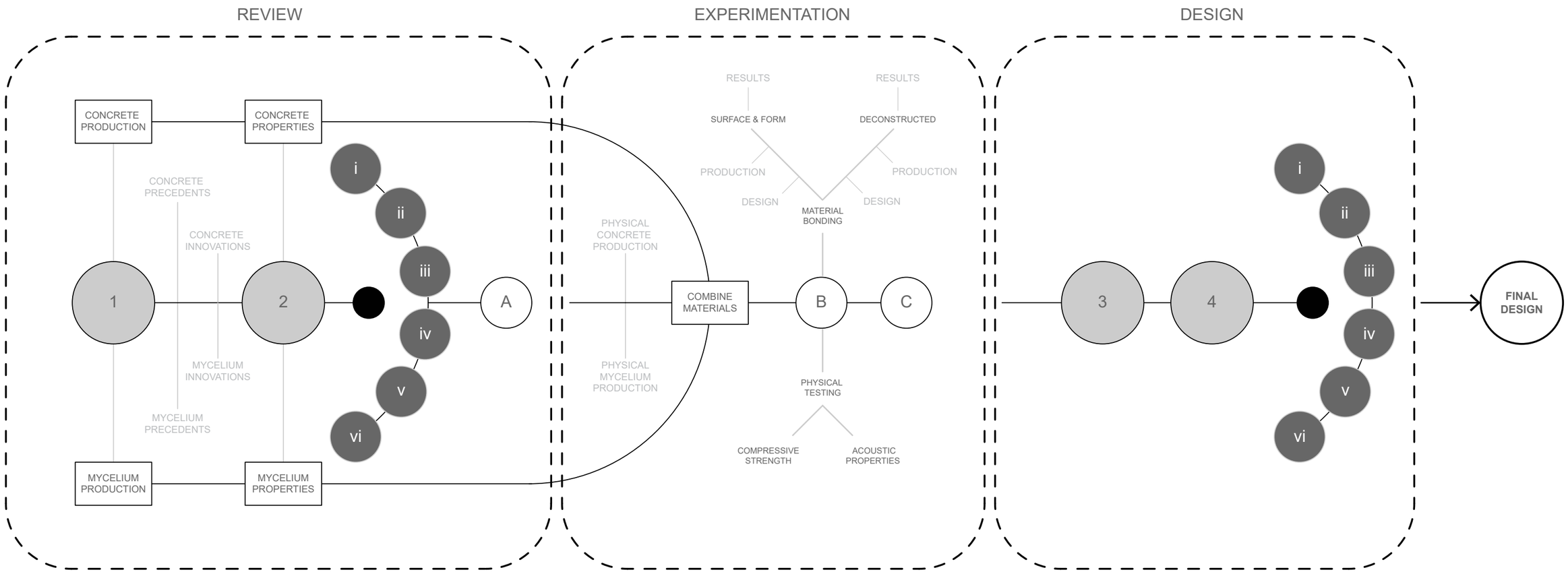


Figure 1.12: Material Experimentation and Exploration.



● CHECKPOINT
Stop and filter information through both philosophy and policy to ensure a sustainable approach to design

i RESPECT FOR THE WISDOM OF NATURAL SYSTEMS
The Biomimicry Principle
ii RESPECT FOR PEOPLE
The Human Vitality Principle
iii RESPECT FOR PLACE
The Economic Principle
iv RESPECT FOR THE CYCLE OF LIFE
The “Seven Generations” Principle
v RESPECT FOR ENERGY AND NATURAL RESOURCES
The Conservation Principle
vi RESPECT FOR PROCESS
The Holistic Thinking Principle

1 UNDERSTANDING MATERIAL
Cultivation, production and its outcome on the final result
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Material experience based on references and studying the value of manipulating its properties
3 VISUAL PROPERTIES
Theory of Diffusion of Innovations and the value of aesthetics and attraction
4 PRODUCT CONCEPTS
New product based on the results of the previous stages

A MATERIAL GOALS
Desired properties of combined materials
MATERIAL EXPERIMENTATION
B Physical experimentation and testing to achieve material goals
DESIGN GOALS
Highlights the results of experimentation and the
C properties that should transition into the final design.

Figure 1.13: Final Integrated Design Methodology.

1.7 Organization

Literature Review

This section encompasses the 'Review' stage of the integrated design methodology. It begins with an overview of concrete and mycelium and the process of their production, the existing sustainable innovations for each material, and precedents that inspired the 'Experimentation' stage of the integrated design methodology. The technical properties of each material are then compared to each other and like materials to better determine which properties should be highlighted in a final product design. These conclusions are then filtered through proposed policies and the six principles of sustainable design to dismiss unsustainable solutions and guide the material goals that conclude this chapter.

Materials and Methods

This section encompasses the 'Experimentation' stage of the integrated design methodology. It describes the process this thesis took in producing concrete and mycelium for material exploration. This exploration was divided into two methods of material bonding: surface and form bonding, and deconstructed bonding. The design, production and results of each method of concrete and mycelium-based composite bonding were documented and illustrated. Surface and form bonding took advantage of the fact that both concrete and MBCs rely on formwork to create their shape. A set of 'puzzle' and 'stitch' formworks were 3D printed to create cast concrete blocks. These blocks were designed to paired and bonded with mycelium, which would fit into the interlocking design. This method tested if MBCs could bond with the surface of the concrete, and if the material was strong enough to bind the two blocks of concrete.

The deconstructed bonding noted possible binding opportunities between recycled concrete and mycelium-based composites, and cement and mycelium-based composites – in other words, MBCs and deconstructed concrete. Twelve variations of these materials were tested – four categories of experimentation (cement, recycled aggregate, cement and recycled aggregate, wet cement and recycled aggregate) with three different ratios of each material based on precedents studied in the *Literature Review*. The deconstructed bonding samples were further explored through physical testing that noted their compressive strength and acoustic properties. The results of the material explorations culminated in design goals that concluded this chapter.

Design Proposal

This section encompasses the 'Design' stage of the integrated design methodology. It begins with an analysis of the visual properties of the materials and reviews them through the Theory of Diffusion of Innovations. This theory notes five perceived material characteristics that must be considered for a material driven product to be better accepted by its target audience (relative advantage, compatibility, complexity, trial-ability and observability). In combination with the design goals established in Materials and Methods, this review narrowed potential product concepts down to insulated concrete forms (ICF), insulated concrete panels (sandwich panels) and insulated concrete masonry units (ICMU). These product concepts were compared using an 'acceptance prediction spider chart,' which determined that ICMUs would be the strongest template from which a hybrid concrete-MBC product could be explored.

This concept was then considered from the perspective of policies and philosophies to ensure the functionality of the product was not in conflict with its sustainability. Finally, after considering each stage of the integrated design methodology, a final proposed design of a functional and sustainable concrete-mycelium-based composite (CMBC) product was presented in the form of an acoustical concrete masonry unit (ACMU). The chapter concludes with drawings and illustrations of the product and its applications.

Conclusion

The concluding section provides a summary the results of the integrated design methodology and whether this study successful in encouraging reflection on the industry's use of embodied carbon, in strengthening mycelium-based composites with concrete, and in proposing a product that is both functional and sustainable. It considers the six principles of sustainable design and whether the holistic design approach taken in this project was sufficient in addressing them. Finally, this section acknowledges the successes and shortcomings of this work, how this research might be further developed in the future.

2

Literature Review

"If it can't be reduced, reused, repaired, rebuilt, refurbished, refinished, resold, recycled, or composted, then it should be restricted, designed or removed from production."

— Pete Seeger

Understanding the value of material in architecture and construction is a subject that must be reviewed from multiple perspectives, the first being the lens of history. It must be approached with the understanding that in the earliest phases of our building history materials were selected for their local availability and functionality. However, as architecture developed over the centuries and the world grew more connected, the goal of material functionality remained but availability had expanded drastically due to a rise in technology and transportation – material selection was now only limited by the architect's imagination. As we became more conscious of sustainable practices in architecture, we did not look to reconsider the impacts of our use of materials and their embodied carbon (from their extraction and production) but instead focused more on reducing our buildings' operational carbon.[74]

Operational carbon has been treated as the priority because in recent years it has contributed to up to 75% of the Building Sector's carbon.[75] As we transition to renewable energy, it is predicted that embodied carbon will surge from 25% to 49% of the Building Sector's carbon emissions by 2050, making material selection crucial to the design of sustainable buildings today and in the near future.[76] Material choices can not only affect the embodied energy of the building, but the operational carbon as well. Materials like concrete can create "micro-climates" within buildings and absorb heat from the sun, forcing additional operational energy and costs, as well as the additional costs its impervious surface can contribute to pumping and treating stormwater due to excess runoff.[77] Within this context it is clear that all materials selected for a project must be properly reviewed from a holistic perspective in order to design a sustainable building. It is also clear that in the design of sustainable materials, we must review what traditional materials have been most successful and why to determine what qualities are required for more sustainable materials to become successful in the future.

In the case of this thesis, the goal is to find the intersection between these sustainability and functionality to define a material that incorporates traditional materials (concrete) with innovative materials (mycelium), and explores the implications it presents regarding the state of materiality of architecture and building construction today. The process of reviewing these materials, as per the methodology laid out in Section 1.6 (Figure 2.1), is to study how each material is produced as well as their technical properties, then run these through the filter of sustainable policies and philosophies to determine which properties and production strategies are best explored in the next stage of the integrated design methodology. These are summarized in a defined set of material goals that will inform the subsequent physical exploration of the combined materials.

74 United Nations Environment Programme, "Building Materials and the Climate." ix
75 United Nations Environment Programme, 7.
76 United Nations Environment Programme, 7.
77 United Nations Environment Programme, 8.

1 UNDERSTANDING MATERIAL
Cultivation, production and its outcome on the final result
2 TECHNICAL PROPERTIES
Material experience based on references and studying the value of manipulating its properties

i RESPECT FOR THE WISDOM OF NATURAL SYSTEMS
The Biomimicry Principle
ii RESPECT FOR PEOPLE
The Human Vitality Principle
iii RESPECT FOR PLACE
The Economic Principle
iv RESPECT FOR THE CYCLE OF LIFE
The "Seven Generations" Principle
v RESPECT FOR ENERGY AND NATURAL RESOURCES
The Conservation Principle
vi RESPECT FOR PROCESS
The Holistic Thinking Principle

A MATERIAL GOALS
Desired properties of combined materials

● CHECKPOINT
Stop and filter information through both philosophy and policy to ensure a sustainable approach to design

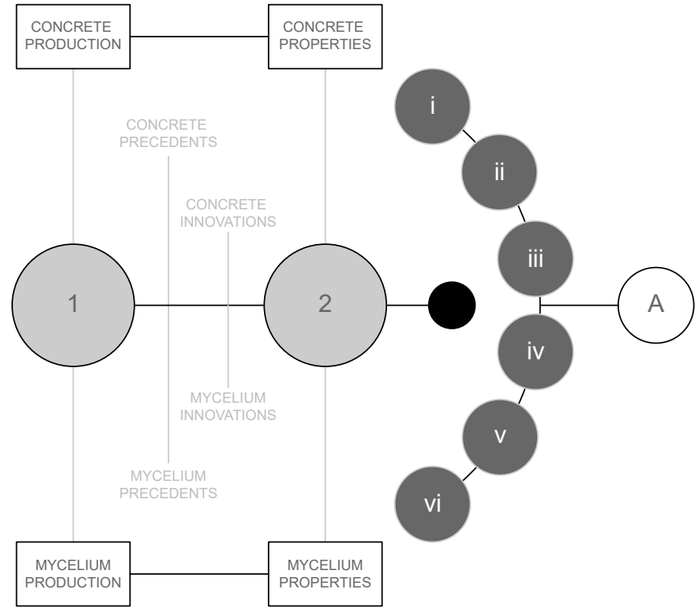


Figure 2.1: Integrated Design Methodology - Review

2.1 Material Production

Reviewing the production process for both concrete and mycelium allows us to identify the greatest sources of embodied carbon emissions for each material, and where they can potentially be reduced. The goal is to gain a deeper understanding of both materials and their stages of production to better determine the best stage both materials might most successfully be combined. This review will also take into consideration the innovations already being made to improve the sustainability, functionality and efficiency of the materials, as well as case studies that contextualize their proper applications and inspire further material exploration in *Materials and Methods*.

2.1.1 Concrete

Concrete's strength and durability are in part the reason why it is the most used construction material in the world.[78] It is a material created by the combination of three ingredients: cement, aggregate and water. The aggregate is most commonly a mixture of fine (sand) and coarse (gravel). Cement acts as the binding material in this mixture. There are two types of cement – hydraulic and non-hydraulic.[79] Hydraulic cements harden when water is added to the material – once this chemical reaction has occurred the material retains its structural integrity, even if placed underwater.[80] Non-hydraulic cements must be kept dry,[81] and are cured through exposure to carbon dioxide in the air.[82] The majority of globally manufactured concretes will use either Portland cement or PLC (Portland-limestone cement) – both are hydraulic.[83]

This thesis focuses on the most popular strain of concrete, which uses Original Portland cement (OPC) as its binder. There are five types of Portland Cement (Table 1), each used for specific use cases.[84] The type studied for the purpose of this material study is Type I. As the general/all-purpose binder, this cement and standard concrete mix will most accurately represent the largest global range of concrete. This will be cast for use in the material exploration (Figure 2.2) alongside recycled (OPC) concrete aggregate. The following material review will cover the production of OPC, the impact of the material on the environment, as well as the innovations that have been implemented to help reduce its impact and that have inspired new use cases for the material.

2.1.1.1 Concrete Production

Concrete remains a popular choice for new construction projects across the globe, consequently dominating the percentage of embodied emissions of newly constructed buildings.[85] The reason this material is so detrimental to the environment is because of the energy intensive and polluting process of producing Portland cement, particularly its method of processing limestone.[86]

78 United Nations Environment Programme, "Building Materials and the Climate." 42.
79 Napp et al., "Decarbonizing Energy-Intensive Manufacturing Industries."
80 Napp et al.
81 Napp et al.
82 Cowland, "What Is the Difference Between Hydraulic and Non-Hydraulic Lime?"
83 American Cement Association, "Cement & Concrete FAQ."
84 Hanson, "A Closer Look: Cement Types I Through V."
85 United Nations Environment Programme, "Building Materials and the Climate," 43.
86 United Nations Environment Programme, 43.

Table 1: Types of Original Portland Cement and their function.

Adapted from: Hanson, "A Closer Look: Cement Types I Through V."

TYPE	FUNCTION	USE CASES
I	Normal/General Purpose	Standard. No special properties required
II	Moderate Sulfate Resistance	Exposed to higher levels of sulfate (e.g. soil or groundwater)
III	High Early Strength	Cold weather temperatures (cold weather can cause concrete to cure slower)
IV	Low Heat of Hydration	Casting large volumes of concrete (reduces the risk of flash setting or thermal shock)
V	High Sulfate Resistance	Sulfate resistance is necessary (e.g. coastal structures, foundations, tunnels and roadways)



Figure 2.2: Test cast of standard concrete mix in preparation for material exploration. Concrete was cast in a wood formwork with a sand-filled silicone insert.

Portland cement is manufactured through a four-stage process (Figure 2.3): (1) crushing and grinding the limestone rock, (2) blending materials in the correct proportions, (3) burning the prepared mix in the kiln, and (4) grinding the burned product (clinker) with gypsum.[87] The process begins by establishing the required chemical composition for a certain type of cement (Original Portland Type I), and subsequently controlling the raw materials that would need to be fed to the crusher. This includes rock extracted from a limestone quarry. The limestone rock (which contains calcium carbonate) is crushed in two stages until a fine ground limestone is produced.

The blending process of limestone, sand and clay occurs either wet (in slurry tanks, mechanically or with compressed air) or dry (in silos, agitated by compressed air), with proportions of each required material dependent on the previously selected chemical composition of the cement. Grinding is then done wet or dry, and the materials are subsequently broken down by stirring them with water in wash mills, creating a fine slurry.[88] This 'raw meal'[89] is passed through screens to remove oversized materials before it is transferred to a preheating tower.[90] From here, the raw meal is transferred to a kiln up to 200m long and 6m in diameter, and it is at this stage that the most environmental damage is done. The kiln is heated to approximately 1450°C,[91] fueled by either pulverized coal, oil or natural gas injected through a pipe.[92] The process of raw meal transforming into clinker is called calcination – the limestone is brought to a temperature high enough to expel its carbon dioxide.[93] These large expulsions of carbon dioxide paired with the intense energy usage that fuels the process is more than 50% responsible for concrete's massive carbon footprint. The resultant clinker is cooled, and can be either be stored for future use, or immediately ground into a fine powder with the required amount of gypsum to produce cement.[94] This finished cement is pumped into storage silos from which it is drawn for packaging, either in paper bags or bulk containers.[95]

The cement itself is composed of four phases (also known as compounds). The proportion of each phase determines the qualities and performance of the types of cement described above.[96] The first is C_3S (tricalcium silicate), which comprises 50% - 70% of Portland cement clinker. This phase controls the early-age strength gain and initial set of the cement.[97] Adding more of this compound increases its early-age concrete strength development.[98] The second phase is C_2S (dicalcium silicate), which comprises 10% - 25% of Portland cement clinker.[99] This compound hydrates and hardens slowly, which allows the concrete to continue to harden and develop strength beyond one week.[100] The third compound in cement is C_3A (tricalcium aluminate).[101] This compound is the most reactive of the four, generating heat within the first few days of hydration.[102] Decreasing the proportion of this compound makes concrete more resistant to sulfates (see Type II and IV). The final phase within Portland cement is C_4AF (tetracalcium aluminoferrite), which comprises up to 15% of Portland cement clinker.[103] It offers a minimal contribution to concrete strength development but is the largest attributor of the standard grey colour of the cement, and subsequently OPC.[104]

87 Lea, Mason, and The Editors of Encyclopedia Britannica, "Cement - Extraction, Processing, Manufacturing."
88 Lea, Mason, and The Editors of Encyclopedia Britannica.
89 Heidelberg Materials, "How Cement Is Made."
90 Lea, Mason, and The Editors of Encyclopedia Britannica, "Cement - Extraction, Processing, Manufacturing."
91 Barbhuiya et al., "Decarbonising Cement and Concrete Production," 8.
92 Lea, Mason, and The Editors of Encyclopedia Britannica, "Cement - Extraction, Processing, Manufacturing."
93 The Editors of Encyclopedia Britannica, "Calcination."
94 Lea, Mason, and The Editors of Encyclopedia Britannica, "Cement - Extraction, Processing, Manufacturing."
95 Lea, Mason, and The Editors of Encyclopedia Britannica.
96 Hanson, "A Closer Look: Cement Types I Through V."
97 Hanson.
98 Hanson.
99 Hanson.
100 Hanson.
101 Hanson.
102 Hanson.
103 Hanson.
104 Hanson.

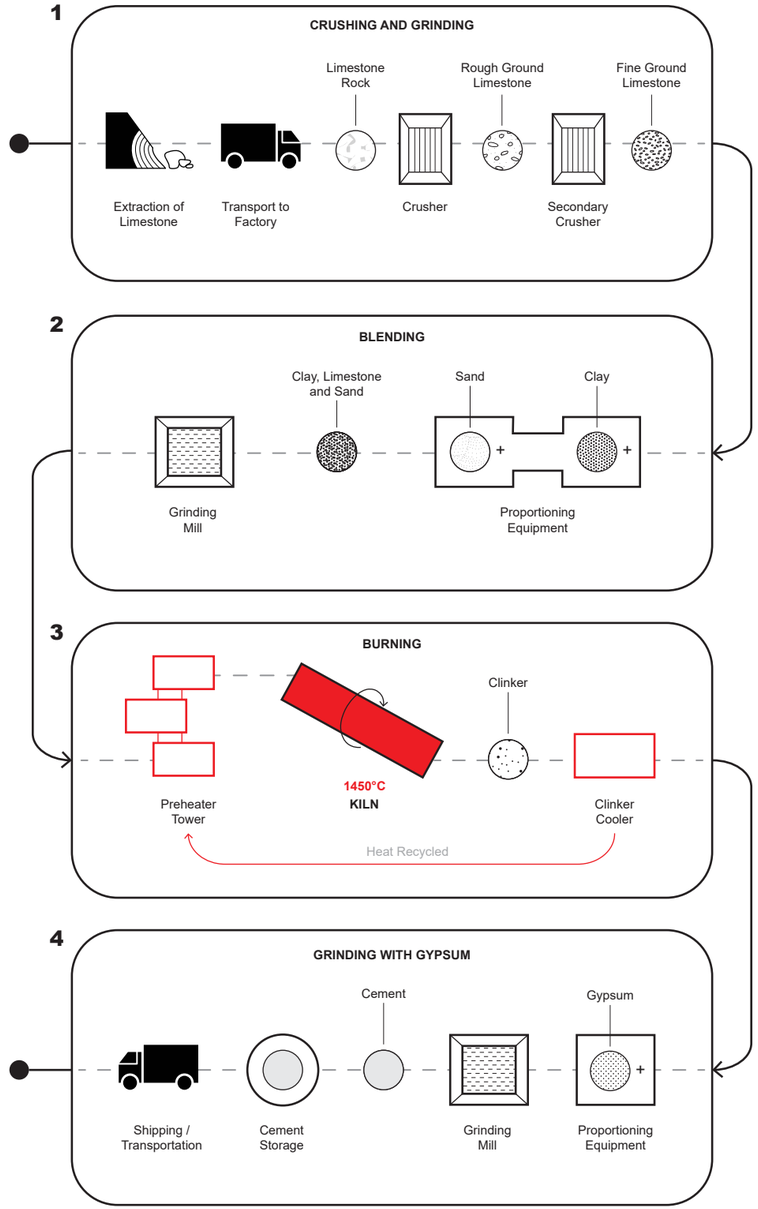


Figure 2.3: The process of cement production.

Adapted from Encyclopedia Britannica, Inc (2007)

The two calcium silicates (C_3S and C_2S) are the most important, as upon hydration they react with water molecules to form calcium silicate hydrate ($3CaO \cdot 2SiO2 \cdot 3H_2O$) and calcium hydroxide ($Ca[OH]_2$).[105] This reaction is often shorted to the shorthand notations **C-S-H** (represented by the average formula $C_3S_2H_3$) and **CH**.[106] It is through this reaction that the dissolution of the parent compounds dissolve, which generates a significant amount of heat, at which point hydration comes to a stop, resulting in a dormant period, which can last for several hours.[107] It is this dormant period that allows hydrated cement to be transported via truck rather than using it immediately upon hydration.[108] Following this dormant period the cement begins to harden as C-S-H and CH are produced, acting as a binder to the aggregate and sand in concrete mixes.

Understanding the process by which cement is activated and how this process allows it to act as a binding agent was crucial for determining in what ways the material might interact with mycelium-based composites. Key takeaways were the importance of hydration and heat in activating the binding compounds (C-S-H and CH) within cement, as well as the well-known fact that once combined with aggregate and water to form concrete, the mixture must be defined by formwork to take shape. Just as important was visualizing the production process and exactly how concrete is capable of emitting such vast amounts of carbon. With this foundational knowledge of standard practices, the next step in understanding material was uncovering what current innovations are being utilized to mitigate this damage.

2.1.1.2 Concrete Innovation

Several strategies have been proposed and implemented to address the decarbonisation of concrete. One of them is to explore alternatives to cementitious materials, such as fly ash, slag and silica fume.[109] Another is optimizing kilns to improve heat recovery systems and implement alternative fuels (e.g. biomass, waste derived fuels, or non-recyclable plastics).[110] The cement industry has even explored new and innovative technologies such as carbon capture and storage (CCS) to capture CO_2 emissions from cement.[111] While each of these strategies carries the potential to significantly mitigate the environmental impact of cement production,[112] this thesis will focus instead on mitigating the use of concrete itself.

Two of the most effective methods of reducing concrete use are employing novel manufacturing processes or recycling and reusing concrete waste as aggregates.[113] The first strategy involves using digital simulations to reduce the required structural form and volume of concrete, then achieving that form through custom formwork, drastically reducing the amount of material waste.[114] One study by Digital Building Technologies (DBT) used 3D printed PVA filament as concrete formwork – this material's ability to dissolve in water allowed for the creation of intricate geometries and undercuts within a load bearing structure (Figure 2.4).[115] This study considered sustainability not only from the perspective of material waste, but also from that of concrete formwork. Traditional one-of-a-kind concrete formworks themselves generate a significant amount of waste from CNC milling before being disposed of.[116] 3D printed PVA only produces the exact volume of material required to complete a cast and is biodegraded after use. [117]

105 Lea, Mason, and The Editors of Encyclopedia Britannica, "Cement - Extraction, Processing, Manufacturing."
106 Lea, Mason, and The Editors of Encyclopedia Britannica.
107 Lea, Mason, and The Editors of Encyclopedia Britannica.
108 Lea, Mason, and The Editors of Encyclopedia Britannica.
109 Barbhuiya et al., "Decarbonising Cement and Concrete Production," 2.
110 Barbhuiya et al., 3.
111 Barbhuiya et al., 3.
112 Barbhuiya et al., 3.
113 Barbhuiya et al., 14.
114 Leschok and Dillenburger, "Dissolvable 3DP Formwork," 188.
115 Leschok and Dillenburger, 196.
116 Leschok and Dillenburger, 196.
117 Leschok and Dillenburger, 196.



Figure 2.4: DBT study of dissolvable 3D printed PVA formwork.

(a) Early 600mm prototype: (left) 1.2mm thick formwork, no additional features, 700g formwork; (right) Cast object, 11 liters of concrete
(b) Lower third showing small cracks caused by formwork deformation

Source: Leschok and Dillenburger (2017)

The current use of concrete produces an extraordinary amount of waste through the processes of construction, demolition and renovation. Rather than discarding it, it can be crushed and screened (sorted by size) into a product known as recycled concrete aggregate (Figure 2.5).[118] This can be used as a substitute for natural aggregates in the production of new concrete, as the recycled aggregate exhibits similar structural properties.[119] Considering the majority of concrete's composition is aggregate (the source of its strength), recycled concrete has the potential to greatly reduce concrete's carbon footprint by limiting the mining, processing, transportation and construction of natural resources. The current uses of recycled concrete aggregates are as a base material for road construction, pavements and foundations.[120]

Its largest barrier from widespread acceptance is the "variability and uncertainty in the quality and properties of the recycled material and how this variability affects the strength, stiffness and durability of reinforced concrete structures",[121] however studies are being undertaken to determine how the material can be used safely in reinforced structures to achieve a more reliable product. The results of these studies have noted that increased service loads deflections, rather than reduced strength, may be the greater limitation for recycled concrete,[122] implying a greater role for the material in non structural architectural applications (such as partition walls). However, it was noted in the previous section that cement is the largest source of embodied carbon in concrete. Combining recycled aggregates with OPC is not enough when working towards a sustainable material, especially when considering the energy required to crush the concrete.[123] This increase in carbon can be offset by the prevention of demolished concrete being transported and landfilled, as well as by partially substituting cement for fly ash, resulting in a net carbon reduction compared to standard concrete mixes.[124] Pursuing the best strategies for effective concrete reuse has extreme potential in the field of sustainable design and therefore plays a large role in how this thesis approaches a hybrid concrete and mycelium material.

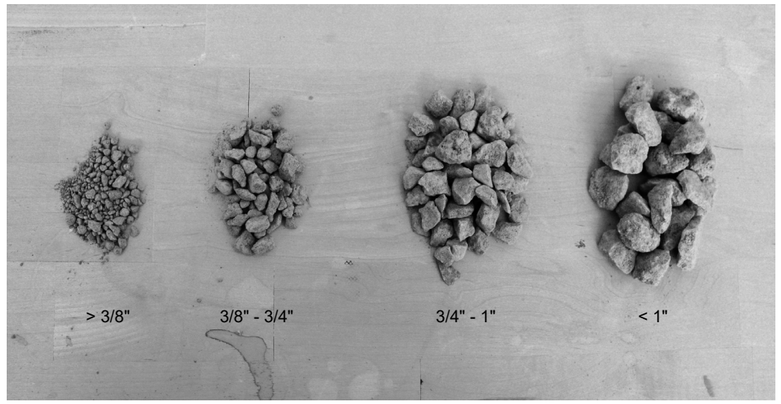


Figure 2.5: Recycled concrete aggregate sorted by size from >3/8" to <1".

118 Barbhuiya et al., "Decarbonising Cement and Concrete Production," 16.
119 Barbhuiya et al., 16.
120 Barbhuiya et al., 16.
121 University of Notre Dame, "Why Not Recycled Concrete?"
122 Knaack and Kurama, "Design of Concrete Mixtures with Recycled Concrete Aggregates," 493.
123 Ma et al., "A Carbon Footprint Assessment for Usage of Recycled Aggregate."
124 Neupane et al., "Environmental Insights in Recycled Concrete Aggregate Production."
125 Luo et al., "Interactions of Fungi with Concrete," 1.
126 Luo et al., 9.
127 Luo et al., 13.
128 Jiang et al., "Improved Cellulase Production of Trichoderma Reesei by Regulating Mycelium Morphology."
129 Hunt, "Green Building With Hempcrete."
130 Hunt.
131 Holland, Nichols, and Nichols, "THE USE OF LIME IN CONCRETE AS A CEMENT REPLACEMENT, CHANGE IN PHYSICAL PROPERTIES," 2.
132 *Basics of Hempcrete - Episode 1 - Safety & Mixing*.
133 Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete."
134 Magwood, "Insulation Alternative: Hempcrete."
135 Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete."
136 *Making Hempcrete Blocks, a Tutorial.*
137 Hempstone, "The Drying of Hempcrete Walls."

2.1.1.3 Concrete Precedents

Strategies for exploring the relationship between concrete and mycelium-based composites were largely inspired by two concrete precedents: self-healing concrete and hempcrete. Self-healing concrete was the focus of a study that explored the concept of fungi as an agent to promote calcium mineral precipitation to fill the cracks in concrete caused by deterioration.[125] The study discovered that out of five species of mushroom, only one strain of spores (Trichoderma reesei) were capable of germinating on concrete into hyphal mycelium, and grew equally well with or without concrete.[126] These fungi spores were then embedded as healing agents through an air-entrainment process during concrete production.[127] These explorations offered a precedent for the successful (albeit microscopic) relationships that could be formed between concrete and mycelium, however the successful fungal strain was unavailable for this thesis. It requires specific lab conditions for cultivation,[128] and its potential applications within mycelium biocomposites were underexplored in comparison to faster growing strains (such as oyster mushrooms).

Hempcrete is a product that combines hemp with lime and water to create a non-load bearing construction material.[129] There are three distinct features that encourage the use of hempcrete in construction projects: air entrapment allows it to act as an insulator, its 300 kg/m3 density allows it to store heat through thermal mass (evening out temperature extremes) and it has a vapor-open structure, storing condensation during high humidity and releasing it as humidity drops.[130] It binds itself with lime, which has a lower compressive strength and higher cost than cement, but is a more sustainable substitute.[131] As with concrete, there is no one standardized recipe for its production, and different ratios of ingredients produce different technical properties. Research has shown a material ratio (by volume) of binder to hemp with samples ranging from 1:2,[132] 1:3,[133] and 1:4.[134] Compressive strength can range from 0.2 to 0.5 MPa depending on the variety of the mixture.[135] Hempcrete is produced by mixing the lime (and occasionally additional sediments like cement and metapor)[136] with water before incorporating hemp. The mixture is then compressed into a formwork and left to air-dry for approximately one week per inch of thickness.[137] This product and its raw material ratio serves as a good foundation from which to explore the relationship between mycelium biocomposites and a deconstructed form of concrete, particularly in seeing how mycelium might interact with a binding agent like cement.

2.1.2 Mycelium Based Composites

Mycelium is the living part of a fungus, and the vegetative root of the fungal body. It is the intermediate phase of the mushroom life cycle, of which there are four basic stages: (1) spore germination, (2) colonisation, (3) fruiting and (4) sporulation.[138] Mushrooms begin life as a spore, which germinates in the environmental conditions suitable for the species.[139] When the spore germinates, strands of hyphae emerge. These are the structures a fungus uses to gather nutrients and energy and are the means by which it continues to grow.[140] Mycelium is a colony of hyphae[141] – as it grows it spreads through a substrate in a process called colonization. The spread of mycelium through the substrate is known as inoculation. Its goal is to colonise as much area as possible – the more substrate a single body of mycelium can occupy, the greater its access to nutrients.[142] It is this natural 'ambition' for growth that makes mycelium such a compelling candidate for further material research and applications.

From this stage there are two paths that can be taken – the mycelium can be exposed to specific conditions that would trigger the fungus' final stages towards a fruiting body, or it could be ceased. This process renders the mycelium inert, the colony binding the substrate into one solid material known as a mycelium-based composite. It is a material with two main ingredients; the filler (substrate) and the binding agent (mycelium).[143] In this way mycelium-based composites work similarly to aggregate and cement in concrete production.

Mycelium-based composites are biodegradable, renewable, and can be produced using low-energy, low waste[144] and low-emission methods.[145] This section will review its methods of production, the innovations in its application that have aided in defining its potential scope and limitations, as well as the precents that directly influenced the methodology for exploring this material alongside concrete.

2.1.2.1 Mycelium-Based Composite Produciton

As noted in the introduction to this section, mycelium is produced following the germination of mushroom spores in a suitable substrate. However, the methods that are successful in nature are not necessarily successfully repeated in a lab environment. Only a small percentage of spores find a suitable environment for germination in nature, but growing mycelium consistently to building standards requires a more reliable cultivation technique (Figure 2.7).

The first stage of MBC cultivation is the inoculation of a substrate. The substrate can be a variety of waste materials such as straw, woodchips, hemp, or sawdust.[146] Supplements can be added optionally to provide additional nutrients – these are typically rich in carbon and nitrogen, like flours, brans and whole grains.[147] The substrate and supplements are mixed with water to reach a certain level of relative humidity for the chosen strain of mycelium.[148]

138 Mycologic, "The Mushroom Life Cycle."
139 Mycologic, "The Mushroom Life Cycle."
140 Sayner, "A Detailed Explanation of the Mushroom Life Cycle."
141 Sayner.
142 Mycologic, "The Mushroom Life Cycle."
143 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 39.
144 Ghazvinian and Gürsoy, 38.
145 Patel and Sharma, "The Possible Applications of Mycelium-Based Bio-Composites in Architecture," 214.
146 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 40.
147 Ghazvinian and Gürsoy, 40.
148 Ghazvinian and Gürsoy, 40.



Figure 2.6: Grey oyster mushrooms from a mushroom growing kit.

This mixture must now be pasteurized or sterilized to prevent infections by eliminating all microorganisms[149] and bacterial spores.[150] Too much bacteria in the bags could overpower the newly introduced mycelium, therefore it is best practice to aim for their total annihilation. Pasteurization is less effective than sterilization, but is a cheaper alternative (most often used by farmers) to buying the expensive autoclave required for sterilization. Sterilization is the preferred option for consistent results and is achieved by transferring the substrate mixture to a heat resistant and sealable bag, and pressurized for 30-45 minutes within an autoclave at 121°C.[151] The mixture is then left to cool until it returns to room temperature. At this stage it can be inoculated with mycelium – the strain is typically from the saprophytic classification of fungi, which feeds on dead organic matter.[152] More specifically, mycelium strains are typically white rot saprophytic fungi which degrades all compounds in wood (including lignin) and results in a white decomposition.[153] The most common strain of mushroom is under the genus P. ostreatus (Oyster Mushroom),[154] which is what was selected for exploration in this thesis (Figure 2.6). It is popular due to its quick growth and generous germination temperature range (10-30°C).[155] They are also widely available – oyster mushrooms are the second most commonly grown in the world, second only to button mushrooms.[156]

Lab growth is the next stage in the cultivation process, and it occurs in two phases. The first takes place within the sterilization bags, where the mycelium is given 5-15 days to cultivate and colonise. During this process, mycelium takes in oxygen and releases carbon dioxide, much in the same way humans do.[157] Filter patches on the sterilized bags facilitate this air exchange while keeping out contaminants. This process creates condensation within the bag. For the most common strains of mushroom (like oyster) a dark environment and room temperature of 24°C is ideal.[158] The second phase of growth occurs when the inoculated substrate is transferred to a formwork. Since the mycelium processes the nutrients of organic materials, plastic is the most commonly used material to shape the biocomposite.[159] This is left to grow for another 5-15 days.

The final stage of MBC cultivation is ceasing. This occurs when mycelium growth is interrupted by heating, which kills it and thus produces an inert MBC.[160] Smaller blocks can be heated in an oven up to 80-95°C.[161] Alternatively, the MBCs can be hot-pressed – this is the process that has the greatest effect on the mechanical properties of the mycelium, changing its material performance from "foam-like to wood-like."[162] Without access to a hot press, this thesis focused on the material properties of MBCs that did not rely on this tool to enhance their mechanical performance.

149 Grimm, Sonntag, and Gerold, "EVALUATION OF DIFFERENT PASTEURIZATION AND STERILIZATION METHODS FOR OYSTER MUSHROOM SUBSTRATES," 1.
150 Keratimanoch et al., "Effects of Tyndallization."
151 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 40.
152 Ghazvinian and Gürsoy, 40.
153 Ghazvinian and Gürsoy, 40.
154 Ghazvinian and Gürsoy, 41.
155 Aditya et al., "Comprehensive Review on Oyster Mushroom Species (Agaricomycetes)," 2.
156 Hoa and Wang, "Effects of Temperature and Nutritional Conditions on Mycelium Growth."
157 Zapach, "Why Mushroom Growth Requires a Fan & Fresh Air Exchange."
158 Ghazvinian and Gürsoy, "BASICS OF BUILDING WITH MYCELIUM-BASED BIO-COMPOSITES," 41.
159 Ghazvinian and Gürsoy, 41.
160 Ghazvinian and Gürsoy, 42.
161 Ghazvinian and Gürsoy, 42.
162 Ghazvinian and Gürsoy, 42.

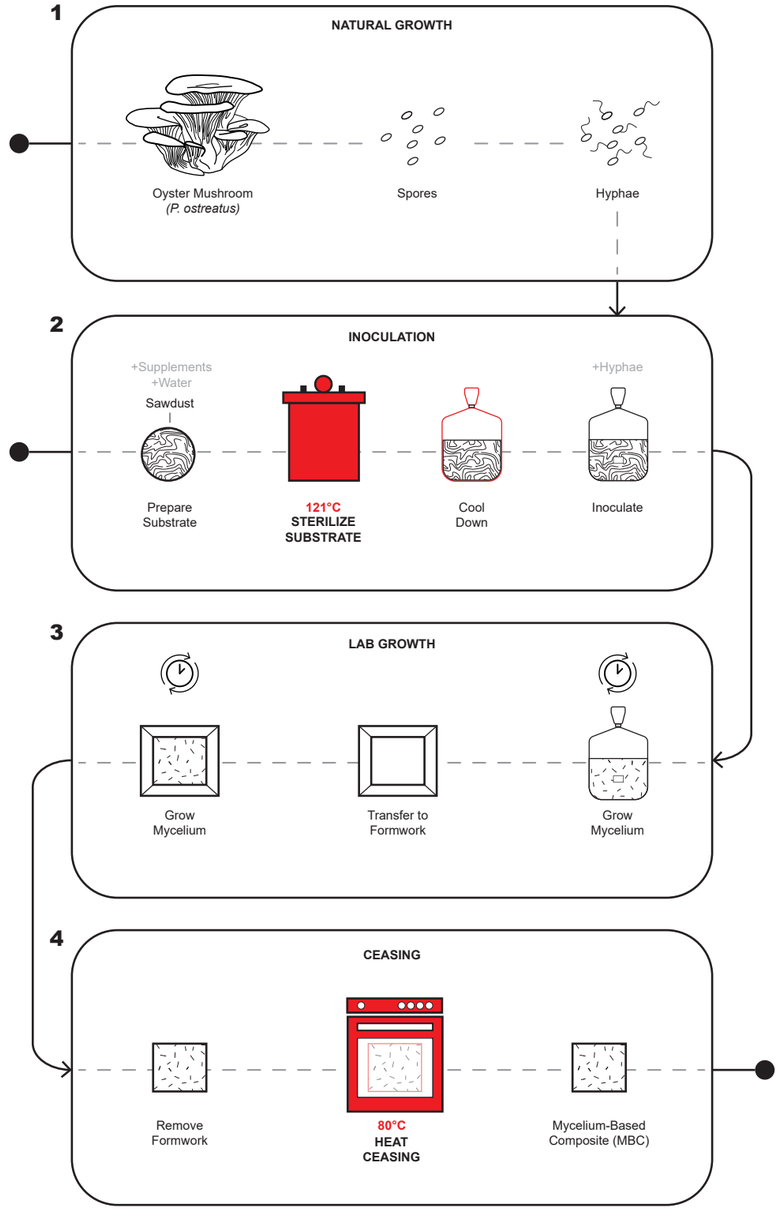


Figure 2.7: The process of mycelium-based composite production.

Adapted from Ghazvinian and Gürsoy (2024)

2.1.2.2 Mycelium-Based Composites Innovations

Mycelium-based composites are currently sold as biodegradable packaging and acoustic panels. In architecture, they have primarily been used as experimental cladding in pavilions. The material is too young to declare any one application of it an innovation, however some of the most interesting material discoveries have been found through these pavilion projects.

The *Monolito Micelio* pavilion, for example, was an experimental use of in-situ casting for the creation of a 'living monolith'.[163] A wooden vault-shell was used to support a one-ton colony of mycelium-stabilized hemp, which was encased by an external formwork of nylon geotextile.[164] Once installed, the mycelium was left to cultivate for 5 days, after which point the geotextile was removed to let the mycelium-based composite air dry for several weeks.[165] This process of in-situ casting likens mycelium production to cast-in-place concrete, proving that as a product, mycelium could be grown into a cohesive material in bulk. It also rebelled against the common practice of producing modular MBC bricks and panels for construction applications. Despite its initial success and its design as a temporary structure, the project is arguably most notable for the process of its decay.

As part of a superstructure, MBCs are susceptible to expansion and contraction in the face of external elements.[166] A combination of temperature swings and rain caused the material to crack, decay and mould – this process was exacerbated by the fact that the structure holding it in place was a stronger and more rigid material than the MBC, and therefore did not accommodate its deteriorating form.[167] Figure 2.8 shows the damage to the material after 3 months in contrast to the infestation of mould that had progressed just one month later.[168] This project reinforced a need to maintain a small scale for concrete-MBC explorations, as well as encouraged the final design towards an interior application.

Contrasting this case study of material limitations is an exemplary project by the SciArt collective MY-CO-X, who specialize in mycelium-based materials. Their pavilion, *MY-CO SPACE* (Figure 2.9), was a wooden fungal sculpture designed to enable an "artistic-scientific discussion about a future social significance of fungi for the creation of places and spaces."[169] Its design was born from their morphological



Figure 2.8: The Monolito Micelio pavilion three months after construction (left) versus only one month later (right).

Source: Dessi-Olive (2022)

163 Garcia, "Living Mycelium," 32.
164 Garcia, 32.
165 Garcia, 32.
166 Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures," 5.
167 Dessi-Olive, 5.
168 Dessi-Olive, 6.
169 Meyer et al., "MY-CO SPACE," 1.
170 Meyer et al., 2.
171 Meyer et al., 2.
172 Meyer et al., 4.
173 Meyer et al., 6.

and philosophical investigations of mycelium, and aimed to simultaneously visualize an alternative future of the built environment and interrogate the relationships between human and non-human life-forms.[170] To achieve this goal, the design of the form and material was approached from an interdisciplinary perspective that involved architects, artists and biotechnologists.[171] Through this collaboration, each discipline was able more comprehensively understand the aesthetic qualities and mechanical behaviour of mycelium-based composites, and thus uncover new concepts for the ways in which they could be used.

From an artistic perspective, the creation and arrangement of MBC panels symbolized deconstruction and reconstruction of organic materials that fungi already enacted in nature, a strength that humans were able to cultivate and arrange into a utopian living space.[172] The visual quality of the material represented this journey from a microscopic to a macroscopic scale. They placed the unique tactile qualities of the material at the forefront of both the exterior cladding and interior furnishings. From a construction perspective, the pavilion was designed with an outer skin of fungal panels designed to take on both the thermal and acoustic functions of the pavilion.[173] From the perspective of an architect, this project was innovative in its reminder to consider mycelium as more than a material that can be exploited for its technical properties or sustainable qualities. Its production, aesthetic and application make a collective statement on both the future of architecture and the future of our planet. Their project does not take a position on whether the use of MBCs is a positive or negative reflection of this reality, but its raw visual properties work to elicit that reflection from anyone who interacts with it. When designing a material that blends concrete with mycelium-based composites, this weighted aesthetic association was kept in mind for the design of a final product.



Figure 2.9: Exterior MBC cladding on MY-CO SPACE Pavilion.

2.1.2.3 Mycelium-Based Composites Precedents

Strategies for exploring this hybrid material were largely inspired by three mycelium-based composite precedents: *Symbiocene*, the *Mycohouse Biocycled Bee Barn Entry* and a thesis project that introduces landfill waste into MBCs.

Symbiocene is a project by PLP Labs that grew mycelium-hemp composites within a permanent formwork. The blocks were designed as part of a modular system that, when connected, could form a partition wall, seating, planters, or a table (Figure 2.10).[174] The intent of their work was to explore the building properties of mycelium-based composites – specifically, their structural capabilities and architectural potential.[175] Their research led them to take advantage of mycelium's ability to break down and bond with wood, and so constructed their integrated formwork out of 3D printed wood filament.[176] This technique allowed them to mold and configure mycelium with a high level of precision, ensuring consistency across each module.

This project was one of the few identified that showed a hybrid pairing of MBCs with a separate material, which was particularly relevant as the added material sought to introduce additional structure to the MBC. Their method of using 3D printed formwork as both a guide and an integrated support for MBC was a large inspiration for the material exploration in Section 3.2.1.

The *Mycohouse Biocycled Bee Barn Entry* was a project by Redhouse that was built for the Refuge Response at Ohio City Farm in 2020.[177] Its main draw was the use of the firm's 'biocycler' – a process by which mycelium was used to bind the sawdust recovered from the construction of the building's outer shell to create its interior insulation.[178] Other viable recyclable materials their biocycler process is capable of recycling include all 'woody' materials like plywood, OSB and framing, as well as gypsum board, ceiling tiles, asphalt shingles and other organic based materials.[179] While they have not yet published their findings or working methodology, they do provide samples of their biocycled material for purchase as proof of its viability. This project serves as a precedent for a mycelium-based composite with the same method of recycled bulk substrate as the one selected for this paper's material exploration.

The final precedent is a Doctor of Architecture thesis that addressed the growing volume of annual landfill waste. Their work proposed taking advantage of mycelium's ability to grow through substrates and test it against pieces of waste that might not exchange nutrients.[180] This hypothesis was first tested against cut up paper cups, then on plastic bottles. Since the mycelium successfully bonded around both types of foreign elements, this study was critical in providing a viable material ratio when introducing recycled concrete to an inoculated substrate in Section 3.2.2.

174 PLP Labs, "Symbiocene."
175 PLP Labs.
176 PLP Labs.
177 Redhouse, "MycoHouse."
178 Redhouse.
179 Redhouse, "Biocycler."
180 Pananganan, "Exploring Mycelium as a Sustainable Building Material," 40.

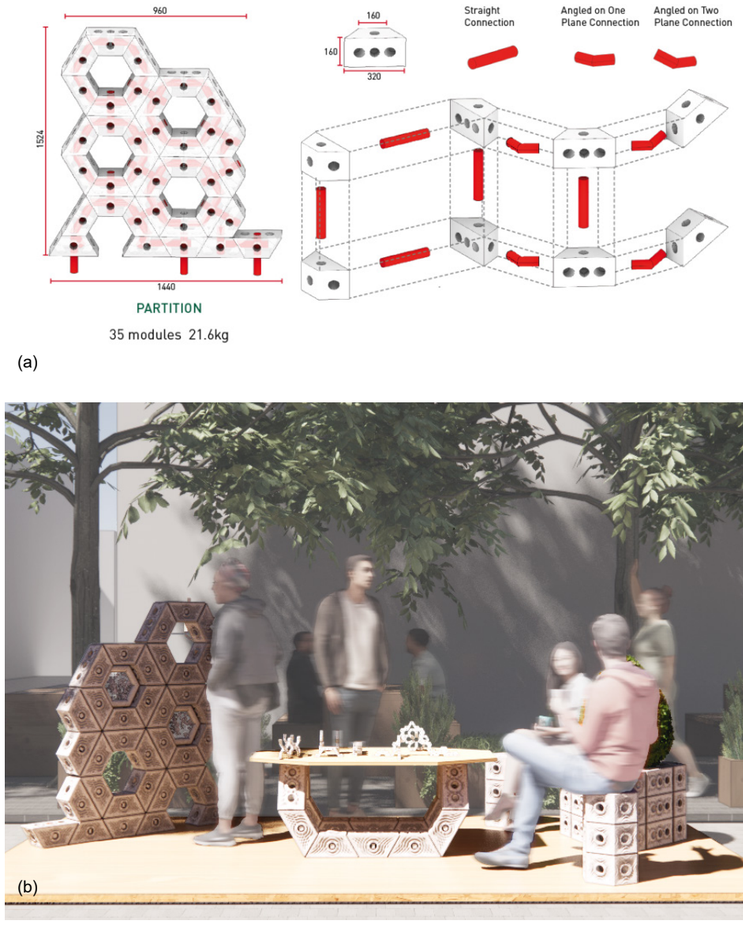


Figure 2.10: Symbiocene by PLP Labs.

(a) Diagram of partition wall modules and assembly
(b) Render of assembled products

Source: PLP Labs (2023)

2.2 Technical Properties

The material properties of concrete, hempcrete, wood products, synthetic foams and mycelium-based composites have been compared in Table 2. It should be noted that (particularly in the case of mycelium-based composites) these figures represent an average of the scope of their properties, as several factors from material selection to material ratio to production technique can greatly affect these properties. For these reasons, both concrete and mycelium will primarily be assessed individually for their greatest technical strengths and weaknesses to hypothesize the best combination of their attributes.

Concrete's popularity in construction stems from its advantageous mechanical properties. It has a high durability and strength, and is capable of withstanding harsh weather conditions, making it ideal for use in foundations, bridges and high-rise buildings. It is known for its high compressive strength (typically ranging from 20-40 MPa), however like with MBCs, this can vary based on its composition and curing time. It has an excellent fire resistance – so great that in most cases it does not require additional fire-protection.[181] It is classified as an A1 non-combustible material.[182] It is also versatile, capable of being formed into any desired shape to suit construction needs.

Aside from its weakness as a sustainable material, concrete has a few technical weaknesses as well. Without reinforcement, it has relatively poor tensile strength and flexural strength – approximately 10% the average compressive strength. It is subject to creep over time, which can eventually lead to structural damage. It also requires reinforcement to address the shrinkage that occurs when it dries, which can lead to cracking if left unchecked. Given enough mass, the porous structure of concrete allows it to become a good thermal insulator, but it has relatively poor insulation properties when compared to other insulation materials (it has an R-value of approximately 0.1-0.2). Finally, concrete does not perform well acoustically. The material works to reflect the sound rather than absorb it.[183]

From a structural perspective, mycelium-based composites are inferior to concrete in every category. MBCs are most technically comparable to synthetic foam insulations, therefore similar material properties should be used to complement concrete's. MBCs have a high fire resistance (with silica), however since concrete again outperforms it, this property was dismissed as a consideration for the combined material design. Mycelium-based composites do have a significantly higher thermal resistance than concrete.[184] Additionally, mycelium-based materials have been discovered to have good sound absorption, though its value changes depending on the material and production method. While both of these advantageous properties are lower when compared to their synthetic insulation counterparts, their method of production and biodegradability reinforce the material as worthy of exploration. Conducting an exploration that integrates these properties with concrete's strength and resilience became one of the driving goals of the material exploration.

181 The Concrete Centre, "Fire Resistance."
182 The Concrete Centre.
183 Fediuk et al., "Acoustic Properties of Innovative Concretes."
184 Chen, "Introduction to Mycelium Insulation."

MATERIAL PROPERTY	MBC	CONCRETE	WOOD PRODUCTS	SYNTHETIC FOAMS	HEMPCRETE	REFERENCES
Compressive strength (MPa)	0.01-1.1	20-40	SW: || 35-43, T 3-9 HW: || 68-83, T 12.7-15.6 PW: || 8-25	PS: 0.03-0.69 PU: 0.002-48 PF: 0.2-0.55	0.2-1.15	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. The Engineering Toolbox, "Concrete Properties." Abdellatef et al., "Properties of Hemp-Lime Composite Building Materials." Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture."
Tensile strength (MPa)	0.03-0.18	2-5	SW: || 60-100, T 3.2-3.9 HW: || 132-162, T 7.1-8.7 PW: || 10-44	PS: 0.15-0.7 PU: 0.08-103 PF: 0.19-0.46	0.02-0.15	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. Abdellatef et al., "Properties of Hemp-Lime Composite Building Materials."
Density (kg/m³)	59-552	2240-2400	SW: 440-600 HW: 850-1030 PW: 35-78	PS: 11-50 PU: 30-100 PF: 0.19-0.46	413	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. Tran Le et al., "Study of the Transient Behaviour of a Hemp Concrete Building Envelope," 847. The Engineering Toolbox, "Concrete Properties."
Flexural strength (MPa)	0.05-0.29	3-5	SW: 9.9-11.5 HW:10.3-11.5 PW: 34-78	PS: 0.07-0.70 PU: 0.21-57 PF: 0.38-0.78	0.06-1.13	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. The Engineering Toolbox, "Concrete Properties." Abdellatef et al., "Properties of Hemp-Lime Composite Building Materials."
Fire resistance	No silica: low 50% wt% silica: high	very high	SW: low HW: low PW: low	PS: very low PU: very low PF: very high	high	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. Delhomme et al., "Physical Properties of Australian Hurd Used as Aggregate for Hemp Concrete."
Acoustic Absorption (NRC)	> 70-75% *no official NRC for MBCs yet	0-0.2	SW/HW: 0.5-0.15 PW: 0.1-0.23	PS: 0.2-0.6 PU: 0.2-0.8	0.6	Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 8. Delhomme et al., "Physical Properties of Australian Hurd Used as Aggregate for Hemp Concrete." NRCratings, "Noise Reduction Coefficients (NRC) for Common Building Materials."
Thermal Resitance (R-value/inch)	3	0.07-0.52	SW: 1.41 HW: 0.71 PW: 1.25	PS: 5 PU: 6.25	1.2-2.1	Chen, "Introduction to Mycelium Insulation." Archtoolbox, "R-Values of Insulation and Other Building Materials." U.S. Department of Energy, "Energy Efficiency in Log Homes." Quinn, "Hempcrete Thermal Modelling Info."

Table 2: Comparison of the material properties between mycelium-based composites, concrete, wood products, synthetic foams and hempcrete.
Wood products: softwood (SW), hardwood (HW), plywood (PW)
Synthetic Foams: polystyrene (PS), polyurethane (PU), phenolic formaldehyde resin (RF)
NRC: Noise Reduction Coefficient. 0 indicates total reflection, 1 indicates total absorption.

2.3 Policies and Philosophies

When designing a sustainable material, it is necessary to examine its impact holistically. While this thesis is written from the perspective of an architect, sustainable design and material decarbonization impact every aspect of the construction industry. While the architect can design a material and consider its source and recovery rate, it is also the responsibility of the manufacturer's, builders and waste managers to trace their own material use and avoid unsustainable land-use patterns. It is the responsibility of financial investors and developers to use economic practices that value natural capital and biodiversity, and to invest in the innovation of low-carbon and recycled materials. And finally, it is the responsibility of the policy makers to reduce the extraction of non-renewable materials and mandate green certifications.[185] These examples of what can be done only scratch the surface of the impact each role can have on the betterment of our planet through material decarbonization, but this impact is meaningless without a cohesive set of guidelines and principles to propel everyone in the same direction. This thesis looks to examine the proposals for these guidelines when they are presented as either philosophies or policies, and the ways in which the exploration of concrete and mycelium-based composites might comply with them on their path to becoming a sustainable combined material.

2.3.1 Policies

There is no official consensus that exists on how to benchmark or baseline the embodied carbon of a building.[186] If the long-term goal of architecture is to design sustainable buildings, then the intermediate goal should be to enforce new policies that develop and regulate approval processes for materials before they enter the marketplace. There should be a push for policies that prioritize the use of secondary and recycled materials (with standardized tests to ensure they reach recognized material standards), as well as policies that incentivize both the research and utilization of biomaterials in construction. Most importantly, there should be industry wide principles that guide the future of architecture and construction toward enacting material decarbonization.[187] The United Nations 2023 report Building Materials and the Climate: Construction a New Future proposed three such principles: Avoid, Shift, and Improve.

Avoid looks to avoid waste by building with less and improving material circularity.[188] Strategies to achieve this include designing for disassembly and implementing computer aided design strategies to optimize material applications. It encourages new policies that support a new supply-and-demand model, as the quantity of quality recycled materials currently available does not meet the current demand. The best strategy to close this gap is to coordinate between disciplines to adopt building codes that require designers to specify "circular" components made with re-usable, renewable materials.[189] The materials of this thesis also look to avoid waste and encourage recycling and 'circularity' in their production. The MBCs recycle sawdust accumulated through waste during the production process of hardwood products. Further down the line of the building life cycle, this work also looks at new ways to reincorporate recycled concrete recovered from demolition. While both these materials can currently be obtained, with several companies already using this construction waste to fabricate these exact recycled products, the lack of policies enforcing proper on-site recycling of waste materials is a detriment to the project's proposed application. This missing link highlighting the challenges of implementing this thesis project on large scale must be considered when determining if the final combined material product is sustainable.

Shift is a principle that prompts the industry to transition towards biomaterials.[190] It encourages an increased use of materials such as wood, dependent on ecologically sound material extraction – the waste can then be transformed into additional materials (including mycelium-based composites). This shift should also expand to materials beyond wood products – this principle calls for a substantial investment in producers and researchers of low-carbon materials and hybrid bio-based materials, alongside incentives and/or enforceable building codes.[191] These investments are critical to the potential implementation of this thesis' hybrid material – it seeks to develop recycled materials as encouraged through the 'Avoid' principle, but one of the reasons these combined materials remains underexplored is a lack of funding and purposeful investment in how best to exploit their properties. As noted in the Introduction, this thesis purposely chose to search for a connection between two materials on opposite ends of the sustainability spectrum. It is the hope of this thesis that in finding a successful blend of the two materials' strongest properties, it will rejuvenate a dialogue in which strategies for the practical incorporation of biomaterials into standard architectural products, and sustainable practices might be discussed with a fresh perspective.

The final proposed principle is to **Improve** non-renewable building materials and processes.[192] This principle focuses on production, pointing out the linear material economy that results in virgin and non-renewable materials (that are energy intensive to produce) are still contributing to most of today's material demand. [193]Particularly in the case of cement and concrete, should the ability to 'Shift' away from the material not be available, the 'Improve' principle then outlines several strategies and policies for its carbon mitigation. These include reducing the clinker-cement ratio, electrifying production with renewable energy sources and mandating pre-fabrication of circular units that can be disassembled and reused for future building. As noted in Section 2.1.1, this thesis looked at two versions of concrete – the first being the standard OPC (representing modern construction practice) and recycled concrete (representing a theme of reuse and lowering embodied carbon, particularly when in combination with MBCs). While this paper focuses less on adjusting concrete production practices and more on how to use the material more sparingly, the direction still fits the under the umbrella of the principle. By focusing on material reduction in conjunction with 'greener' material alternatives, this project seeks to improve its efficiency relative to its role and recontextualize its final design as a recyclable material, thus reducing the need for further production of concrete.

185 United Nations Environment Programme, "Building Materials and the Climate." xxv
186 United Nations Environment Programme. xix
187 United Nations Environment Programme. xi
188 United Nations Environment Programme. xi
189 United Nations Environment Programme. xi
190 United Nations Environment Programme, "Building Materials and the Climate." xii
191 United Nations Environment Programme. xii
192 United Nations Environment Programme. xiv
193 United Nations Environment Programme. xiv

While these principles currently have only slight influence on the direction of the project, these principles are being presented by the United Nations Environment Programme as a guideline for future sustainable building policies. Should the final design prove itself to be both functional and sustainable while remaining in line with the above principles, it can serve as a proof of concept for these future policies. With this in mind, budget should also factor into the design of the final product to ensure the material goals do not overshadow the practicality of its implementation within the construction industry.

2.3.2 Philosophies

The philosophy used for this thesis is based on McLennan's six principles of sustainable design. The basis of the philosophy was described in Section 1.6 – this section focuses on the principles themselves and how they might influence the use of materials. By reflecting on how these materials fare within the philosophy of sustainable design, the method through which they should be employed becomes easier to discern.

The first principle is **Biomimicry** (Respect for the Wisdom of Natural Systems). This principle is a call to turn away from the destructive thinking that came with the Industrial Revolution that separated us from nature and take inspiration from it instead. McLennan described this principle as "an attitude towards climate and place, the use of energy and materials and ultimately our own comfort and well-being."[194] This thesis sits at the intersection of modern industrialism and biomimicry – it looks at how an organic material can be made to adapt to and grow around one that has been so destructive to our planet. In this way it falls under the umbrella of the Biomimicry Principle, but the connection could be improved by pushing the direction of the project towards the **Human Vitality** Principle. This principle acknowledges that sustainable design must be placed in the context of modern architecture and therefore cannot sacrifice human comfort for the purpose of leaning too far into the inspirations of nature. Human comfort should in fact be at the forefront of sustainable design, as an ingrained respect for people will likely be the element that is the most important for adapting all the principles of this philosophy. It follows that the proposed hybrid material product should be designed to maximize human comfort – this translates into a material whose primary function is either shelter, warmth, or acoustic isolation (or some combination of the above).

The **Economic** Principle describes a respect for place – buildings should respond to place on a macro and micro level. To enhance the material design, it should consider a proposed site. What climate might best suit the combination of concrete and mycelium and their intertwined material properties? Which site would be unsuitable? Designing for a location with an abundance of demolished concrete and a humid climate would be ideal for an overall low-carbon production (reduced transportation, existing facilities), with the humid climate specifically favorable for the growth of Oyster mushrooms.

194 McLennan, The Philosophy of Sustainable Design, 43.

195 McLennan, 86.

196 McLennan, 95.

This leads to the **Conservation** Principle, which acknowledges that there are finite resources on our planet despite the trend of treating these resources as infinite, and the selected materials for this project strive to represent this fact though limited use, recycling and low carbon growth. The **"Seven Generations"** Principle shows respect for the Cycle of Life. Humans only exist on this planet for a fleeting moment, yet the materials we produce last for centuries, long after we still have a need for them. This adapted indigenous principle states that every decision made should result in sustainable relationships for seven generations. This is something to consider within the life-cycle of the proposed product – how long is this material expected to last? Mycelium is biodegradable but concrete is not. This principle forces the hybrid product to consider its longevity and how it might be repaired, replaced, recycled or disposed of. These questions should influence both the material and the product design, as the degree to which the materials are integrated would greatly impact its end-of-life trajectory.

The final principle is arguably the most important, as it summarizes the philosophy of sustainable design. The **Holistic Thinking** Principle is the simplest of them all in that its major message can be summed up by a single sentence; "if we want to change a result, we must first change the process that led to the result."[195] When paired with the reductionist method, holistic thinking serves as the guide for this thesis' methodology. The goal of this principle is to reward innovation, challenge rules of thumb, and enforce the need to "find the fortitude to try vastly different things than we currently embrace."[196] This material combination begins with a radical extreme of sustainable materials and looks to find a point of compromise between them, both through what they represent and what they can physically achieve. Utilizing a holistic approach, and considering as many relevant influences as appropriate to the scale of the proposal, should lead to a well-rounded and considered product backed with supported research that can represent the ideals of sustainable design.

2.4 Material Goals

The purpose of understanding both concrete and mycelium-based composites, of learning their innovations within their fields and comparing their properties, was to devise a set of material goals that could be carried into the next phase of the integrated design methodology. With the added guidance of proposed policies and sustainable design philosophies, the following conclusions can be drawn.

Any meaningful integration of concrete and mycelium-based composites should feature the material's strongest technical properties – in this case, the material should be designed with the goal of bringing strength and durability to MBCs as they bring acoustic absorption and thermal resistance to concrete. Both materials rely on formwork to achieve their desired form – material explorations should play with the idea of the materials leaning on each other for support, both physically and metaphorically. Both cement and the bulk substrate of MBCs require a certain percentage of hydration to achieve their functions – material explorations should look at combining individual elements of each material throughout the early stages of production to determine if there are any overlaps in the process of manufacturing that would benefit the technical properties of the combined material. In modern construction practices, both concrete and mycelium-based composites are striving towards sustainable production – the material studies should focus on either 'avoiding' concrete waste or recycling existing concrete. Both case studies and the Human Vitality principle have proven that an often overlooked aspect of sustainable design is placing people first – the material should be made to enhance human experience through a combination of form and function.

Based on these conclusions, the material goals of a concrete and mycelium-based composite are as follows:

1. MBC and concrete must strike a balance between strength, durability, acoustics and thermal resistance
2. MBC and concrete must take advantage of their similar production processes to find an overlap that benefits both materials
3. Concrete use must be directed towards either 'avoiding' waste or re-using existing materials
4. Human vitality should be an underlying consideration that carries over into the design goals of the project.

3

Materials and Methods

“Being too risk averse leads to mediocrity. Sometimes it seems amazing that buildings get built at all with how risk averse the industry has become. It is essential to find ways to support emerging territories of technologies and approaches. If we are to be successful at safeguarding the environment for future generations and maintaining the quality of life we now enjoy, we will need to find the fortitude to try vastly different things than we currently embrace.”

— Jason F. McLennan

Since the combination of concrete and mycelium-based composites has remained largely unexplored, it is necessary to physically work with the material to find a methodology that best serves the material goals outlined in Section 2.4. As per the overarching methodology of integrated design, material experimentation is the best method to bridge the gap between the material goals and design goals.

This chapter provides a detailed overview of the method used to produce both the concrete and mycelium-based composite for this project before presenting the three main methodologies used to explore the combination of the two materials – Surface and Form Bonding, Deconstructed Bonding, and Material Testing. The results of these explorations are then summarized as design goals that guide the Design Proposal in Chapter 4.

B MATERIAL EXPERIMENTATION
Physical experimentation and testing to achieve material goals

C DESIGN GOALS
Highlights the results of experimentation and the properties that should transition into the final design.

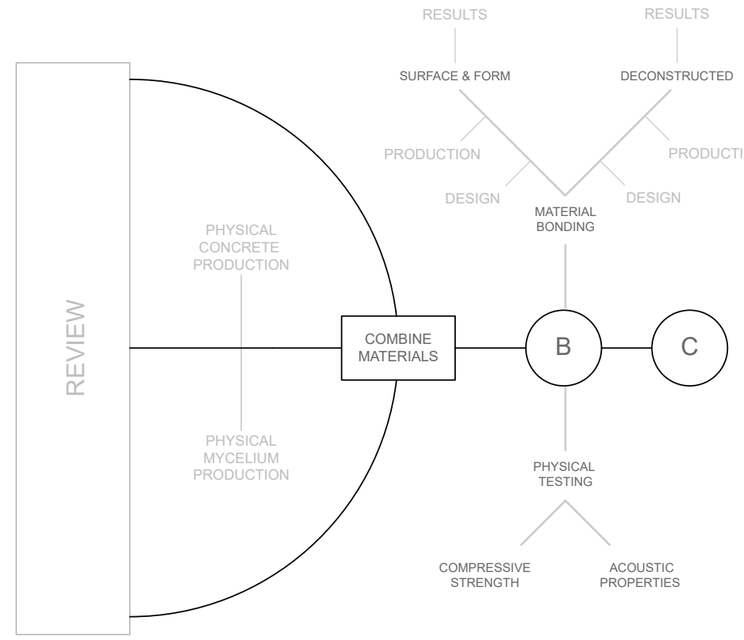


Figure 3.1: Integrated Design Methodology - Experimentation

3.1 Materials

3.1.1 Concrete

Concrete production within this thesis used a consistent stock of materials: Original Portland Cement (OPC), high performance bedding (A) for the aggregate (ranging from 1-8mm), all-purpose sand (Sa), and water (W). The material ratio was 2A:2Sa:1C:0.5W. While the standard mix ratio for concrete is 3A:2S:1C:0.5W, the above ratio was chosen for its high relative strength for the size produced, with the primary benefit being a smoother finished surface (Figure 3.3). All concrete was hand-mixed in small batches measured for each individual formwork to reduce concrete waste. All leftover materials were donated to the Waterloo School of Architecture for the use of future students.

Recycled concrete was sourced from a local landscaping company to gain a more complete understanding of the quality of the product as it currently exists in the market, rather than from the controlled destruction of concrete specifically produced for this thesis. It was crucial to source the recycled concrete in this way, as it provided a more accurate sample of the technical properties that can realistically be achieved when proposing a recycled concrete-MBC material as a viable product. The recycled concrete was packaged as “recycled crush” and marketed as ‘repurposed concrete materials’ with a diameter ranging from 1-35mm. This material is typically used “as a base material in combination with screening under driveways, patios, walkways and retaining walls.”[197] Given the large range of sizes, it was determined that exploration of the material in conjunction with mycelium must also explore the spectrum of its scale to better understand the impact of aggregate size on the quality of the combined material (Figure 3.2).

197 Van Beek’s Landscape Supply, “Recycled Crush.”



Figure 3.2: Recycled concrete aggregate segregated by size.



Figure 3.3: Test cast of concrete with standard ratio of 3A:2S:1C:0.5W. Subsequent casts used a reduced volume of aggregate for a smoother surface finish.

3.1.2 Mycelium-Based Composite

As noted in the *Literature Review*, the selected mycelium for material experimentation was blue oyster mushroom (Pleurotus ostreatus columinus). The selected substrate was a mixture of hardwood sawdust and wheat bran. Oyster mushrooms were chosen for their quick growing time in a wide range of temperatures, which allowed for both quick production and a reduced chance of bacterial contamination – the fast-growing mycelium could establish itself before bacteria took hold. This quality made growing oyster mushrooms forgiving in the absence of lab equipment.

This study began with a blue oyster mushroom liquid-based culture (a nutrient-rich solution that contains actively growing mycelium).[198] This was injected into a sterilized grain (hulled white millet) to produce a grain spawn. Beginning mycelium growth through a liquid culture rather than a purchased inoculated substrate allowed this study to gain a deeper understanding of the process of growing mycelium as well as a more accurate representation of how mycelium-based products would be grown in the field. When working with a sawdust bulk-substrate, which is low in nutrients, it is recommended to supplement it with a grain spawn.[199] The small size of the nutrient-rich grains (filled with starch and sugars)[200] allows for an increased surface area for the mycelium to latch on to, and the inoculated grains then encourage a more uniform and consistent growth within the bulk substrate (allowing more predictable results) as well as reduce the risk of contamination. This intermediate step before adding mycelium to the bulk substrate thus provides a stable foundation for growth and an early opportunity to determine if the liquid culture has already been contaminated.[201]

Millet was the chosen for the grain spawn since its small size in comparison to grains such as rye or rice leads to a larger number of inoculation points, and therefore a faster inoculation (Figure 3.4).[202] As noted in the Literature Review, any material that contacts mycelium must first be sterilized to eliminate all microorganisms and bacterial spores, which gives the mycelium the best chance at clean growth. The sterilization method chosen for this exploration was Tyndallization (also known as intermittent or fractional sterilization).[203] It is an alternative method of sterilization that involves heating the substrate multiple times with resting periods in between.[204] Unlike sterilization, this process does not require expensive equipment such as a pressure cooker or an autoclave, nor the necessity of bringing the product to a temperature of over a 110°C.[205] This process also differs from pasteurization, as Tyndallisation eliminates all microorganisms, reducing the risk of contamination.[206] The method is very effective when lab equipment is unavailable, with the only disadvantage being the prolonged time to produce a sterilized product and strict timing between stages. Because of the extended production timeline, this method is not recommended when mass producing mycelium, however it lends itself perfectly to this small-scale application. The only equipment required for this method were mushroom growbags to contain the substrate, elastics and tape to seal the bags, and a pot to boil them in.

198 Webb, "What's the Difference between Mushroom Spawn and Liquid Culture?"
199 Fungi Ally, "Understanding the Best Grain for Mushroom Spawn Propagation."
200 Shields, "Different Types Of Grain Spawn."
201 Circular Harvest, "Making Commercial Grade Grain Spawn for Mushroom Cultivation."
202 Fungi Ally, "Understanding the Best Grain for Mushroom Spawn Propagation."
203 Keratimanoch et al., "Effects of Tyndallization."
204 Keratimanoch et al.
205 Keratimanoch et al.
206 Mycosphere, "Pasteurization and Sterilization."

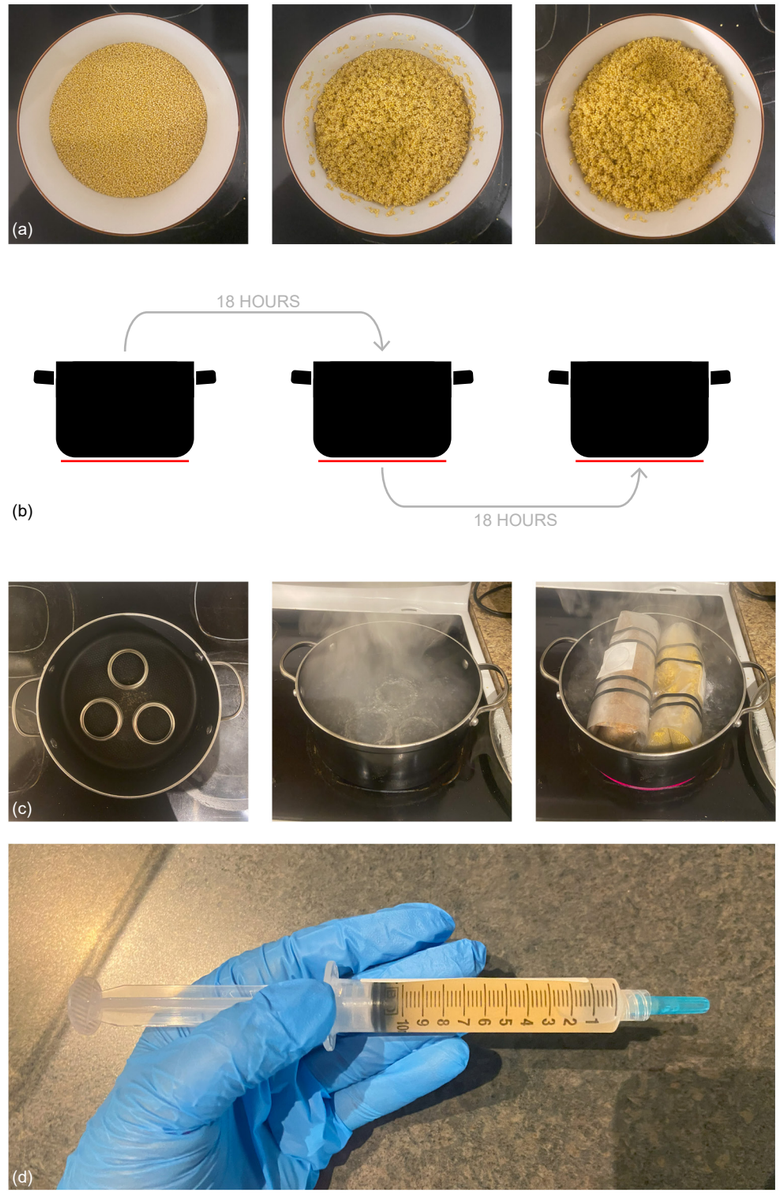


Figure 3.4: Millet grain spawn production.

(a) From left to right: Measured grain spawn. Addition of water. Grain expansion after soaking.
(b) Diagram of Tyndallisation process requires a consistent rest period of 18 hours between rest cycles.
(c) From left to right: Jar lids at base of pot. Boiling water. Addition of grain spawn (right) and an unsuccessful softwood sawdust spawn (left).
(d) Blue oyster mushroom liquid culture.

This process began by measuring 3 ¼ cups of millet, which were then soaked in 1 ¼ cups of water for 4 hours.[207] This step hydrated the grains, which helped unlock the nutrients within as well as cause contaminants to sprout, making them more susceptible to being killed through the heat cycles.[208] Once the millet had finished soaking it was transferred to a mushroom grow bag - a heat-resistant plastic bag with a filter patch that allows for gas exchange.[209] This bag was then securely wrapped with elastic bands and sealed shut with duct tape. The millet was transferred to a pot of boiling water lined with jar lids to protect the bag from sitting directly against the heat from the burner. The water was maintained at a simmer at 100°C for 45 minutes before the pot was removed from the heat. The millet then rested in the water (to gradually drop the temperature) for two hours before it was transferred to a sealed plastic bag where it could incubate at room temperature for the next 18 hours. This process was repeated two more times – Tyndallization is typically achieved by performing three heating cycles.[210] The rest periods allow microbes to develop in the millet, and the next heat cycle eliminates them (Figure 3.4).[211]

Once the millet had completed the Tyndallisation process, it was left to cool for 24 hours. The grain was then inoculated with 10cc of Blue Oyster liquid culture. The surface of the mushroom grow bag was prepared with 99% isopropyl alcohol, and the needle of the syringe was heated to red hot with a lighter to reduce the risk of bacterial contamination. 5cc of liquid culture was injected into the millet, and the hole was sealed with micropore tape. This grain spawn was stored in a dark container at room temperature (ranging from 20-22°C) for three weeks. As the mycelium grew, the grain was shaken periodically (roughly every 5-6 days) to ensure it grew evenly.

As the grain spawn developed, a mixed sawdust and wheat bran bulk-substrate was prepared. This substrate is commonly used for oyster mushrooms, particularly within the home-grown mushroom community.[212] It is the combination of its proven success through low-tech methodologies (that fit well within the scope and limitations of this project) and the potential for reused construction waste (hardwood sawdust) that made this substrate the ideal choice for this thesis' material exploration.

To make this substrate, five parts of hardwood sawdust (3 ¼ cups) were soaked to an approximate 60-65% water content – enough water to allow the sawdust to be moist but not dripping with water.[213] One part wheat bran (2/3 cups) was then mixed into the sawdust. This acted as a supplement to enrich the substrate and boost mushroom growth.[214] This mixture was added to a mushroom grow bag, then sealed and put through the same Tyndallization process as the millet. Once the substrate had cooled for 24 hours, it was ready to be inoculated with grain spawn. All nearby surfaces were coated with 99% isopropyl alcohol, and both the grain spawn and the sterilized substrate were handled with gloved hands and a mask to mitigate contamination. Approximately 1/4 of the grain spawn was added to the bulk substrate, which was promptly sealed with a zip tie (Figure 3.5). The grain spawn and substrate mixture were then shaken until the millet was dispersed evenly

207 Circular Harvest, "Making Commercial Grade Grain Spawn for Mushroom Cultivation."
208 Shields, "How to Make Perfect Grain Spawn For Growing Mushrooms At Home."
209 Dean, "Growing Mushrooms on Sawdust."
210 Supriadi et al., "Evaluating Tyndallisation's Potential for Composite Food Products and Quality Considerations," 1053.
211 Supriadi et al., 1053.
212 Dean, "Growing Mushrooms on Sawdust."
213 Dean.
214 Dean.



Figure 3.5: Bulk substrate production.

(a) Hardwood sawdust pellets
(b) Hardwood sawdust after soaking in water and mixing with wheat bran
(c) Grain spawn (left) ready to inoculate bulk substrate (right), with zip ties, scissors and isopropyl alcohol.

throughout the sawdust to encourage even mycelium growth. The bulk substrate was then kept in the same dark container as the grain spawn and grew under the same conditions over the course of four weeks (Figure 3.6). This inoculated substrate methodology was used in all subsequent mycelium exploration within this thesis.



DAY 8 DAY 10 DAY 15 DAY 23 SHAKEN / REDISTRIBUTED

Figure 3.6: Bulk substrate growth since inoculation.

3.2 Methods

After the production of these two base materials, the next stage of this methodology was to explore the potential ways in which they could work together harmoniously. As per the material design goals established at the end of the Literature Review, the new composite material must find a way to utilize the strength of concrete to enhance the mycelium-based composite. The new material must also retain the insulating and acoustic properties of the mycelium. To achieve these goals, this study considered two different approaches to combining the materials. The first was combining them on a macro scale, testing for a surface bond between the materials and whether their interlocking forms might be enough to ensure a strong connection. The second approach was combing them on a micro-scale by deconstructing the ingredients that make up concrete and determining which would have the most significant impact on increasing the strength of mycelium. These exploratory studies were then tested for their compressive strength and acoustic absorption properties to determine to what extent concrete would impact the mycelium-based composite's technical properties. A design goal for a product that best takes advantage of these results was then determined, which was further explored in the Design Proposal.

3.2.1 Surface and Form Bonding

The initial approach to combining concrete and mycelium was by crafting a unified block with both materials. Each unified block was to contain two concrete blocks bound with mycelium-based composite. This design allowed for several material design goals to be tackled at once. The design strove to use an aesthetic formwork to infuse the concrete with the thermal and acoustic properties of the MBC. This formwork also looks to minimize concrete waste by hollowing out these concrete blocks to make room for the MBC, while still providing strength and durability. Finally, this approach to material combination took advantage of the similar production process of both materials – their reliance on formwork. The unique form of the concrete block becomes the formwork for the MBC.

This approach explored the limits of the existing flexural strength of mycelium-based composites. Most projects that have used mycelium in construction have looked at the material in the form of either a panel or a brick. This exploration asked; how might mycelium perform as a binding agent for concrete blocks? How effective would it be in this role, and at what point might the strain of binding the concrete cause the mycelium-based composite to fail? From this question came two others: Would mycelium bond to the surface of concrete, and if not, what form must the concrete blocks take to allow for the mycelium to lock them in place? As established through the self-healing concrete case study, mycelium and concrete have been successfully bonded before, but only through a specific strain of mushroom and a particular mix of concrete. How might the most commonly used strain of mushroom in construction behave against OPC? Would an unsanitized concrete contaminate the inoculated substrate? Given the uncertainty of this material reaction, the form of the concrete blocks and the mycelium's ability to interlock them then became a crucial element to the design of the blocks. In summary, a successful completion of a unified block of concrete and mycelium-based composite would further knowledge of the flexural strength of oyster mycelium, how it reacts to the surface of OPC and how the thoughtful design of concrete blocks might strengthen this bond.

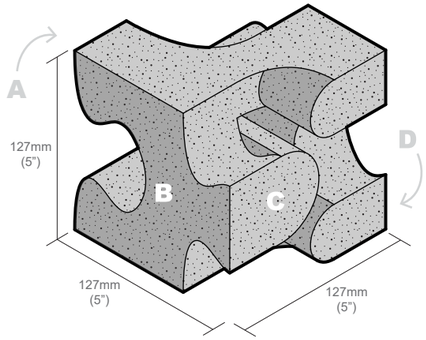
3.2.1.1 Design

To better understand the impact of form on bonding concrete and MBC, two themes were explored. The first was 'puzzle' (Figure 3.7), inspired by interlocking jigsaw puzzle pieces and reimagined in three dimensions. The second was 'stitch' (Figure 3.8), inspired by a running stitch in sewing. Both designs only required one formwork to create both concrete cubes, and when the cubes were rotated their designs offered stronger opportunities for the mycelium to interlock between them through both the voids within and the shape of their façades. Both designs were considered in thirds to help plan the design of the formwork and simplify its removal once the concrete was cast. The outer two thirds of the block served as the façade, which used a different interlocking MBC strategy than the center third. Creating two approaches to an interlocking design also allowed for an exploration of how the ratio of concrete to mycelium within the unified block might impact its properties. The 'puzzle' block was designed to hold a 50:50 ratio of MBC to concrete, while the 'stitch' was designed with a 64:36 ratio favouring MBC (Figures 3.9 and 3.10). The scale of the interlocking openings ranged from 4-6 cm. This scale was chosen for the convenience of not requiring specialized tools to incorporate MBC in smaller openings, and was approximately 1/3 the dimensions of the block. Through observation of similar interlocking designs (i.e. puzzle pieces, wood joinery, ect.) this ratio was determined to be the most efficient for the purposes of this study. The designs for both variations of concrete block were developed first through sketches then through *Rhinoceros* (Figures 3.11 and 3.12).

3.2.1.2 Production

With the concrete design was complete, formwork could be reverse engineered by isolating and defining the voids of the blocks. These voids were 3D printed and placed within a wooden 5x5" cube (Figures 3.13 – 3.22). Once this cube was screwed together, it would lock all the 3D printed pieces in place. The design of the 3D printed formwork had to consider the orientation of the cube as the concrete would be poured in so that the pieces would not shift when tamping the concrete. Knowing this formwork would need to be reused, it was also important to consider that the geometries of these voids eventually be encased in solid concrete – both designs involved complex curvatures that would be unable to be removed in one piece, therefore the formwork needed to be further spliced for simpler removal. Small notches were introduced to act as handles when removing the formwork from the cast concrete. Once the custom formwork was printed and secured within the wooden box, it was sprayed lightly with a non-stick cooking spray to ensure the concrete did not bond with it. The concrete was cast in shallow layers, tamping and vibrating the mixture into place regularly for a clean cast. The concrete was left to cure for 24 hours before removing the formwork (Figures 3.23 – 3.28).

PUZZLE



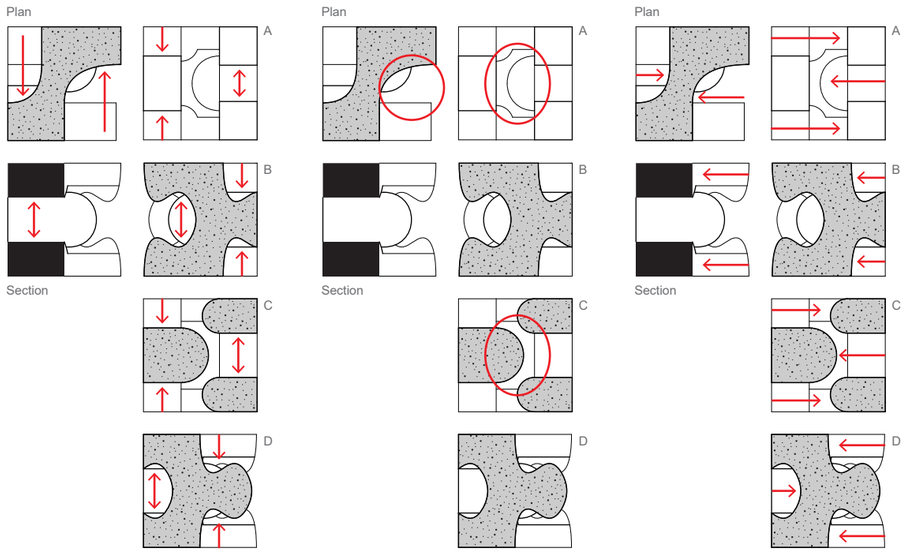
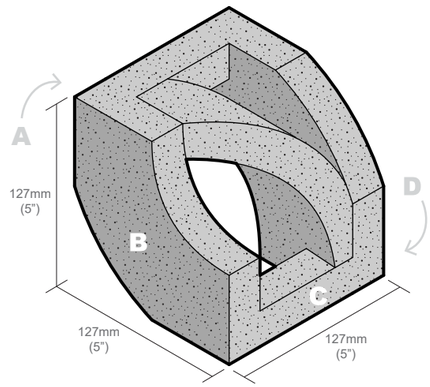


Figure 3.7: Puzzle concrete block design drawings showing the perspective, plan, section and elevations. Red circled note where the inoculated substrate is able to pass through the block. Red arrows note the interlocking design strategy for the introduction of MBC - no matter what direction the MBC is moved, it will be faced with the opposing force of the concrete.

STITCH



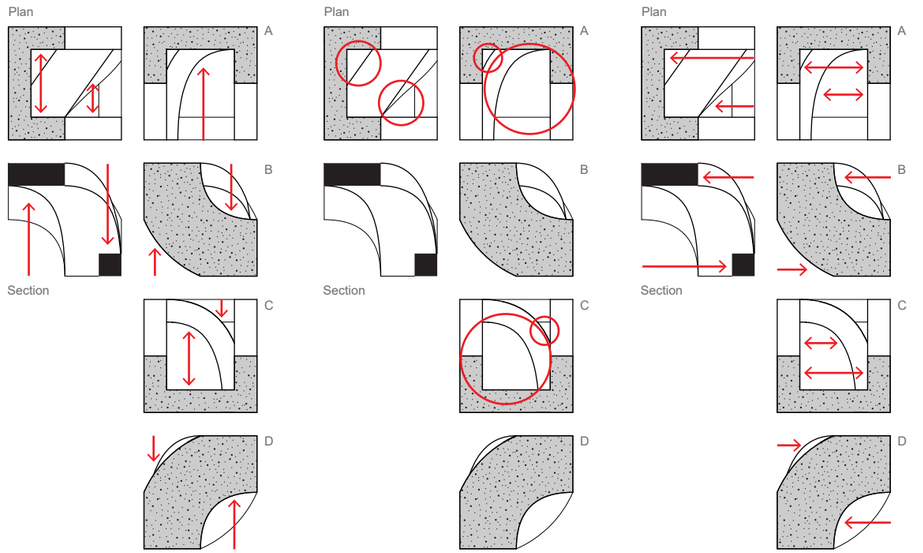
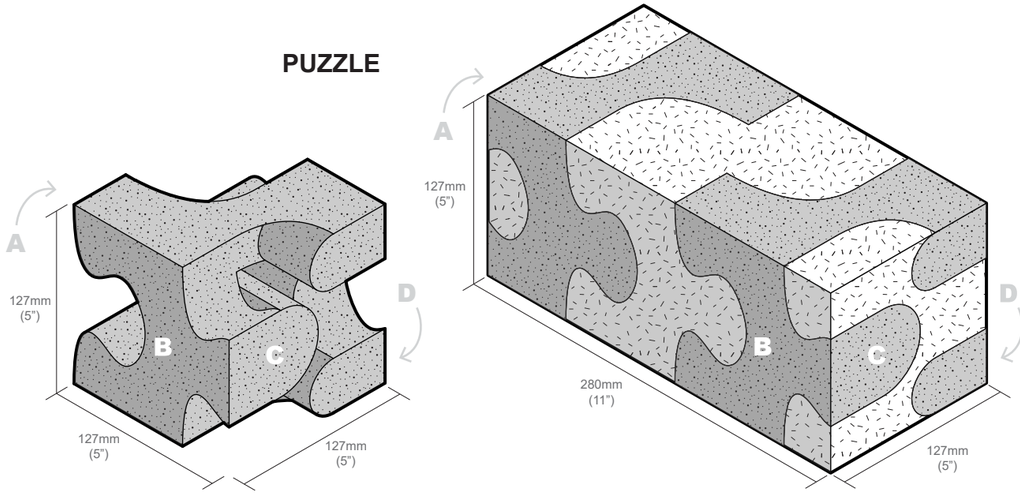


Figure 3.8: Stitch concrete block design drawings showing the perspective, plan, section and elevations. Red circled note where the inoculated substrate is able to pass through the block. Red arrows note the interlocking design strategy for the introduction of MBC - no matter what direction the MBC is moved, it will be faced with the opposing force of the concrete.

PUZZLE



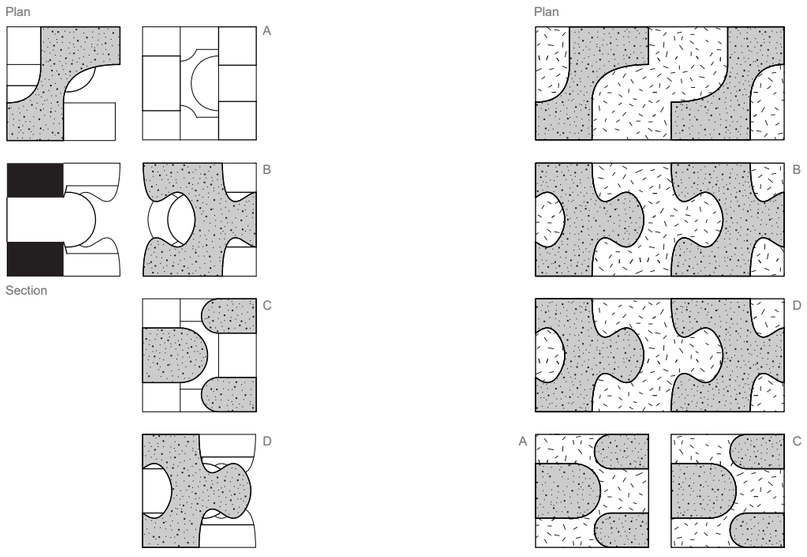
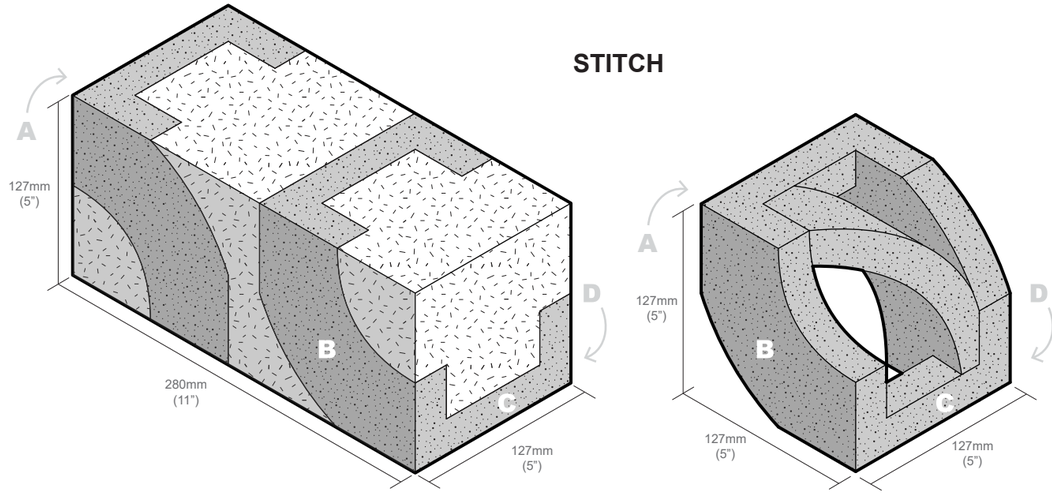


Figure 3.9: Puzzle unified concrete and MBC (CMBC) block design drawings showing the perspective, plan, section and elevations.

STITCH



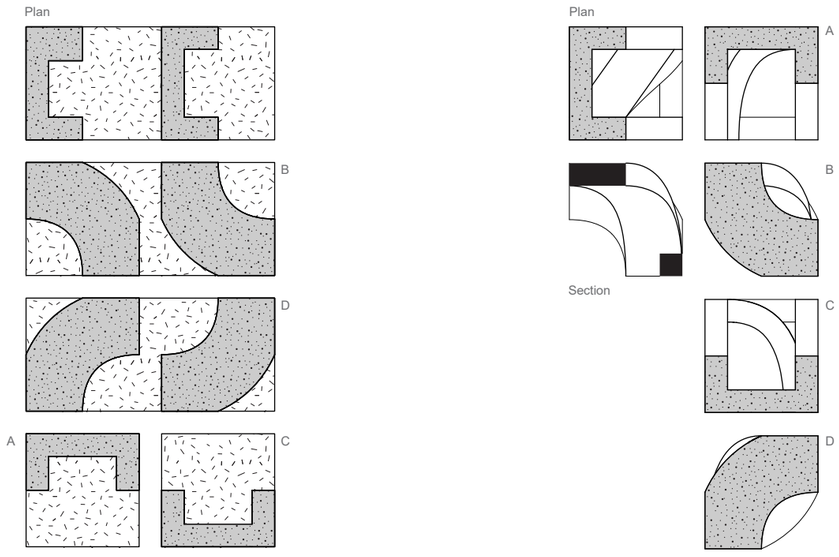


Figure 3.10: Stitch unified concrete and MBC (CMBC) block design drawings showing the perspective, plan, section and elevations.

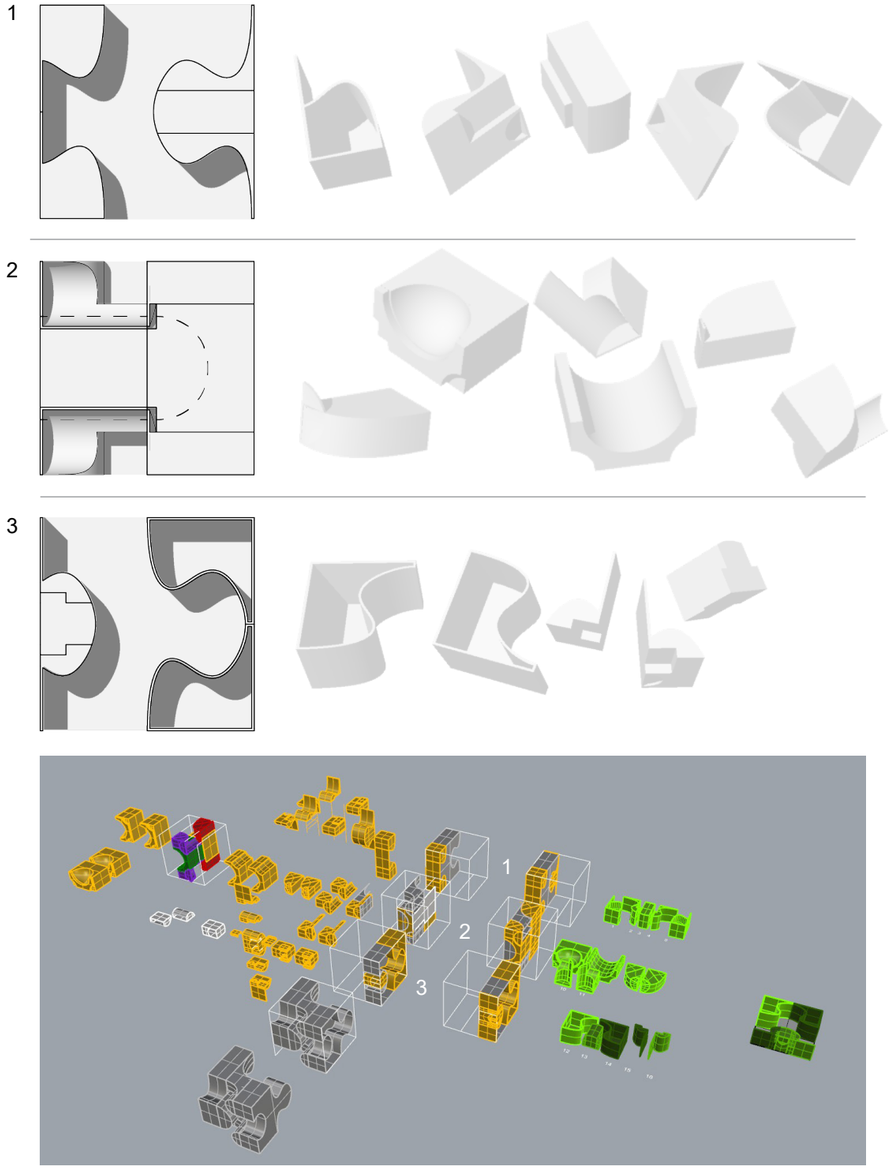


Figure 3.11: Puzzle formwork design. Formwork was simplified in thirds for simpler removal from the cast concrete.

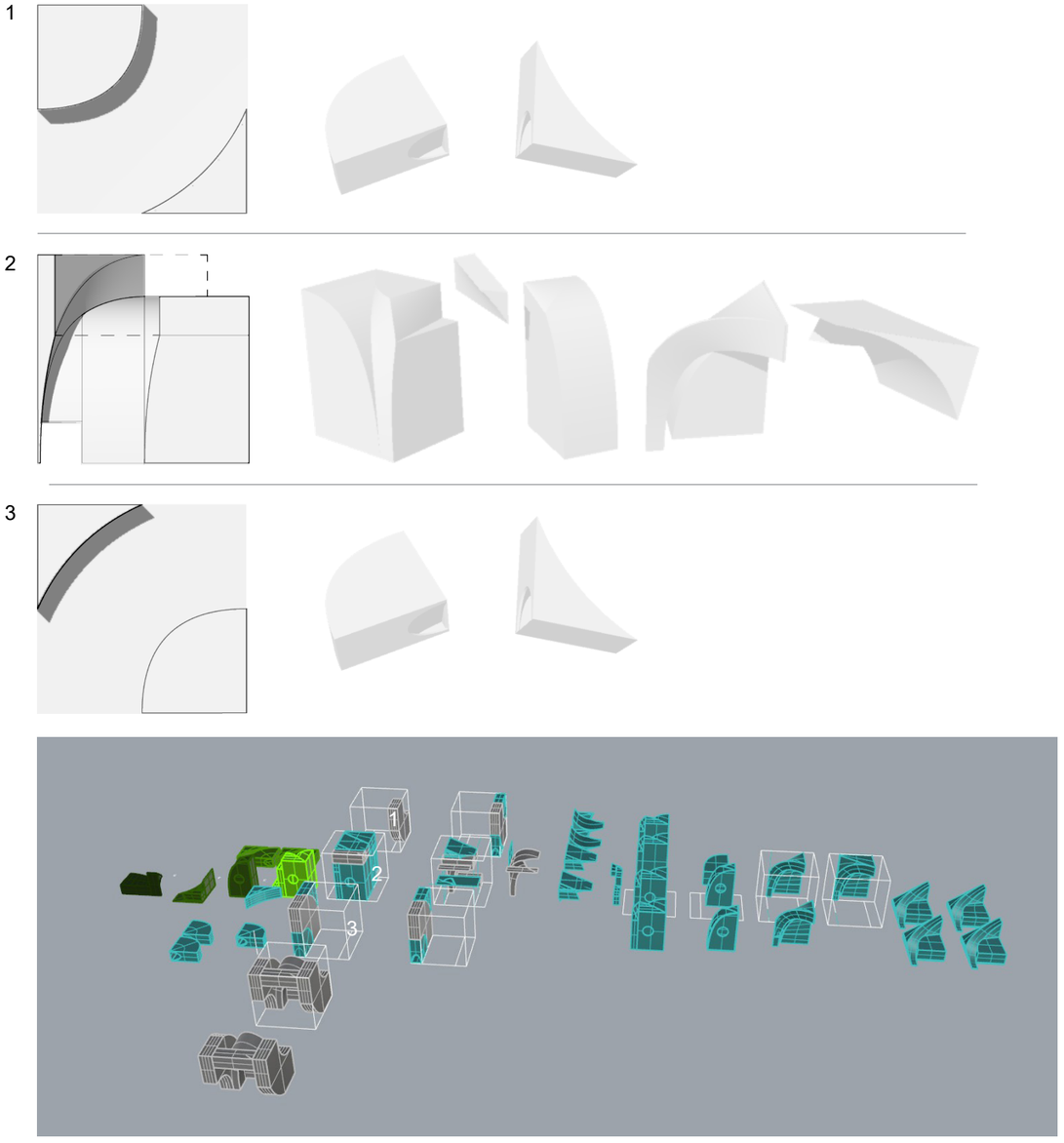


Figure 3.12: Stitch formwork design. Formwork was simplified in thirds for simpler removal from the cast concrete.

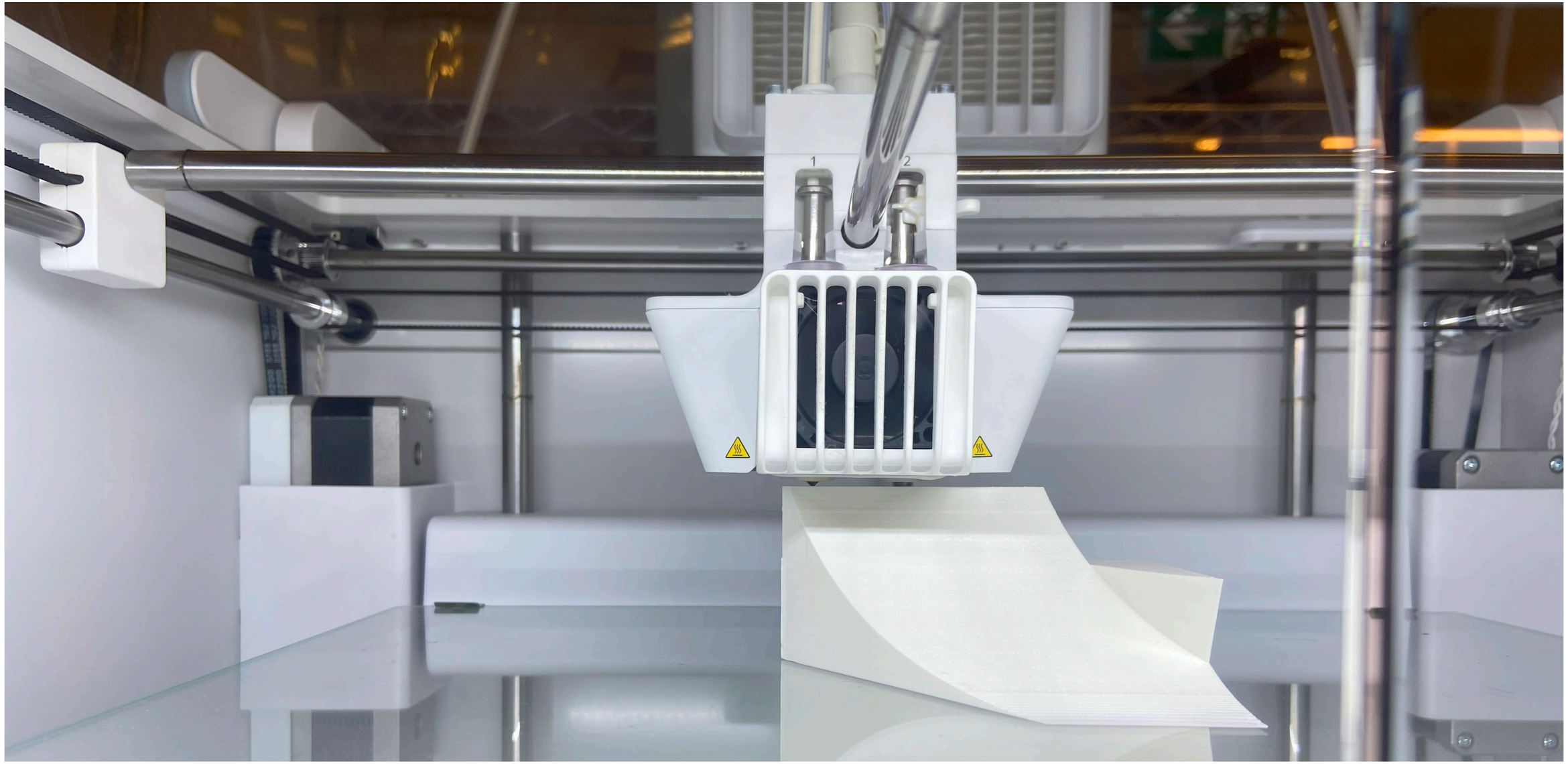


Figure 3.14: 3D printing concrete block formwork.

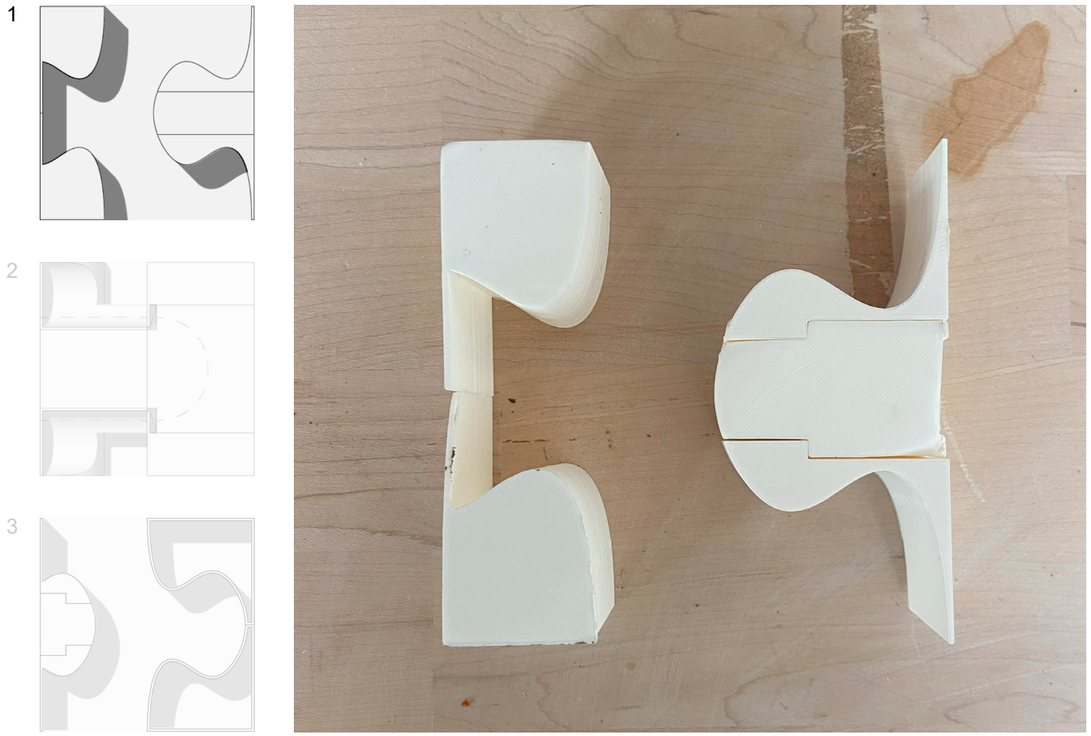


Figure 3.15: Puzzle formwork - Layer 1.

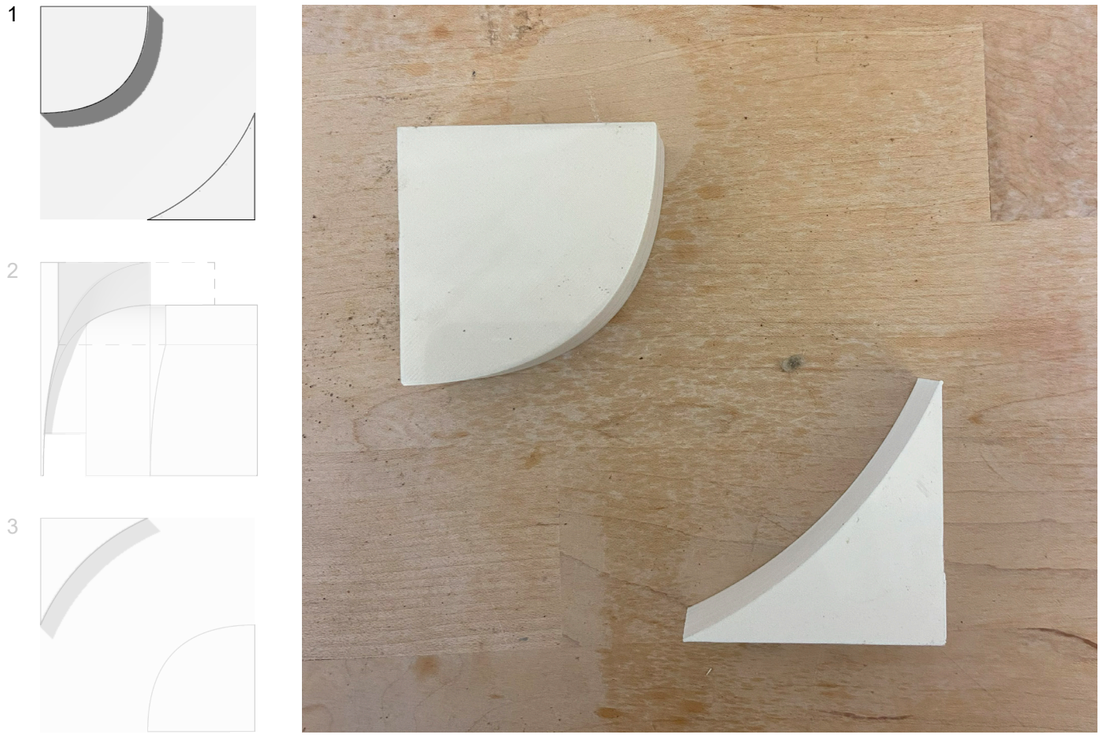


Figure 3.16: Stitch formwork - Layer 1.

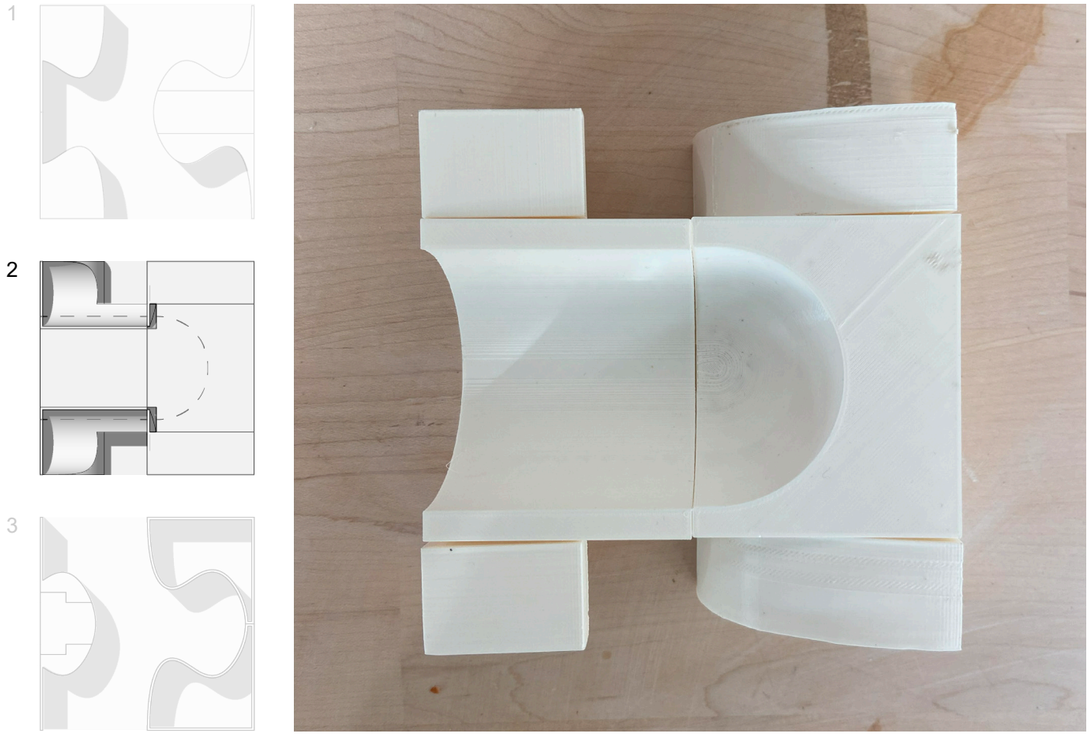


Figure 3.17: Puzzle formwork - Layer 2.

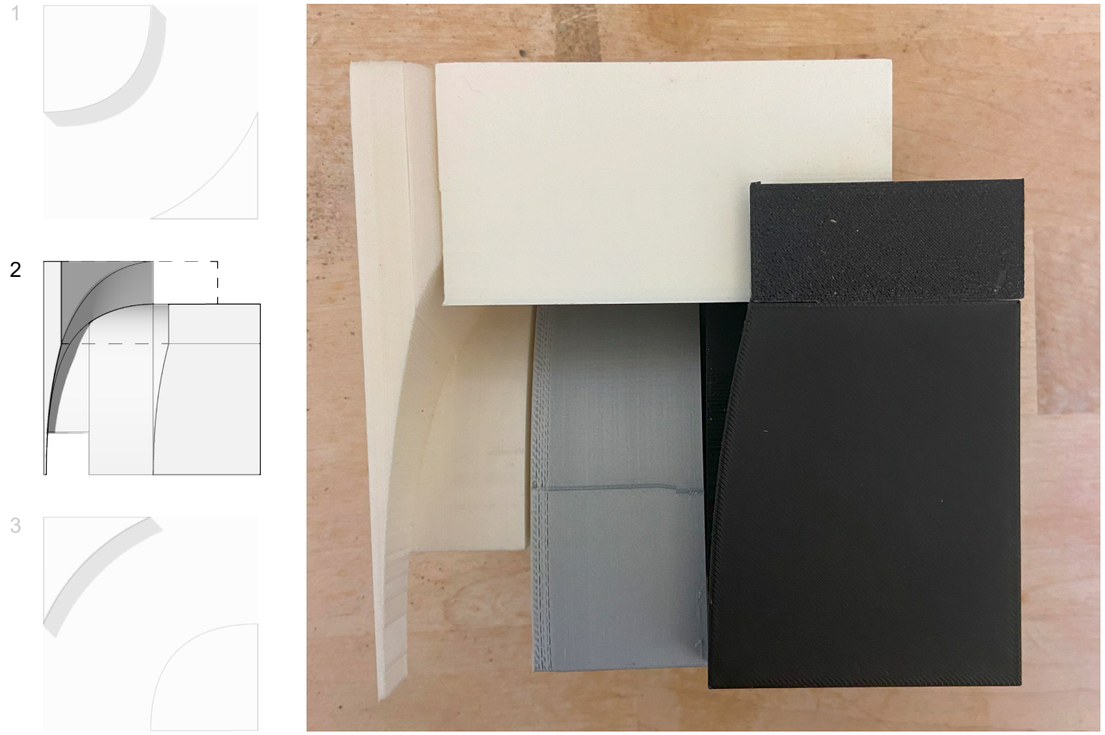


Figure 3.18: Stitch formwork - Layer 2.

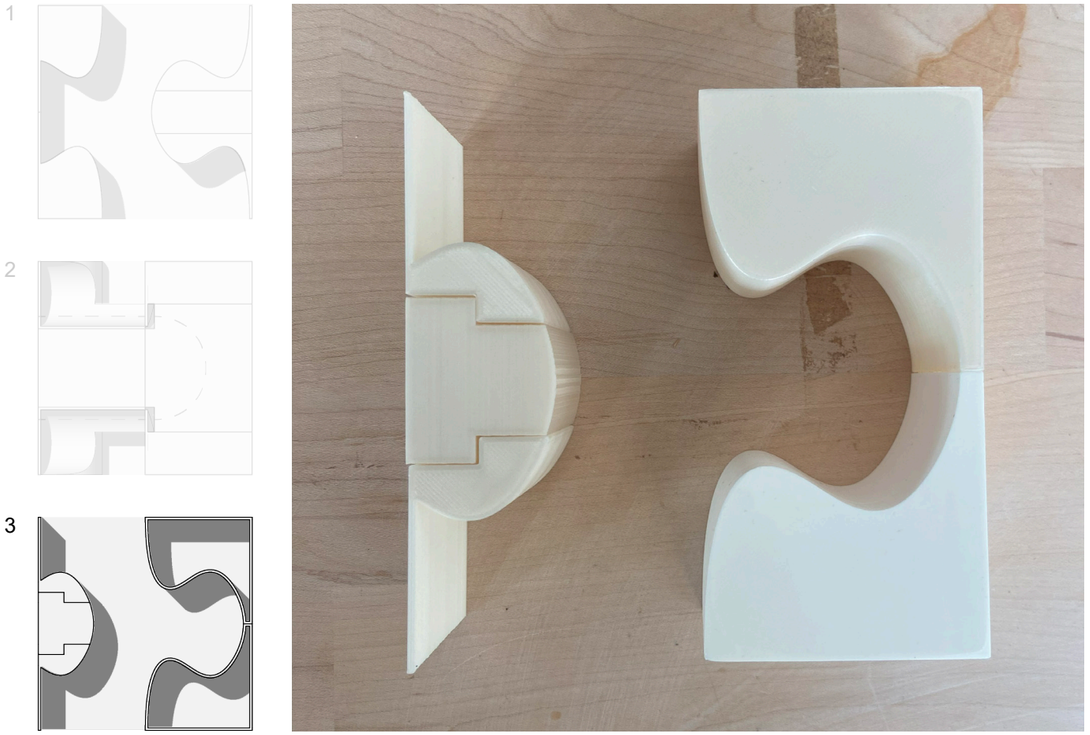


Figure 3.19: Puzzle formwork - Layer 3.

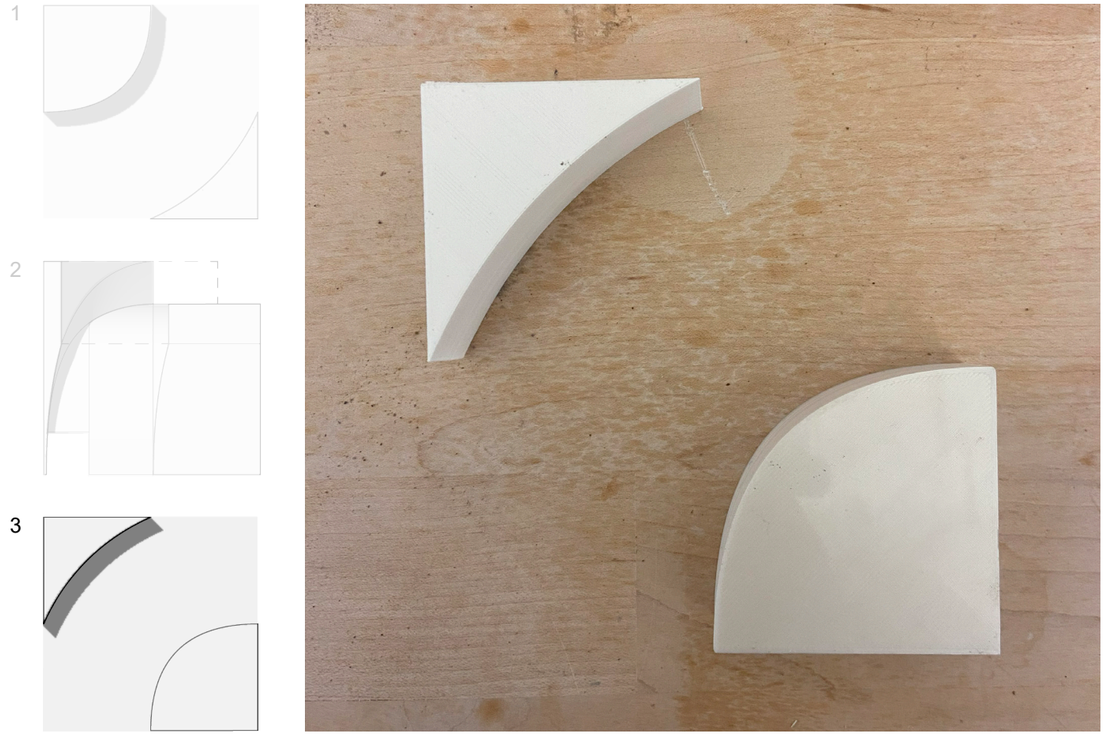


Figure 3.20: Stitch formwork - Layer 3.

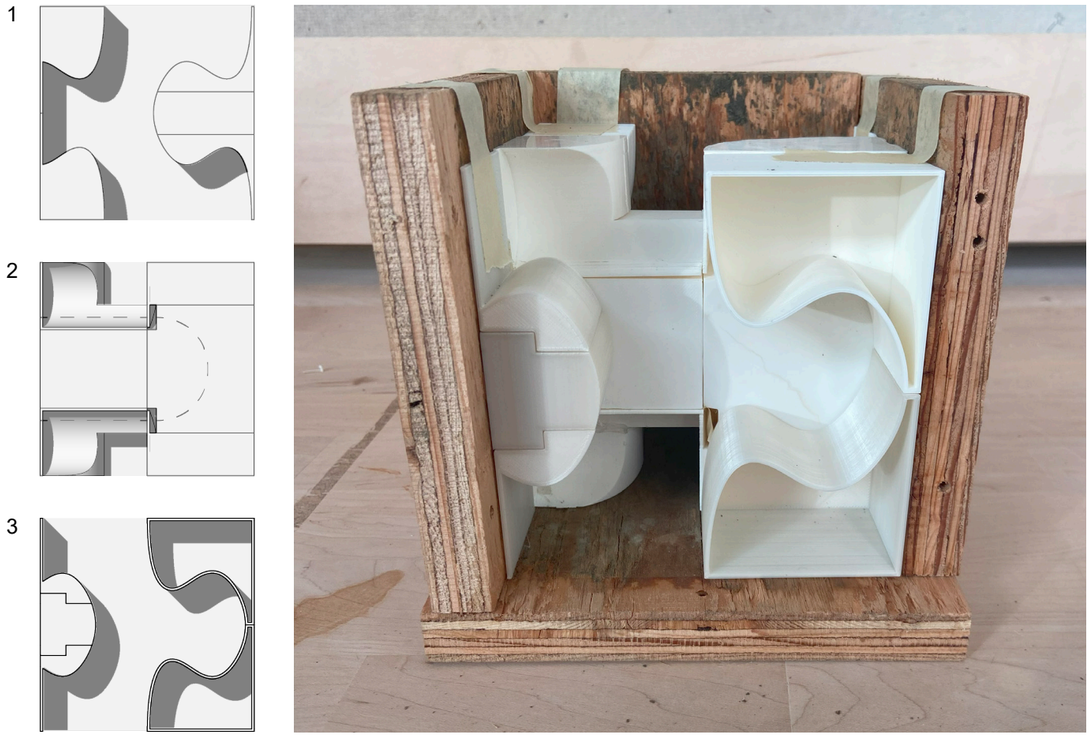


Figure 3.21: Assembled puzzle 3D printed pieces within wooden formwork.



Figure 3.22: Assembled stitch 3D printed pieces within wooden formwork.



Figure 3.23: Cast puzzle Block.



Figure 3.24: Cast stitch Block.



Figure 3.25: Final concrete puzzle block.



Figure 3.26: Final concrete stitch block.



Figure 3.27: Final concrete puzzle block.



Figure 3.28: Final concrete stitch block.

The resultant casts matched the design intent. Removing the formwork on the outer thirds of the cubes was straightforward, however the central formwork removal proved difficult with layers of concrete tightly pressed against the formwork on either side. Removal required the concrete blocks to be chiselled until they split in half along a stress point. All subsequent casts used controlled joints through the addition of separators at the stress points to allow the cube to split more easily. The cast blocks were repaired with a combination of construction glue and mortar. The textures of the formwork were imprinted on the concrete surface, with the 3D printed formwork leaving a relatively smooth surface and the wooden formwork leaving a noticeable grain along the façades. This was ideal, as an untextured surface would allow for a cleaner observation of how the mycelium would interact with the OPC without the subtle wood grain ridges that could provide additional grip.

The concrete cubes were designed to be 5x5" so they could fit exactly into the base of a mushroom grow bag (Figure 3.29). Using these bags as the mold for the unified blocks limited the variables that might affect the mycelium growth – both the grain spawn and the bulk substrate had been successfully inoculated using these bags. One edge of the bags was cut to better position the first concrete cube within the bag before being resealed with tape. A sanitized spoon was used with gloved hands and a mask to transfer the inoculated substrate into the bag, occasionally shaking the substrate into position. As more substrate was added, the plastic of the bag flexed, allowing the substrate to slip between the surface of the bag and the concrete block façade. More substrate was added, as well as the second concrete block, to match the desired dimensions of the unified block despite the flexibility of the bag. During this processm one of the 'stitch' blocks cracked severely along the edge of the facade, disconnecting it from the rest of the block. The bulk of the mycelium-based composite kept it in place, though it remmained loose to the touch. Both bags were sealed with a zip tie. This flexing particularly affected the puzzle unified block, which was approximately 1" shorter than the desired length. Both concrete facades were obscured by mycelium biocomposite during the growing phase (Figures 3.30 - 3.33).

The unified blocks were left to develop mycelium over the course of four weeks before allowing them to air dry for 48 hours (Figures 3.34 and 3.35). This was an atypical step to the standard process of creating functional MBC products. It was done because much of the condensation from growing had soaked into and coated the concrete – it was safest to allow the concrete to air dry before transferring it to a hot environment and risk thermal cracking. Once the unified block was dry it was heat-ceased in the oven at 180°C for 2 hours, rotating every 20 minutes to allow for even heat exposure.



Figure 3.29: Isopropyl alcohol, mushroom grow bag, concrete puzzle block and inoculated substrate.



Figure 3.30: Inoculated substrate transferred to concrete blocks and mushroom grow bags.



Figure 3.31: Mycelium growth through bulk substrate in unified puzzle block.



Figure 3.32: Mycelium growth through bulk substrate in unified stitch block.



DAY 1



DAY 7



DAY 28

Figure 3.33: Progression of mycelium growth in both unified blocks.



Figure 3.34: Unified puzzle block immediately after removing mushroom grow bag. Mycelium growth allowed the block to hold its shape, and it was transferred to a drying rack.



Figure 3.35: Unified stitch block immediately after removing mushroom grow bag. Mycelium growth allowed the block to hold its shape, and it was transferred to a drying rack.

3.2.1.3 Results

The resultant blocks were sturdy in comparison to the delicate and damp condition they were in when first removed from the mushroom grow bags. During this processm one of the 'stitch' blocks cracked severely along The mycelium biocomposite that bound the concrete was dry, smooth and firm to the touch. The consistency was not as firm as the concrete – moderate pressure dented the material, and the thick mycelium coating behaved similarly to Styrofoam (Figures 3.37 – 3.44).

Most of the MBC that coated the concrete façades peeled off at a gentle touch or through the process of ceasing, proving the two materials on their own have a very poor surface bond. It was observed that the mycelium grew thickest on the outer perimeter of the MBC, while there was comparatively very little mycelium holding the substrate together within, appearing as dry sawdust where exposed. It was also observed that the mycelium biocomposite shrank and cracked during the drying and ceasing process, peeling itself away from the surface of the concrete with noticeable gaps (Figure 3.36). There were occasional instances of mycelium that had grown beyond the substrate and on to the surface of the concrete. This mycelium remained strongly bonded to the concrete throughout the ceasing process. This growth occurred on both the concrete façade (wood texture) and along the internal voids (3D printed texture).

The unified blocks held their form well when lifted with both hands (gently supporting the block from each side), and the ratio of mycelium to concrete appeared to have little effect on this basic bond. Within the stitch block, the broken facade remained held in place by the MBC but the connection was not secure as the piece could be manipulated and readjusted with light prodding. When testing the flexural strength of the MBC as a binder for the concrete by slowly allowing the weight of the concrete to pull at the central MBC, a large crack appeared down the centre of the unified block (tested on the unified puzzle block). Had this test continued, the block would have split in half. It is acknowledged that these observations stem primarily from visual assessment. Shear testing of the resultant blocks was considered for further analysis, but given time resrtraints and the damage already imposed on the finished blocks this was left as an option for future research development.

The results of the surface and form bonding exploration led to the conclusion that a combined material that best takes advantage of the properties of both concrete and mycelium must not rely purely on a surface connection between the materials, as there is a negligible bond. It must not rely on the interlocking forms of the materials, as mycelium shrinks when put through a heat-ceasing treatment. Despite the bond being poor, mycelium biocomposites will not be contaminated if put in contact with concrete in a controlled environment. A combined material must not rely on the ability of an MBC to act as a bonding agent between large blocks of concrete, as it is too weak to carry the strain. A combined material must take advantage of the layer of mycelium that grows on the outer perimeter of the MBC

and avoid instances where it would need to be cut, as the interior of an MBC block is its weakest area. These lessons were taken into consideration when designing the next phase of material exploration – bonding mycelium-based composites with deconstructed elements of concrete.



Figure 3.36: Detail image of puzzle unified block. A combination of the air-drying process and the heat ceasing shrunk the MBC away from the surface of the concrete.



Figure 3.37: Final unified puzzle block - Elevation B. Note the prominent cracks running through the MBC from flexural testing.



Figure 3.38: Final unified puzzle block - Perspective B-C.



Figure 3.39: Final unified puzzle block - Elevation D.



Figure 3.40: Final unified puzzle block - Perspective D-A.



Figure 3.41: Final unified puzzle block - Elevation B.



Figure 3.42: Final unified puzzle block - Perspective B-C.



Figure 3.43: Final unified puzzle block - Elevation D.



Figure 3.44: Final unified puzzle block - Perspective D-A.

3.2.2 Deconstructed Bonding

The second method of exploration looked to existing case studies of how 'like' materials to concrete and MBCs have been successfully combined, and in part recreated these techniques through a series of material samples. Rather than continue down the path of exploring concrete and mycelium on a macro scale, this phase looked to observe the relationship between the materials on a micro scale by deconstructing the elements of concrete and determining which element(s) might best compliment the properties of the mycelium-based composite.

This deconstructed bonding also looked to address several material goals at once. The primary goal was to use the individual elements of concrete to provide strength and durability to the MBC. It minimizes concrete waste by looking for new ways to utilize recycled concrete and take inspiration from overlapping production processes of both materials, particularly the condensation produced by mycelium and the water required to hydrate cement. In total, there were 12 different material combinations tested with various degrees of success.

For each of the material sample compositions, the following legend was used:

C – Cement (Original Portland)
S – Substrate (inoculated)
A – Aggregate (recycled concrete)
W – Water

3.2.2.1 Design

The first three deconstructed explorations looked to combine MBC with cement. As noted in Section 2.1.2 (Mycelium-Based Composites), mycelium takes in oxygen and releases carbon dioxide in much the same way humans do. It was observed in the production of grain spawn, bulk substrate, and especially in the production of the unified blocks, that this process results in much condensation within the mushroom grow bags. It was also noted in Section 2.1.1 (Concrete) that the presence of calcium silicate hydrate (C-S-H) in cement is what gives the material its strength, and is triggered by the hydration process, which in turn triggers a heat reaction.

This combination of materials looked to take advantage of the intersection of these phases of material production. It theorized that if cement were combined with inoculated substrate within a controlled and sanitized environment, the condensation produced by the mycelium would hydrate the cement. By hydrating the cement, the mycelium would then unlock its strength, hardening it in clumps throughout the MBC. The chemical reaction from this hydration would heat the temperature within the bag, encouraging faster mycelium growth (as per the oyster mushroom growth temperatures discussed in Section 2.1.2). Should this series of material production events work together harmoniously, the result was hypothesized to be a unified material of evenly dispersed and hardened cement encased by a thick layer of mycelium with a reduced production time.

215 Avudaiappan et al., "Experimental Investigation on the Physical, Microstructural, and Mechanical Properties of Hemp Limecrete."
216 Asghari and Memari, "State of the Art Review of Attributes and Mechanical Properties of Hempcrete."
217 Magwood, "Insulation Alternative: Hempcrete."
218 Pananganan, "Exploring Mycelium as a Sustainable Building Material."
219 Pananganan, 41.
220 Pananganan, 43.

Inspiration for designing the ratio of materials came from hempcrete (Section 2.1.1.3). Being a relatively new and in itself experimental material, the successful ratio of binder to hemp ranged in cases from 1:2,[215] 1:3[216] and 1:4[217]. These these ratios were followed for experimentation with cement and mycelium biocomposites, with the addition of a 1:4 ratio. It was predicted that the 1:4 ratio would be most successful, as there would be no additional water added once the materials were mixed, therefore a higher percentage of mycelium to cement might allow for the formation of more condensation in compensation.

These material combinations were referred to as Series One. The materials were delegated as follows:

1a – 1C:2S
1b – 1C:3S
1c – 1C:4S

The next three samples looked to explore the relationship between recycled concrete and mycelium. As discussed in Sections 2.1.1 and 2.3, there is an abundance of concrete that already exists in the world. If the goal of designing a stronger biomaterial is to lower embodied energy in construction materials, then the solution should look to recycle what we have – specifically demolition waste. Inspiration for combining mycelium with recycled material came from *Redhouse Architecture's* plans to incorporate 'biocycling' into their designs by grinding construction waste to a pulp and combining it with mycelium (see Section 2.1.2.3). Homing in on recycled concrete as an additive allowed for more controlled results while still repurposing demolition materials. In theory, the small size of the recycled concrete embedded within the MBC would allow the mycelium to grow around it and lock it into position. The resultant combined material was hypothesized to increase the surface area mycelium had to grow on within the substrate, strengthening the material with additional mycelium as well as the concrete's own compressive strength.

Since little has been published on the science behind this studio's experimentation, the ratio for recycled concrete to mycelium biocomposite was taken from a thesis that explored mycelium as a waste management tool.[218] In it, the study combines materials like paper coffee cups[219] and plastic bottles[220] with a mycelium-based composite. Regardless of the material, the ratio of waste to MBC remained 1:2, therefore this ratio was consistent throughout all the samples in this series as well. The recycled concrete obtained for this experiment was sold in crushed sizes that ranged from 1/32" to over 1" in width. With limited research available concerning the benefits of combining mycelium with aggregates such as concrete, and with the benefit of a consistent material ratio, this series of samples focused on how the size of the recycled concrete crush would affect the structure and strength of the MBC.

These material combinations were referred to as Series Two. The materials were delegated as follows:

2a – 1A:2S (< 3/8")
2b – 1A:2S (3/8" – ¾")
2c – 1A:2S (> ¾")

Series Three looked at combing cement, recycled concrete, and mycelium. The benefits of this exploration were to be a combination of both Series One and Two. Should both the hypotheses be correct, a combination of all three materials at the correct ratio should create a mycelium-based composite that benefits from the material properties of concrete, the most important of which being compressive strength. If successful, this material combination had the potential to be used in construction in non-load bearing capacities. For consistency, an equal portion of each size of recycled concrete was chosen for the aggregate (3/8" – ¾").

The ratios for these samples were selected based on the previous Series. Sample 3a used a ratio of 0.5A:0.5C:2S. This is a combined ratio of one part additive to two parts inoculated substrate. The ratio of cement to substrate remained at 1:4. The ratio of aggregate to substrate was lowered to compensate for the cement. Sample 3b used a ratio of 1A:0.5C:2S. This mixture used the same logic as sample 3a, but did not compromise the percentage of aggregate, thus skewing the accepted total ratio of additives to substrate. Finally, sample 3c used a ratio of 1A:1C:2S. This material exploration took the maximum part additives to substrate for each category (cement and recycled concrete) and combined them to create a 1:1 ratio of additives to substrate. Should the final sample prove successful, it would have the highest potential to introduce more strength and versatility to mycelium-based composites.

For comparison, the material ratios of Series Three are listed below:

3a – 0.5A:0.5C:2S
3b – 1A:0.5C:2S
3c – 1A:1C:2S

If cement hydration through condensation was insufficient, a fourth series was created to test whether hydrated cement would make a difference in achieving the combined material hypothesis. The material ratios were chosen by expanding the ratios of series 3 to include the relevant quantity of water required for the quantity of cement used (1W:2C).

For comparison, the samples of Series Four are listed below:

4a – 0.5A:0.5C:0.25W:2S
4b – 1A:0.5C:0.25W:2S
4c – 1A:1C:0.5W:2S

221 Walter and Gürsoy, "Sound Absorption Properties of Mycelium-Based Composites," 8.
222 Rigobello, Colmo, and Ayres, "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour," 2.

The selected size for samples had to be large enough to properly showcase the impact of the additives on the structural integrity of the MBC, but small enough to mass produce without unnecessarily wasting materials. Dimensions for such a sample were provided by an acoustic mycelium study,[221] providing a sufficient sample size of 100x100x38mm.

3.2.2.2 Production

To properly observe the growth of the mycelium, the containers were constructed out of clear plexiglass. The height of the containers was increased from 38mm to 50mm (Figures 3.45 and 3.46). This was done to allow for additional air exchange once the containers were sealed in plastic. The edges of the containers were sealed with clear packing tape and sanitized with 99% isopropyl alcohol.

All materials were measured (Figure 3.47) then evenly shaken in a sealed bag (Figure 3.48) before being transferred to the container (Figure 3.49). The combined material was tamped down with gloved and sanitized hands to encourage denser mycelium growth, as this has been shown to result in higher compressive and flexural strength in the ceased MBC.[222] The containers were then placed in sealable plastic bags, with the edges taped down to create a tight seal. A small hole was cut into the taught surface of the bag and covered with micropore tape – this simulated the filter patch of a mushroom grow bag on a smaller scale (Figure 3.50). This process was repeated with each sample. The samples were set in a shaded corner for three weeks at room temperature (ranging from 23-28°C) (Figures 3.51-3.54).

Samples that successfully grew mycelium were heat-ceased in the oven at 180°C for 2 hours, rotating every 20 minutes to allow for even heat exposure.

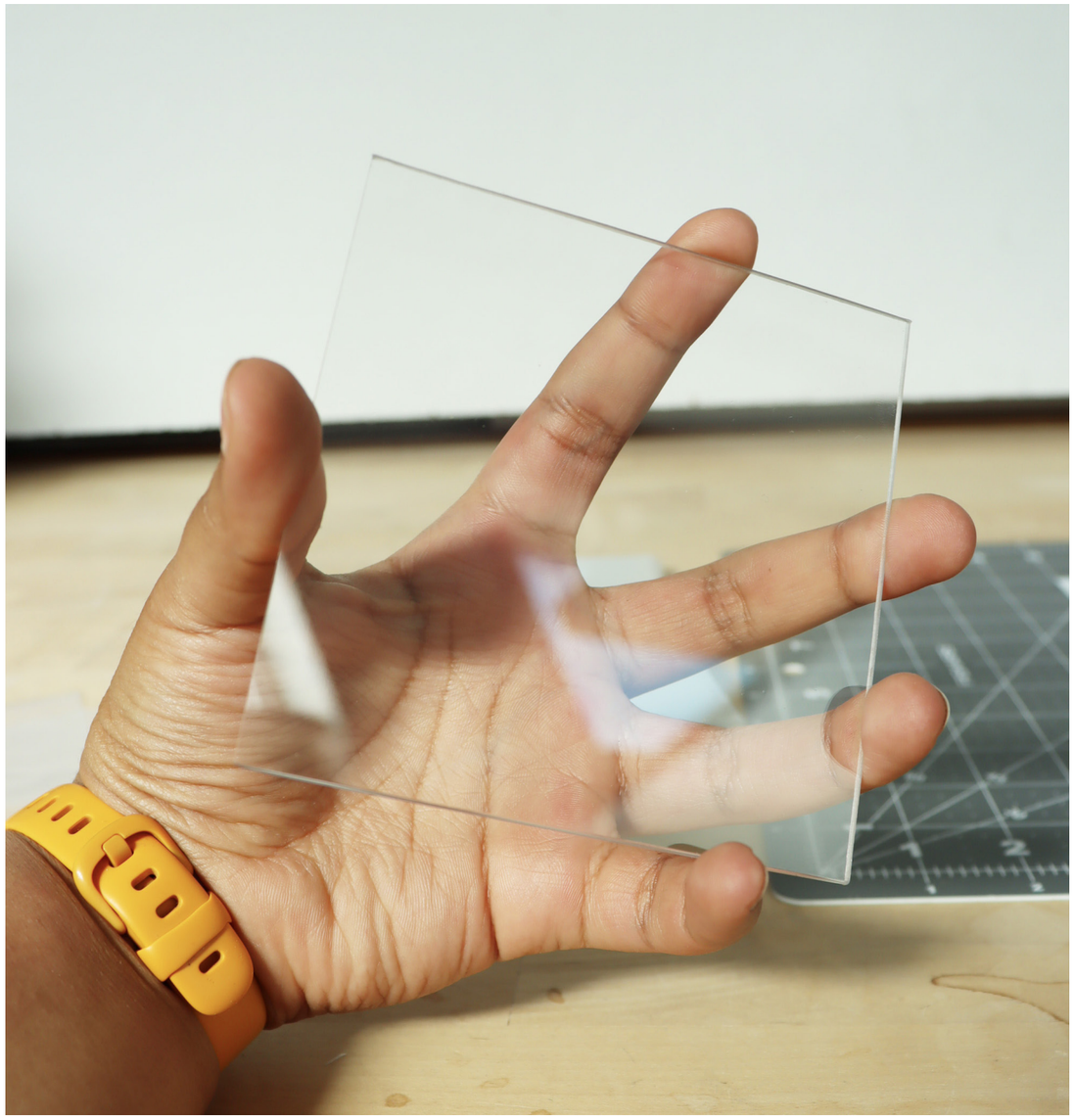


Figure 3.45: Clear plexiglass for deconstructed bonding experimentation, cut to 100x100mm for the container base.

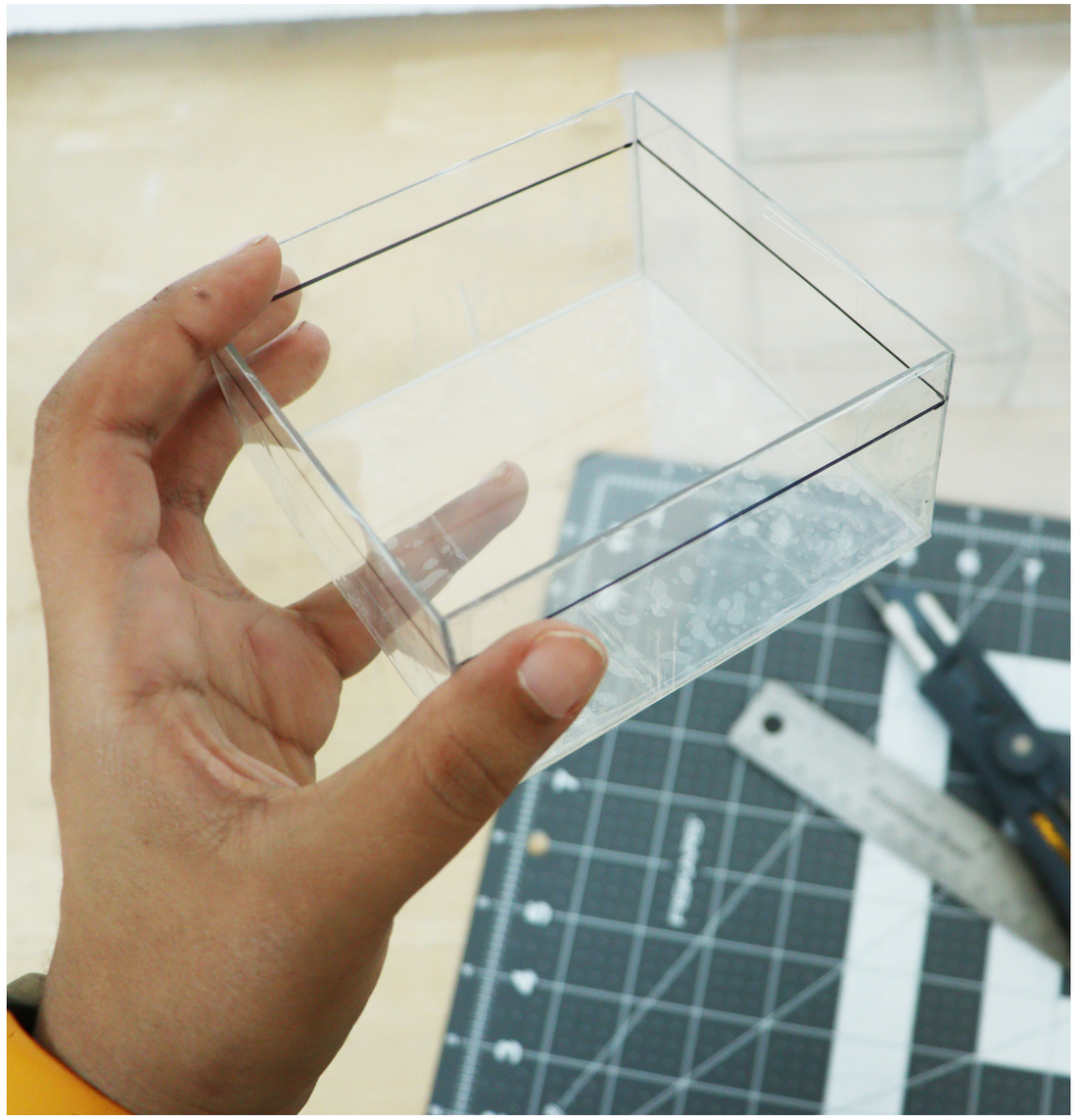


Figure 3.46: Completed plexiglass container built to 100x100x50mm. The 38mm height of the sample is marked in black.



Figure 3.47: Comparison of Series One material ratios. (a) 1C:2S, (b) 1C:3S, (c) 1C:4S.



Figure 3.48: Process of mixing materials - Sample 2b.



Figure 3.49: Material transfer to plexiglass container - Sample 2b.



Figure 3.50: Compiled Samples (excluding Series Four - this was added when Series One and Three were not showing sufficient growth). Containers were wrapped in plastic and pierced with a small hole to allow airflow. This was covered with micropore tape and labelled.

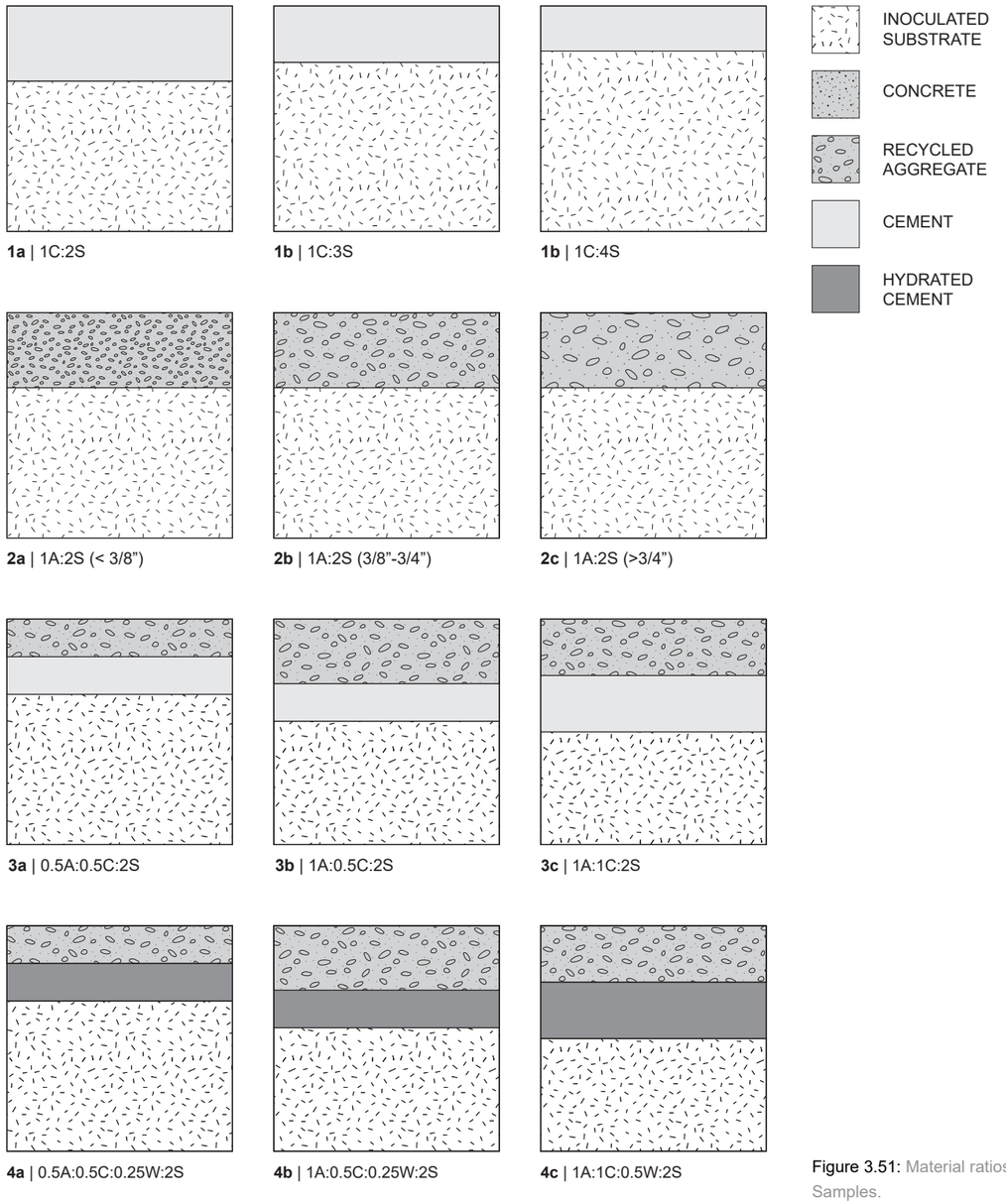


Figure 3.51: Material ratios for all Samples.



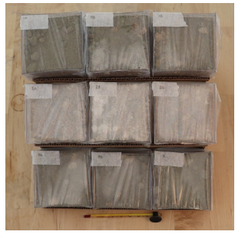
Figure 3.52: Material Samples captured at initial blend.



DAY 1



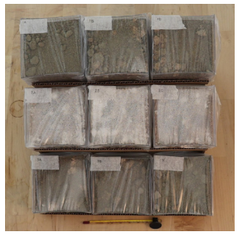
DAY 3



DAY 5



DAY 7



DAY 9



DAY 11



DAY 13



DAY 17



DAY 19



DAY 23



DAY 25



DAY 28

Figure 3.53: Sample growth over time.



1a | 1C:2S



1b | 1C:3S



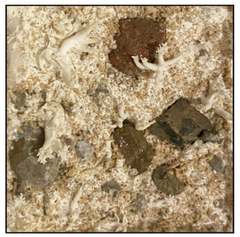
1b | 1C:4S



2a | 1A:2S (< 3/8")



2b | 1A:2S (3/8"-3/4")



2c | 1A:2S (>3/4")



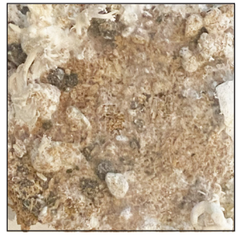
3a | 0.5A:0.5C:2S



3b | 1A:0.5C:2S



3c | 1A:1C:2S



4a | 0.5A:0.5C:0.25W:2S



4b | 1A:0.5C:0.25W:2S



4c | 1A:1C:0.5W:2S

Figure 3.54: Material samples captured at end of growth.

3.2.2.3 Results

Mixing the materials for Series One (cement and MBC) caused the cement to spread evenly throughout the inoculated substrate. In the days following, condensation appeared on the interior surface of the bag – a sign that the mycelium had continued to grow. After 7 days all the condensation had eventually disappeared. The samples showed no indication of additional mycelium growth. It was theorized that since the cement was so fine, it 'suffocated' the surface area of the sawdust and prevented the hyphae of the mycelium from accessing nutrients. As a result, the minimal amount of condensation produced was not sufficient to trigger the hydraulic chemical reaction of the cement, and the material combination remained unchanged (Figures 3.56-3.58).

The results for Series Two were more successful as mycelium grew around the recycled concrete aggregate as predicted. After heat-ceasing the samples, it was determined that the size of the aggregate did have an impact on the structural integrity of the combined material (Figures 3.59-3.61). Sample 2a (< 3/8") was extremely delicate to the touch and effectively disintegrated when it was transferred to a plastic bag for safe keeping. It appeared that the small pieces of aggregate were too abundant and evenly dispersed throughout the MBC – as observed in the Surface and Form Bonding exploration (Section 3.2.1), the MBC does not have a strong surface bond with concrete. By blocking and minimizing the opportunities for the mycelium to reach the nutrients within the substrate, the mycelium was likely unable to create strong interior connections, resulting in a weak material.

Sample 2b was the most successful of this series (Figure 3.55). Using recycled concrete crush that ranged from 3/8" – ¾", the mycelium was able to grow around the aggregate and lock the pieces in place. Closer observation revealed that there were some signs of cracking and shrinkage post heat-ceasing, but not enough to compromise its structural integrity. Just as in the surface and form bond exploration, the mycelium formed a weak bond with the surface of the concrete – all exposed pieces of aggregate sat tenuously within the combined material. Interestingly, when removing these loose pieces of aggregate, the mycelium was revealed to have grown in a solid layer beneath them. This would imply that the addition of the recycled concrete encouraged increased mycelium growth within the MBC.

Sample 2c achieved similar results to sample 2b. The larger aggregates created less of a continuous impediment for mycelium growth, which had hindered sample 2a. Following the heat-ceasing process, the MBC showed signs of cracking along the edges of the recycled concrete. With gentle handling, the sample split along the edges of the larger concrete pieces. This led to the conclusion that a combination of size and poor surface bonding led to a weakness in the combined material. Additionally, a key factor to this failure must be the size of the sample. The recycled concrete used ranged in size from ¾" and greater, with some pieces wider than 1". Given the thickness of the sample was 38mm (1.5"), even if the concrete had been perfectly set in the center there would have been minimal mycelium available to

anchor it in place. This experiment may have been more successful with a larger sample size.

Series Three had similar results to Series One. There was not enough condensation produced by the mycelium to hydrate the cement (condensation only present for the first 7 days), nor enough mycelium grown to lock the recycled concrete into place (Figures 3.62-3.64).

The results for Series Four varied for each sample, but the one consistency was slower growth times. These samples were left to grow for six weeks, with visible growth only occurring after 10 days. While samples in Series Two showed signs of mycelium growth after four days, these samples grew half as quickly, and with less visible mycelium overall (Figures 3.65-3.67).

Sample 4a was the most successful of the three. Despite taking six weeks, the mycelium appeared to grow throughout the entirety of the sample. After heat-ceasing for 2 hours, the sample still felt wet and spongy to the touch. The sample underwent the treatment for a total of five hours until dry. After resting for 24 hours, the sample remained delicate. It was carefully transferred to a sealed bag, but its poor material cohesion caused it to disintegrate when placed among the other samples. Sample 4b showed signs of mycelium growth for the first 12 days before the condensation within the bag disappeared, and sample 4c did not show any signs of growth. From these results it can be concluded that while hydrated cement can, when used sparingly, be used in combination with a living MBC, the resulting product does not develop into a stronger or more durable material.

The results of the four series of deconstructed bonding are summarized in Table 3. Before drawing final conclusions on which combined materials might be best suited for implementation in the design of a product, the most successful of these samples were tested for their compressive strength and acoustic properties.

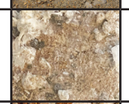
NAME		PHOTO	CONTENTS	RESULT
SERIES ONE	1A		1C:2S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
	1B		1C:3S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
	1C		1C:4S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
SERIES TWO	2A		1A:2S (< 3/8")	PARTIALLY SUCCESSFUL Achieved mycelium growth, unstable final product
	2B		1A:2S (3/8" – ¾")	SUCCESSFUL
	2C		2c – 1A:2S (> ¾")	PARTIALLY SUCCESSFUL; Achieved mycelium growth, unstable final product
SERIES THREE	3A		0.5A:0.5C:2S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
	3B		1A:0.5C:2S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
	3C		1A:1C:2S	UNSUCCESSFUL No hydraulic reaction from cement, no mycelium growth
SERIES FOUR	4A		0.5A:0.5C:0.25W:2S	PARTIALLY SUCCESSFUL Achieved mycelium growth, unstable final product
	4B		1A:0.5C:0.25W:2S	UNSUCCESSFUL No significant mycelium growth
	4C		1A:1C:0.5W:2S	UNSUCCESSFUL No mycelium growth

Table 3: Summary of the deconstructed bonding sample results (Series 1-4).



Figure 3.55: Sample 2b - the most successful of the deconstructed bonding experiments due to its ability to maintain its structural integrity.



Figure 3.56: Result - Sample 1a



Figure 3.57: Result - Sample 1b



Figure 3.58: Result - Sample 1c



Figure 3.59: Result - Sample 2a



Figure 3.60: Result - Sample 2b



Figure 3.61: Result - Sample 2c



Figure 3.62: Result - Sample 3a



Figure 3.63: Result - Sample 3b

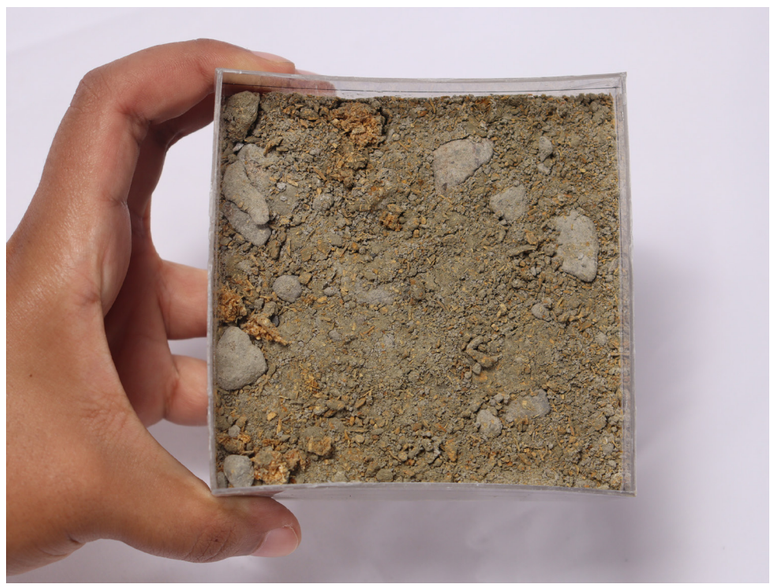


Figure 3.64: Result - Sample 3c



Figure 3.65: Result - Sample 4a



Figure 3.66: Result - Sample 4b



Figure 3.67: Result - Sample 4c

3.2.3 Material Testing

Three mycelium-based composite samples were selected for physical testing – a standard MBC with no additional materials, an MBC with recycled concrete (taken from sample 2b - 1A:2S), and an MBC with hydrated cement (taken from sample 4a - 0.5A:0.5C:0.25W:2S). The standard MBC represented a neutral base from which the other two material combinations could be compared. These samples would then be compared to the known properties of concrete/cement mortars to more accurately study their differences. The samples were constructed to the standards of ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).[223] This test method was selected due to it being used as a standard for testing Portland cement mortars (1 part cement to 2.75 parts sand proportioned by mass) as well as mycelium-based composites. Since mycelium is a new and non-standardized material, there is no current standard for its production. This has led material scientists to adapt existing standards for similar materials to MBC production. While among these MBC explorations there has been no consensus on which ASTM standard test method is best suited for the material (Table 4), ASTM C109 was referenced frequently and was therefore determined to best suit the work in this thesis.

The three selected samples were produced identically to their sample counterparts in Sections 3.1.2 and 3.2.2.2. They were grown in plexiglass formwork sized 50x50x60mm – the additional 10mm in height allowed a gap for air exchange – then sealed in a plastic bag with a micropore tape filter patch. Three of each material sample were produced.

Despite following the same production procedure as Series Four, the sample with MBC and hydrated cement was not able to be successfully repeated – it did not grow new mycelium. The following tests were performed on the two successful material samples (standard MBC and recycled concrete MBC).

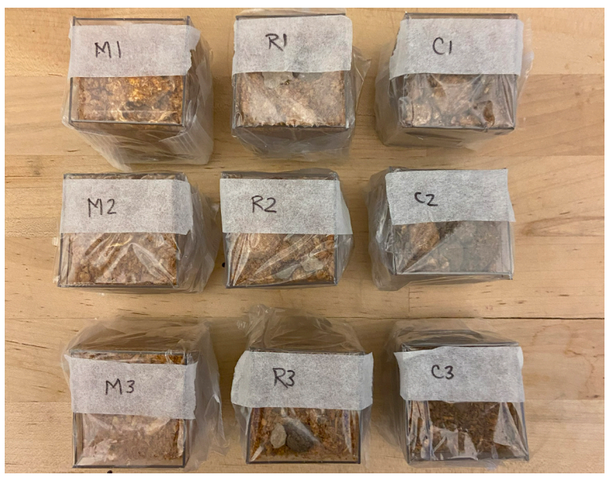


Figure 3.68: Samples sized according to ASTM C109 captured at initial blend.

223 ASTM International, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars."

ASTM No.	ASTM DESCRIPTION	MBC DIMS	MYCELIUM STUDY / APPLICATION	REFERENCE
C109 /C109M-20	Standard Test Method for Compressive Strength of Hydraulic Cement	50x50x50 mm	Mycelium-Based Composite Graded Materials: Assessing the Effects of Time and Substrate Mixture on Mechanical Properties	Ghazvinian and Gürsoy, "Mycelium-Based Composite Graded Materials."
C109	Ibid	Ibid	Fabrication of mycelium (oyster mushroom)-based composites derived from spent coffee grounds with pineapple fibre reinforcement	Kohphaisansombat et al., "Fabrication of Mycelium (Oyster Mushroom)-Based Composites Derived from Spent Coffee Grounds with Pineapple Fibre Reinforcement."
C109	Ibid	Ibid	Valorization and biorefinery of local agricultural and textile wastes through mycelium composites for structural applications	Ruiz et al., "Valorization and Biorefinery of Local Agricultural and Textile Wastes through Mycelium Composites for Structural Applications."
C165-07 (2017)	Standard Test method for measuring Compressive Properties of Thermal Insulations (Procedure A)	180 mm diameter 35 mm thick	Compressive Resistance of the Mycelium Composite	Vidholdová et al., "COMPRESSIVE RESISTANCE OF THE MYCELIUM COMPOSITE."
D1037-12 (Reapproved 2020)	Standard Test Methods for Evaluating Properties of Wood-Base Fibre and Particle Panel Materials (Part A)	520x72x20 mm	Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour	Rigobello, Colmo, and Ayres, "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour."
D1037-12 (Reapproved 2020)	Standard Test Method for Evaluating Properties of Wood-base Fibre and Particle Panel Materials	75x50x50 mm (compression) 200x80x15 mm (flexural)	Engineered mycelium-based composite materials: Comprehensive study of various properties and applications* * Since this is a soft material, they referenced the wood-based fibre and particle panel standard and made modified test rigs for flexural and compressive tests to manually obtain the loads. These modifications were made due to limitations in lab equipment	Lingam et al., "Engineered Mycelium-Based Composite Materials."

Table 4: Comparison of mycelium-based composite studies that referenced ASTM test standards as a means to measure their technical properties (specifically the compressive strength). This thesis chose C109 based on the overlap between concrete and MBC studies, the quickly produced sample size and the frequency of its use across several different MBC studies and researchers.

3.2.3.1 Compressive Strength

Considering one of the material goal was for the technical properties of the concrete to strengthen the MBC, samples were created to test the compressive strength of the combined material. As noted in Section 3.2.2, hydrated cement has been proven to weaken the structural integrity of the MBC. When it grew mycelium, it remained wet and spongy long throughout the ceasing process. When the process was complete the combined material was extremely fragile and crumbled to the touch. The hydrated cement and MBC material was unable to be grown again for this compressive test.

The remaining samples (sized according to ASTM C109) were divided into two series. The standard mycelium-based composite was labelled Series 'M', and three samples were produced (M1, M2 and M3). The recycled concrete aggregate and MBC combined material was labelled Series 'R' and three samples were produced (R1, R2 and R3). It was hypothesised in Section 3.2.2 that introducing recycled concrete aggregate to MBC would increase the surface area of the thick layer of mycelium that grew on the material's perimeter, thus increasing its strength. It was also predicted that the compressive strength of the aggregate itself would contribute to the overall compressive strength of the combined material.

Both series were grown and ceased successfully. After ceasing, Series 'R' ran into a similar structural integrity issue as Sample 2c in Section 3.2.2 – the combined material would break along the edges of the recycled concrete aggregate. This was likely due to the smaller size of the sample – there was less mycelium to lock the aggregate in place. Two of the samples partially broke in transportation to engineering lab for material testing and thus were not used. These broken samples were instead used to test the capacity of the Hydraulic Cylinder testing Machine to register the resistance of the material. The combined material did not register on the CanTrol Model 2420011. Neither did the first of the Series 'M' samples, M1. It was partially compressed before all remaining samples were transferred to a new hydraulic cylinder testing machine, the MTS Criterion – Model 43, which was able to register the resisting force.

224 Vidholdová et al., "COMPRESSIVE RESISTANCE OF THE MYCELIUM COMPOSITE," 33.



Figure 3.69: Series 'M' sample tested in the MTS Criterion - Model 43.

The samples were tested with a consistent loading rate of 1800 kN/s at 0.3mm/second. Each were compressed with a flat plate that evenly distributed the loading force. Refer to Table 5 for the peak load of each sample, and any additional notes associated with their testing. The compressive resistance of each material was calculated as follows[224]:

$$S = W / A$$

where:

S - compressive resistance [MPa]
W – maximum load at material failure [N]
A – average area of tested sample [2500mm^2]

All tested samples had a compressive resistance within the MBC range noted in Table 2 (0.01-1.1 MPa). The impact of introducing recycled concrete aggregate to mycelium-based composites was found to be negligible at best (should the combined material stay intact, there appeared to be no change to the compressive resistance), and detrimental at worst (the aggregate weakens the structural integrity of the sample, causing it to break apart easily). This rudimentary study therefore concludes that neither hydrated cement nor recycled concrete aggregate should be mixed into mycelium-based composites to increase their compressive strength.

SAMPLE No.		PEAK LOAD (N)	COMPRESSIVE RESISTANCE (MPa)	NOTES
SERIES 'M'	M1	13	0.0052	Discard result. Partially compressed on different machine.
	M2	157	0.062	N/A
	M3	115	0.046	N/A
SERIES 'R'	R1	120	0.048	N/A
	R2	N/A	N/A	Broken in transportation
	R3	N/A	N/A	Broken in transportation

Table 5: Peak Load and Compressive Resistance per sample.



Figure 3.70: Material samples sized to ASTM C109 standards.

(a) Series 'M' - Standard mycelium-based composite.
(b) Series 'R' - Mycelium-based composite and recycled concrete aggregate.
(c) Series 'C' - Mycelium-based composite and hydrated cement.

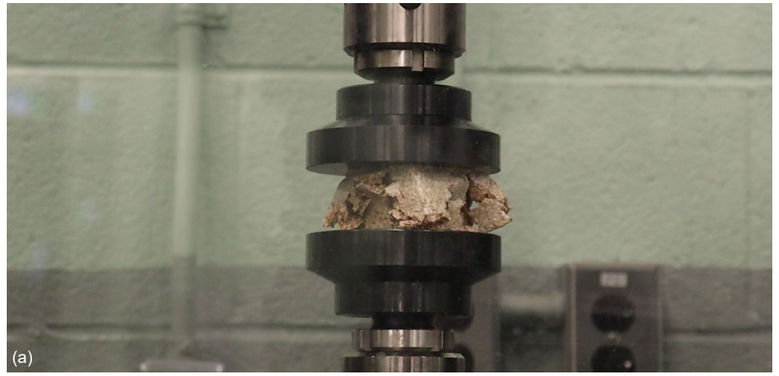






Figure 3.71: Completed material samples.

(a) M2
(b) M3
(c) R1



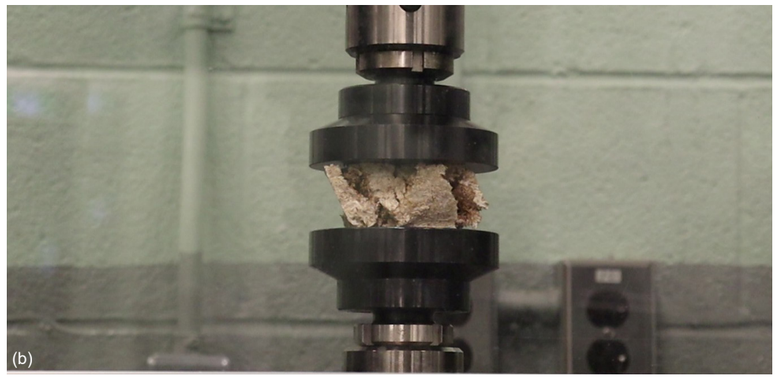




Figure 3.72: Compression tests on MTS Criterion - Model 43.

(a) Material Failure - M2
(b) Material Failure - M3
(c) Material Failure - R1

Given the mixed results of physical experimentation of an MBC's ability to compress and the impact of including recycled concrete aggregate on the overall material strength, this thesis looked toward digital simulation as a method to further clarify the results of the deconstructed bonding exploration.

A study on the *Mechanical behavior of mycelium-based particulate composites* done in 2018[225] was integral in understanding the material model of the mycelium matrix, and why more data is required before simulations can predict the impact of the addition of a large aggregate like recycled concrete. This study recorded the material properties of a mycelium and corn stover composite, and using this data worked to replicate a digital model of the material. One of the key takeaways from this work was that mycelium-based composites work on two scales: the microscale and the macroscale (Figure 3.73). The microscale refers to the mycelium network, which is composed of hyphae approximately 1 µm in diameter.[226] Given that it is organic, there is no garuntee that this microscopic network of growth would grow uniformly throughout the chosen substrate (whose particles exists on a macroscale, which itself is composed of an organic material and is not guarenteed uniformity). Both the mycelium network and substrate can very in density depending on the method of production, the success of the mycelium to grow throughout and the density/consistency of the material at each scale. Therefore, the research team developed seperate models to replicate the organic diversity of each material before combining these into a composite model that was capable of replicating the results of their phyical compression tests.[227]

This final model required three equations to develop the model: one for the microscale, one for the macroscale, and one that would then document the hyperelasticity throughout the combined material, which required inputs for strain density and damage.[228] This was crucial in determining how long the digital MBC would remain intact and at which stage it would fail.

Given this information, work went into adapting and simplifying the study's collected data for the purpose of recreating a sawdust-based material in Autodesk's *Fusion 360*. Unfortunately, the material property inputs did not allow for the same accuracy of strain density and damage, without which it would be difficult to confirm the accuracy of the model. Additionally, there have been no studies found where an aggregate so large as recycled concrete has been added to mycelium, and little information regarding the strength of the microscopic connections mycelium may form to the aggregate while growing in a sawdust substrate. Without this information, combined with the results of the physical testing, there is no way to rely on the digital model as a means of accurately representing how the two materials might act together when strained with this current data. This study therefore had to be tabled for future research in lab conditions with more sensitive tools capable of calculating this strain between concrete and MBC, supported by additional physical testing that can confirm the uniformity with which the mycelium has grown through a sawdust substrate.

225 Islam et al., "Mechanical Behavior of Mycelium-Based Particulate Composites."
226 Islam et al.
227 Islam et al.
228 Islam et al.

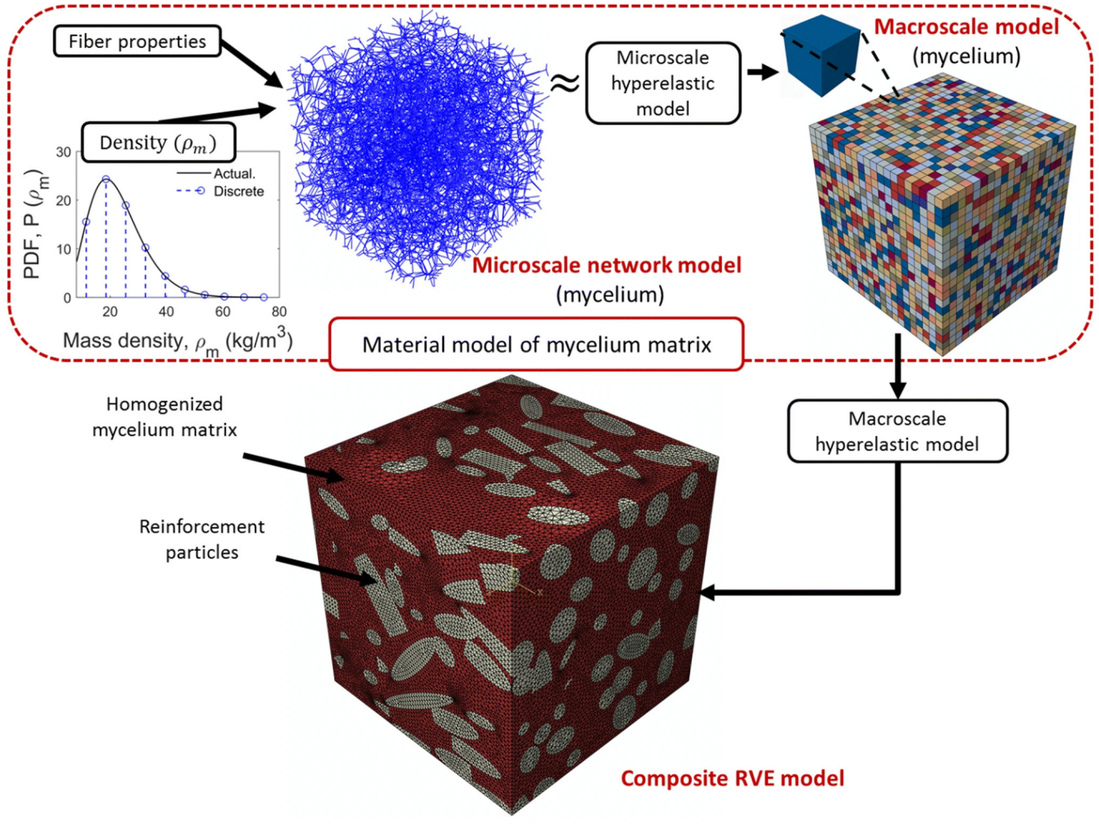


Figure 3.73: Schematic representation of the multiscale modeling procedure developed for mycelium composites.

Source: Islam et al.,(2018)

3.2.3.2 Acoustic Properties

Given that one of mycelium-based composites most notable properties is its acoustic dampening, this thesis set up a simple test to measure the impact concrete might have on its effectiveness. A double layered cardboard box was constructed, large enough to encase an iPhone. The phone used an app called *Decibel X* to record the surrounding environment and document the decibels (dB) of volume live. The end of the box that faced the phone's microphone housed a slot to test different materials – cardboard, standard MBC, and recycled concrete MBC (sample 2b). Refer to Figure 3.73 for a diagram of the completed 'sound chamber' and material slots.

A recording of the app's decibel readings was made for each of the following materials within the slot: open air, cardboard, standard MBC, and recycled concrete MBC (Figures 3.74 and 3.75). These recordings were ran twice – once with the ambient noise from the quiet room, and once with 13 seconds of audio from a '600 Hz Test Zone'[229] sample, played from a laptop at full volume. The box was placed so the phone's microphone was 6" from the laptop speakers. This study produced eight recordings, summarized in Table 6, which describes the average decibels over that period of time.

The findings of this acoustic test showed that a standard MBC had the greatest properties of acoustic dampening of the materials tested (reducing the test tone by approximately 9 dB), closely followed by the recycled concrete MBC (reducing the test tone by 7 dB). Based on these results, this 1:2 ratio of recycled concrete to MBC reduces the effectiveness of the MBC's acoustic properties by 33%. This is consistent with the percentage of the MBC sample that contains concrete. This simple study therefore concludes that the effectiveness of the acoustic properties of an MBC containing recycled concrete is inversely proportional to the percentage of concrete within the material.

MATERIAL	QUIET ROOM (dB)	600 Hz TEST ZONE
Air	41	60
Cardboard	40	57
Standard MBC	42	51
Recycled Concrete MBC	41	53

Table 6: Average decibals over time for each material sample.

229 *600 Hz Test Tone.*

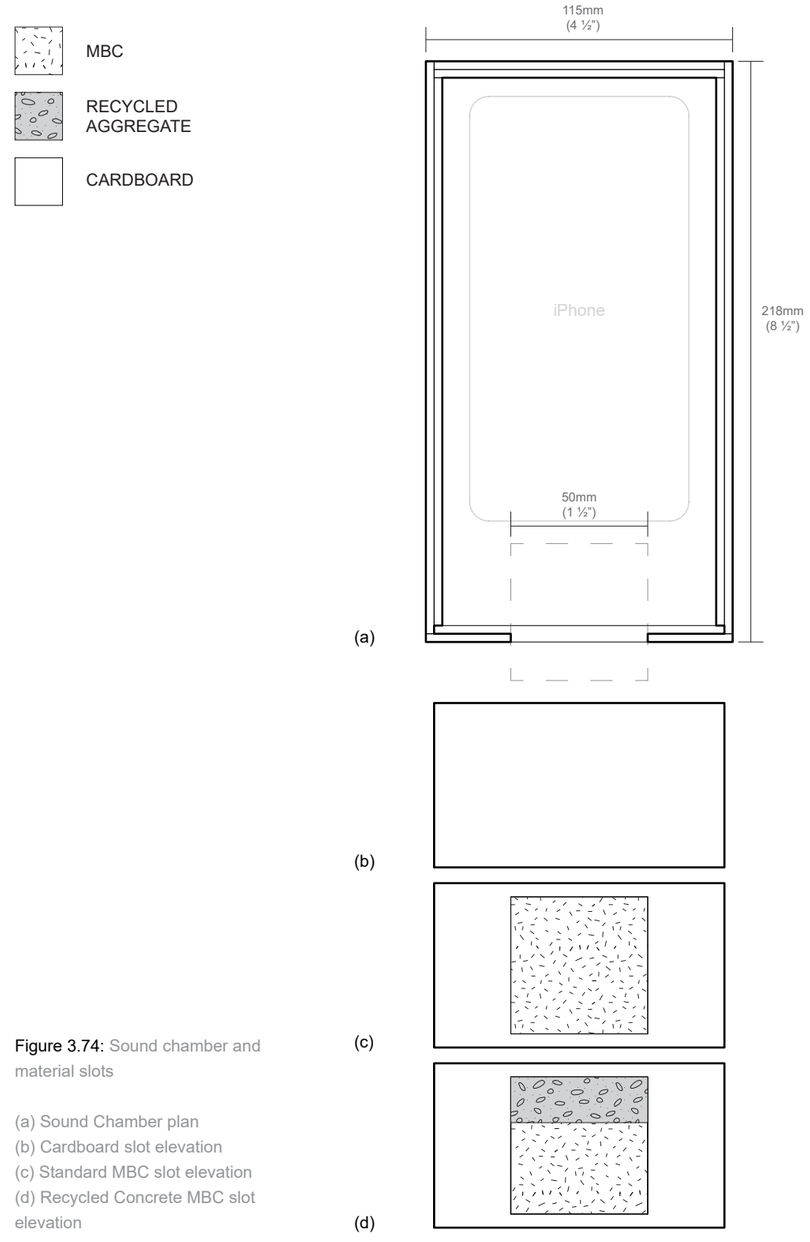


Figure 3.74: Sound chamber and material slots

(a) Sound Chamber plan
(b) Cardboard slot elevation
(c) Standard MBC slot elevation
(d) Recycled Concrete MBC slot elevation

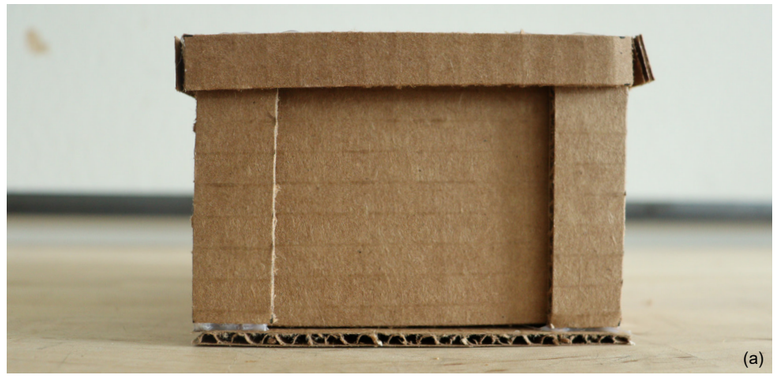






Figure 3.75: Material slots installed in sound chamber - elevation.

(a) Cardboard
(b) Standard MBC
(c) Recycled Concrete MBS



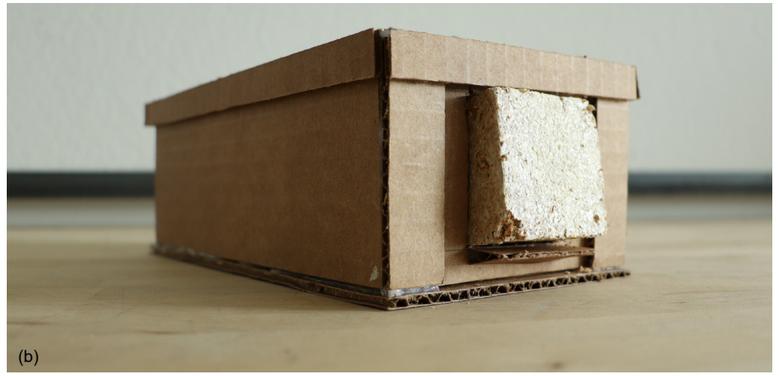




Figure 3.76: Material slots installed in sound chamber - perspective.

(a) Cardboard
(b) Standard MBC
(c) Recycled Concrete MBS

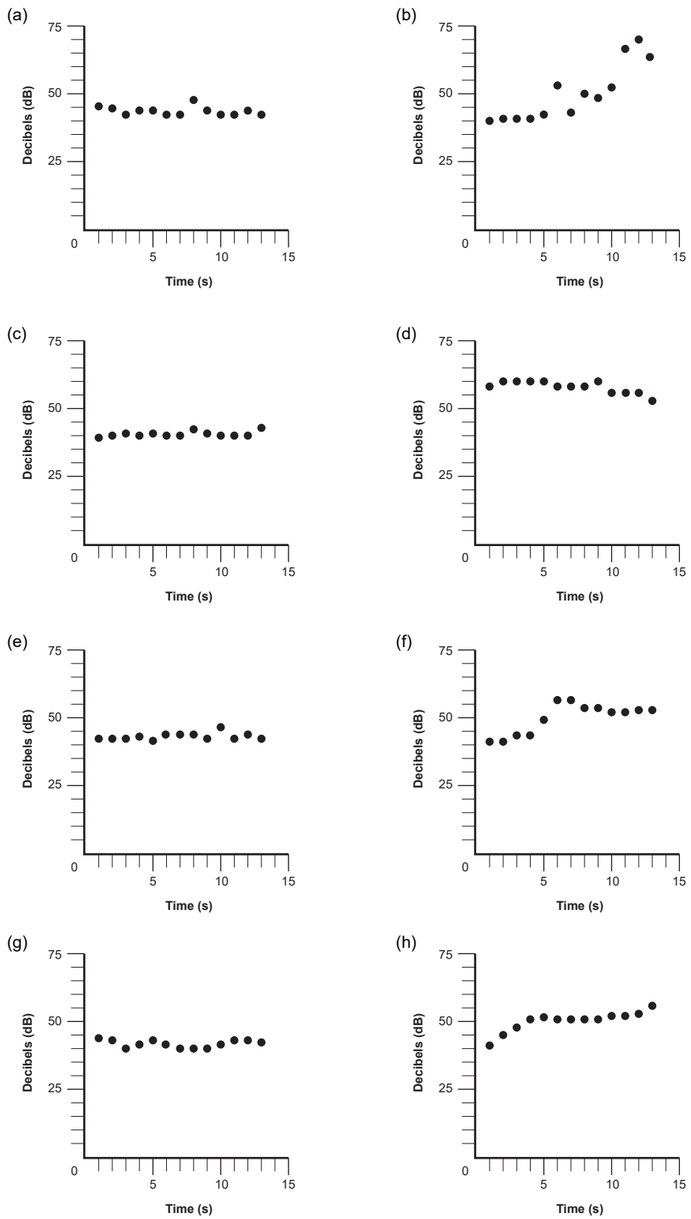


Figure 3.77: Graphs showing decibel readings over time

(a) Air - Quiet Room
(b) Air - 600 Hz
(c) Cardboard - Quiet Room
(d) Cardboard - 600 Hz
(e) Standard MBC - Quiet Room
(f) Standard MBC - 600 Hz
(g) Recycled Concrete MBC - Quiet Room
(h) Recycled Concrete MBC - 600 Hz

3.3 Design Goals

Material exploration has allowed for a greater clarity on what methods of material combination would best suit the pairing of concrete and mycelium-based composites. The desired properties from the material goals outlined in Section 2.4 have remained consistent – the combined materials must emphasize the compressive strength and durability of concrete and the acoustic and thermal properties of mycelium-based composites. Guided by these material goals and the results of this Chapter, the following conclusions can be drawn.

Mycelium-based composand concrete have a poor surface bond, regardless of the texture of the concrete. MBCs do not have the flexural strength to act as a bonding agent (like mortar) to large blocks of concrete, but they are capable of bonding smaller blocks of recycled concrete aggregate (ideally between 3/8” – ¾”). Despite the successful mycelium growth, the additional recycled concrete does not enhance the compressive strength of standard MBC. Additionally, this integrated recycled concrete reduces the effectiveness of an MBCs acoustic dampening. Finally, cement, either dry or hydrated, does not improve the structural integrity of an MBC.

Based on these conclusions, the design goals of a concrete and mycelium-based composite product are as follows:

1. Mycelium-based composites should be left without additional aggregates to maximize their structural, thermal and acoustic properties.
2. Mycelium-based composites should be grown in isolation as either a panel or a block to maximize the amount of external mycelium growth.
3. Concrete should act as a continuous support for the mycelium-based composite without intersecting it
4. Concrete should use its durability to protect and/or encase the mycelium biocomposite, which is vulnerable if the substrate is exposed beyond the exterior mycelium layer.
5. The connection between the two materials should not rely on a surface bond.
6. Human vitality should be an underlying consideration in the reception and use of the product (carried over from Material Goals).

4

Design Proposal

"A great building must begin with the immeasurable, must go through measurable means when it is being designed, and in the end must be unmeasured."

— *Louis Khan*

A large portion of the Integrated Design Methodology was influenced by Material Driven Design (MDD) – it was referred to as the 'reductionist method' when set in conjunction with the philosophy of sustainable design. As noted in Section 1.6.1, MDD is a four-stage process that aims to "aid in the design process when the desired subject material serves as the starting point."[230] The first two stages of this process have already been achieved in Chapter 2 by taking the time to understand the concrete and mycelium biocomposites, as well as note their technical properties. The third stage is to consider the visual properties of the proposed product that would be created when combining these materials.

Evaluating the visual properties helps in both narrowing a target audience as well as possible products that would suit the client needs, the material goals and the design goals simultaneously. From here the next step in developing a product would be selecting a base product that embodies the above before further developing and exploring it through the knowledge gained from studying concrete and mycelium-based composites. This design process will be covered in this Chapter, and is complimented with an additional checkpoint of policies and philosophies to ensure the proposed product is sustainable. This Chapter then concludes with a practical and sustainable final design proposal – the end goal of the integrated design methodology.

230 Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 4.

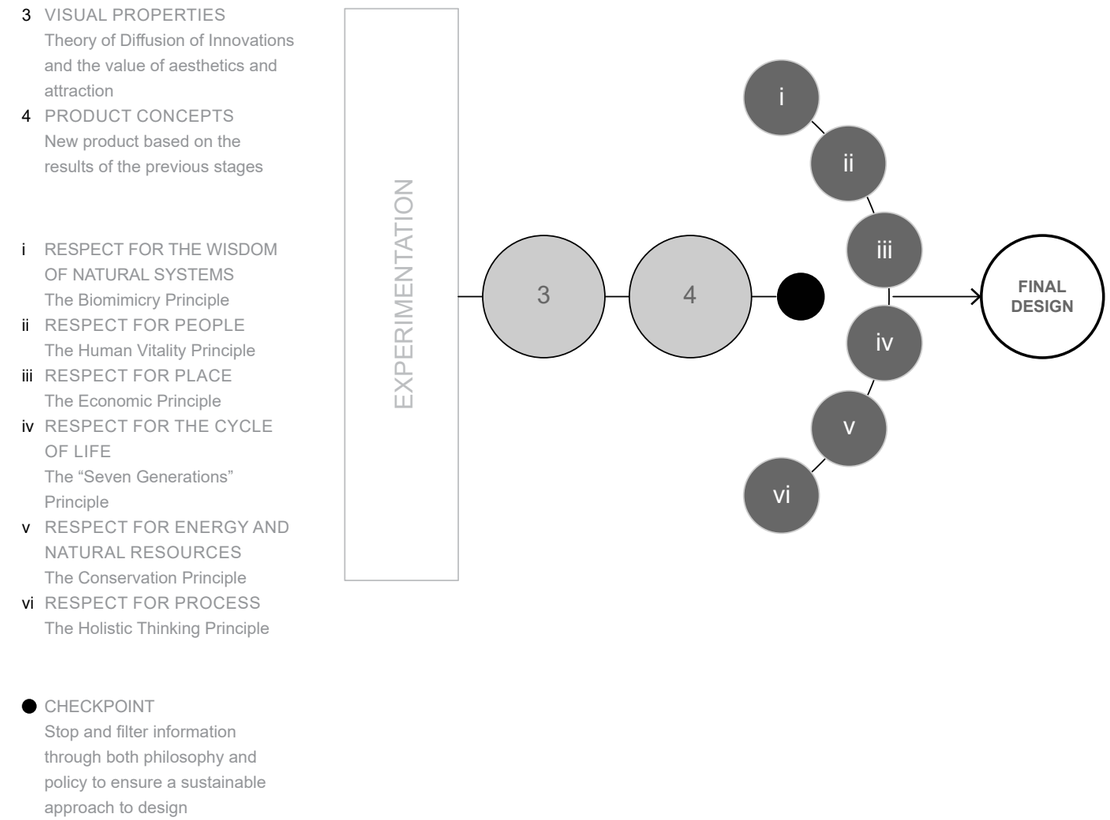


Figure 4.1: Integrated Design Methodology - Design

4.1 Visual Properties

It is at this stage of the design process that the materials' sensory attributes, and their contextual material experience patterns for individual settings begin to influence the form and function of a final product. This stage is further developed with the introduction of the *Theory of Diffusion of Innovations*, which has been used to describe the process through which new concepts, products or technologies are accepted by society and in what ways that acceptance can be predicted.[231] Given the innovation of mycelium-based products, several MBC researchers have incorporated this theory into their product and material designs to best predict in what forms the material might be accepted by their target audience.[232]

This theory is implemented through the creation of an 'acceptance prediction spider chart' (Figure 4.2) which highlights five perceived material characteristics: **relative advantage** (i.e., the degree to which an innovation can be perceived as better than what it is superseding), **compatibility** (i.e., the degree to which an innovation is perceived as consistent with the existing values, past experiences and needs of potential adopters), **complexity** (i.e., the degree to which the innovation might be considered difficult to use), **trial-ability** (i.e., the degree to which an innovation may be experimented with on a limited basis) and **observability** (i.e., the degree to which the results of the innovation are visible to others).[233]

Analysing the material experience patterns of both mycelium-based composites and concrete pushes product design in a direction that would maximize their appeal to the ideal early adopters (in the case of this thesis, policy makers, architects, engineers, construction managers, etc..) while still prioritizing the material's strongest attributes. It is therefore important to contextualize what material design properties would best suit the five material characteristics of innovation to transfer these qualities to a product that is both successful and sustainable.

The relative advantage of using a combined concrete and MBC product should be the value of their strongest technical properties. As discovered through the both the material review in Chapter 2 and the material exploration in Chapter 3, the resultant product should lean into concrete's strength and durability and MBC's acoustic and thermal resistance. Since there are currently no insulating materials that can also be relied on for structure, product precedents must use a combination of materials. Within the construction industry, the established products that most closely share these properties: insulated concrete forms (ICF – concrete poured within two layers of rigid insulation), insulated pre-cast concrete panels (sandwich panels – rigid insulation sandwiched between two layers of concrete), and insulated concrete masonry units (ICMU – insulation with a concrete masonry unit). A mycelium composite and concrete product could present itself as an advantage over these existing examples through the inexpensiveness and sustainability of the materials for a comparable performance.

This also ties into the compatibility of a combined concrete and MBC product (CMBC) – if it is to be compared to existing products with the same technical properties, it should also be designed to perform the same functions. Given the similar technical properties of mycelium biocomposites to synthetic insulations,

231 Rogers, Singhal, and Quinlan, Diffusion of Integrations.
232 Madusanka et al., "A Review of Recent Advances in Fungal Mycelium Based Composites," 5.
233 Karana et al., "When the Material Grows," 128.

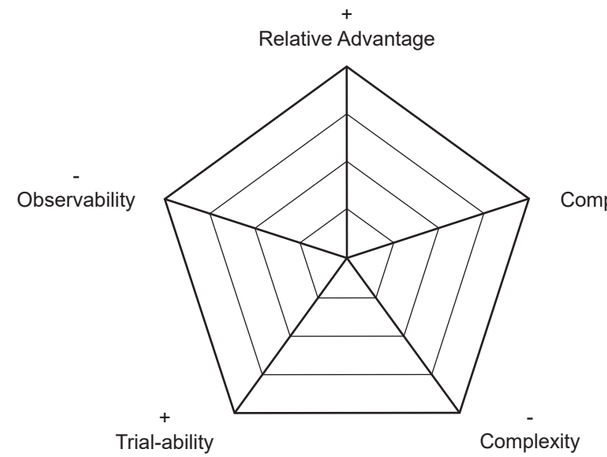


Figure 4.2: The Five Material Characteristics of Innovation, adapted for use in combining a concrete and MBC product.

Adapted from Karana et al. (2018)

this means the MBC should be introduced in a way that allows it to be slotted seamlessly into existing product installation processes and be manufactured to suit these standards. In doing so, the incorporation of CMBCs in the construction industry is an operation that lowers in complexity, since there are minimal new technologies, production methods or installation techniques required to learn to integrate the materials into current construction practices.

This technique of incorporating the combined material would then lend itself very effectively to trial-ability, especially when compared to precast insulated concrete products. Existing international standard testing methods can be used as a baseline for experimentation, much like they were in this thesis – the exterior concrete layers and the mycelium core could be adjusted independently to determine to what extent they impact the strength and thermal resistance in comparison to the standard product.

Finally, there is the characteristic of observability. The aesthetic qualities of mycelium are by no means universally appreciated – the surface varies between a solid, off-white layer of mycelium to a patchy reveal of the underlying substrate. Since mycelium was at one point living, there is also often trace evidence of **exudates** (an odorless, yellow discharge) which can stain the surface. This organic look can potentially find a target audience, as there is an increased desire for more sustainable materials in architecture and design and some may then appreciate MBC's flawed surfaces. In fact, some companies such as *MYCEEN* have already embraced this aesthetic in their (industry recycled) sawdust-based mycelium acoustic panelling (Figure 4.3). However, this niche appearance could limit the pool of early adopters willing to implement the material. Putting aesthetic aside, mycelium biocomposites have a greater potential to wear over time due to the inconsistent surface layer of mycelium. This could not only lead to a negative public perception of the material as it deteriorates but it could also, as one industrial design study noted, lead to the urge to break and pick at it,[234] decreasing its functionality as a building material. Therefore, for both increased functionality and the safety of a traditional aesthetic, this thesis proposes that a combined CMBC should have its mycelium-based composites encased in concrete. A low observability of MBC would be considered successful.

Based on the additional context provided from the five characteristics of innovation, this process has provided three potential products that could be used as a platform to explore the relationship between concrete and mycelium-based composites: insulated concrete forms, insulated concrete panels, and insulated concrete masonry units.

234 Karana et al., "When the Material Grows," 128.



Figure 4.3: MYCEEN's Acoustic Mycelium Panels.

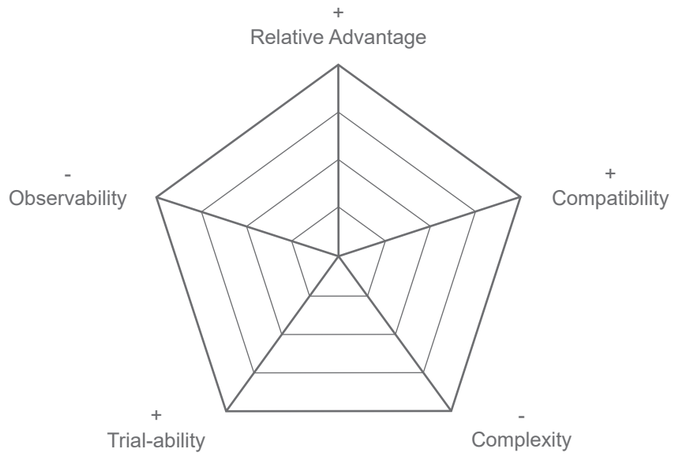
4.2 Product Concepts

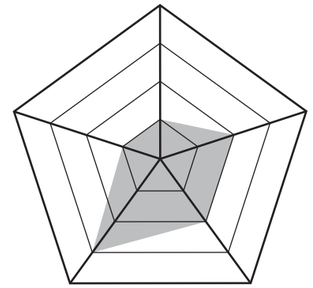
The three products selected for their material relevance to a proposed concrete mycelium product were further analysed using the acceptance prediction spider chart (Figure 4.4). Insulated Concrete Forms (ICF) were noted to be the weakest foundation for a CMBC exploration. ICFs typically use close-celled foam to act as a formwork for concrete that is poured on site and are intended for the same use cases as wood frame construction.[235] The relative advantage of swapping the insulation for mycelium is weak, since closed cell insulation is selected for its moisture resistant and non-absorbent properties, as well as its resistance to rot and mould.[236] Mycelium underperforms in each of these categories, particularly with its well-known susceptibility to mould when exposed to the elements. This also lowers its compatibility, as it would be an inferior product in the eyes of early adopters. The primary complexity of a potential mycelium based ICF product would be in creating a sturdy formwork. The existing ICF design uses polypropylene ties embedded within the insulation to hold the form unit together[237] – mycelium biocomposites would need to be further developed to both increase their density and strength to carry this weight, as well as address how the material would handle the strain of the ties intersecting its weaker interior. Because of these necessary advancements in technology, the potential for trial-ability and innovation is high. The observability of the innovation would also be high, but considering the exposure would only serve to highlight where MBCs fall short of the existing product, it is undesirable.

Insulated Concrete Panels are a more favourable template for the exploration of concrete and MBCs. These sandwich panels can serve both a structural and thermal function within a building, lending themselves well to the goal of producing more structural biomaterials. The observability of the innovation is low – the MBC would be encased between two panels of concrete, and mycelium insulation panels are already a highly researched material. The compatibility of concrete and mycelium is more complex to navigate – since mycelium has a lower R-value than commercially used rigid insulations, it would require a thicker layer to prove an equivalent efficiency to what is currently available. Since this product design also uses ties to connect the exterior and interior panels through the insulation, the mycelium would be compromised by both a higher ratio of its weaker interior substrate to exterior skin, and by the intersecting ties. Additionally, mycelium production would need to greatly increase in scale to create a large panel as necessary for this product – this scale increases the risk for contamination. These weaknesses lower the relative advantage and unnecessarily increase the complexity of the project. For these reasons, this thesis shifted to exploring how concrete and mycelium could be explored through Insulated Concrete Masonry Units (ICMU).

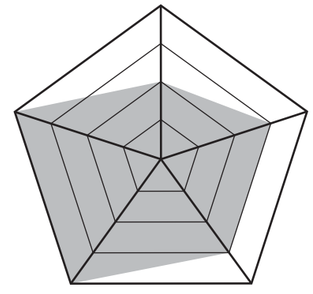
By focusing on the smaller scale of the ICMU, material production can be more easily controlled, particularly during the crucial early phases of mycelium inoculation. Also known as thermal blocks, this product integrates insulation within a concrete masonry unit core through either molded inserts, foams, expanded perlite or vermiculite granular fills.[238] Replacing this core with mycelium-based composites allows for the material to remain unobserved (preserving the familiar concrete aesthetic) and fully protected by the strength of the concrete.

235 Jenkins, “Insulated Concrete Forms.”
236 Jenkins.
237 Jenkins.
238 Concrete Masonry and Hardscapes Association, “Insulating Conrete Masonry Walls.”

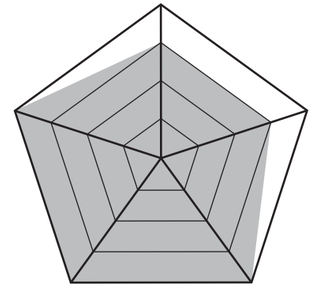




(ICF)
Insulated Concrete Forms



(Sandwich Panels)
Insulated Concrete Panels



(ICMU)
Insulated Concrete Masonry Units

Figure 4.4: The Five Material Characteristics of Innovation applied to ICF, Sandwich Panels and ICMU.

Adapted from Karana et al. (2018)

Existing studies on how best to increase the thermal efficiency of ICMUs can be adapted to include the effectiveness of MBCs,[239] creating a great potential for trial-ability. The simple method for integrating insulation to the CMU is ideal for low complexity, which also aligns with leaning into the relative advantage and compatibility of incorporating mycelium to an existing system. The only area that causes implementation concerns would be the method of production. The current process of ICMU fabrication uses prefabricated blocks with either a friction fit or site added insulation. Neither method is ideal for an MBC insulation. A friction fit runs the risk of removing the exterior mycelium layer. Growing mycelium within the block, as discovered in Chapter 3, will require heat-ceasing, which will shrink the MBC away from the surface of the concrete. Adapting ICMUs to utilize MBCs will either require a new production methodology or increased care when joining the materials.

239 Urban et al., "Arranging Insulation for Better Thermal Resistance in Concrete and Masonry Wall Systems."

4.3 Policies and Philosophies

Within the integrated design methodology, the first checkpoint of policies and philosophies served as a counterpoint to the technical observations of concrete and mycelium-based composites. Its intent was to contextualize the material study within the reality of the modern construction industry and aim the design towards the goal posts set by ideal industry benchmarks and a holistic worldview. Within that reflection arose difficult questions that material design alone could not answer. With a clear direction established for the product design, this checkpoint of policies and philosophies now aims to address these lingering issues.

The first of these considerations was an acknowledgement of the Human Vitality Principle within the design. This has in part been addressed through the 'observability' characteristic of innovation. This thesis acknowledged the potential polarizing acceptance of the visual appeal of mycelium-based composites, and therefore chose to favour product forms that minimized its exposure. This was also acknowledged through the function of the product. ICMUs are designed to imbue traditional concrete masonry units with the qualities of insulation while simplifying installation and lowering overall material cost, which benefits the target audience noted in Section 4.1. Arguably more importantly, providing better warmth and acoustic separation of spaces serves to benefit the people who will eventually be occupying them, demonstrating the value of the Human Vitality Principle.

It was important to further contextualize this connection to people by connecting the material to place. The Economic Principle asks materials to respond to their site on a macro and micro level. Considering this thesis proposes the production of a modular product it will focus on the broader macro level of the environmental context – the climate and region in which it is produced. From the broadest perspective of climate, the primary concern with an ICMU design is an abundance of concrete, which makes it an overall high carbon and unsustainable material. This should be addressed by adapting one of the following strategies noted in Section 2.1.1: using an alternative cementitious material, minimizing concrete waste or using recycled concrete aggregate. Considering the theme of reusing construction waste as a substrate for the mycelium (hardwood sawdust), it would be fitting that the concrete chosen for the final product design does the same. The proposed concrete mix uses recycled concrete aggregate in combination with fly ash or blast furnace slag, an alternative, lower carbon cementitious alternative.

Since the product is to be made of both recycled concrete and mycelium-based composites, its location should feature an abundance of demolished concrete, concrete recycling facilities, and a humid and warm environment that encourages the growth of oyster mushrooms. Through research it was discovered that the ideal region would be China.

According to the United Nations, since the mid-2000s China has built the world's largest in-use cement stocks (the amount of cement embedded in existing buildings and infrastructure), with 80% used within its buildings (Figure 4.5).[240] There, concrete is used where lower carbon materials would have sufficed because of an established supply chain and infrastructure.[241] Should bio-based materials be so readily available as concrete, many of their buildings under 12 stories could shift to these new assemblies, bar the foundations.[242] The current rate of recycling waste concrete in China is less than 5%, which is lower than other developed countries, but research in its potential is gaining traction.[243] Due to the reduced compressive strength of recycled concrete aggregates in comparison to OPC, their use has been restricted to specific applications – most notably for this thesis, this includes the creation of non-structural concrete blocks.[244]

China is also – by a wide margin – the largest producer of oyster mushrooms in the world (Figure 4.6).[245] It already has the existing growing facilities, materials and expertise to mass produce oyster mushrooms commercially. With some adjustments to include the transfer of inoculated substrate to formwork and heat-ceasing completed panels, these factories could potentially be adapted to producing mycelium-based composites. This thesis proposes that the production of this hypothetical ICMU take advantage of both the recycled concrete block and oyster mushroom production facilities that currently exist in China. Localizing production to a region that has both the supply and demand for the product also reduces the embodied carbon of the materials – there are lower transportation costs associated with gathering and delivering them, as well as minimal construction of new facilities to accommodate specialized production methods.

The final sustainability concern that arose from the study of ideal policies and philosophies was from the "Seven Generations" Principle. Too often materials are designed with no thought for their life-cycle. From the perspective of sustainability, there appear to be a handful of acceptable options for the end-of-life handling of a material. They could be designed for disassembly and reuse (e.g. steel structure), designed for planned obsolescence (e.g. biodegradable MBCs) or they could be designed to be recycled (e.g. recycled concrete). In the case of this thesis project, the direction is unclear. The two materials individually have different end of life trajectories – mycelium can not be recycled in the same way as concrete, and concrete does not biodegrade. Designing the blocks to be infinitely reusable is not feasible, as while the full life expectancy of MBCs is unknown, they are not likely to extend past the life of the building they are designed for. The blocks could potentially be designed to separate the materials from each other for individual disposal, but that process would be finicky, time consuming and ultimately unworthy of the effort. Failing these options for sustainable disposal, the combined product must then follow the unsustainable path and be demolished and transported to a landfill. Since it did not rise to the goal of the "Seven Generations" Principle, it should be the aspiration of its production that it recycles as much waste as it produces.

240 United Nations Environment Programme, "Building Materials and the Climate," 42.
241 United Nations Environment Programme, 43.
242 United Nations Environment Programme, 43.
243 Wang et al., "Experimental Research on the Performance of Recycled Waste Concrete Powder (RWCP) on Concrete."
244 Zhan, Poon, and Shi, "CO2 Curing for Improving the Properties of Concrete Blocks Containing Recycled Aggregates."
245 Aditya et al., "Comprehensive Review on Oyster Mushroom Species (Agaricomycetes)," 2.

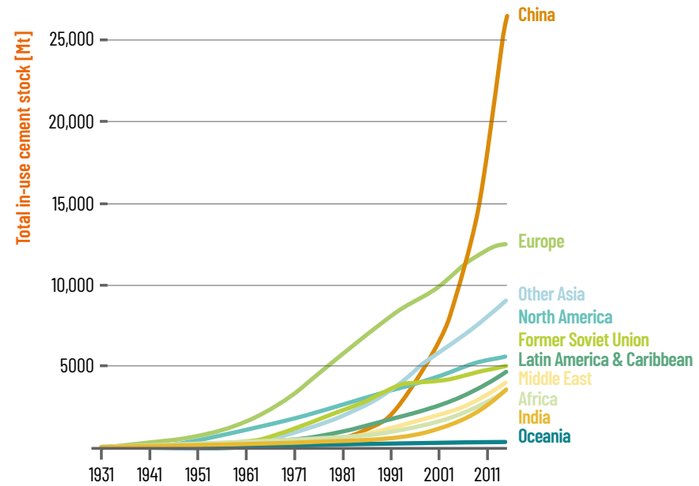


Figure 4.5: Total in-use cement stocks, by region, 1931-2014.

Source: United Nations Environment Programme (2023)

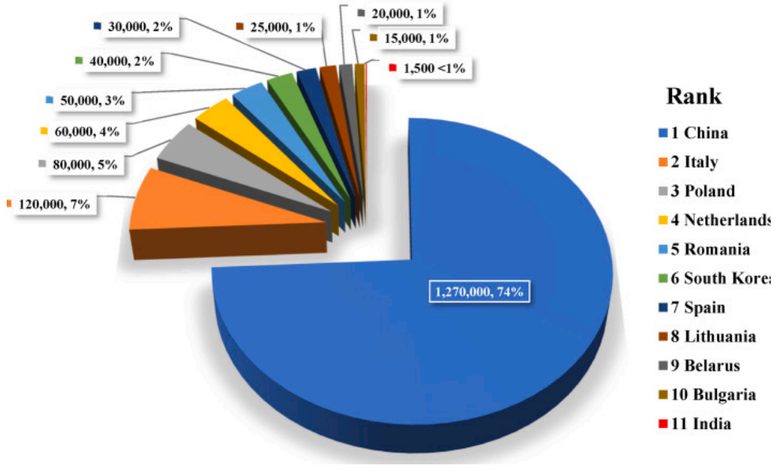


Figure 4.6: Global oyster mushroom production share (tons).

Source: Aditya et al. (2024)

4.4 Final Design

Having established Insulated Concrete Masonry Units as the base product for the recycled concrete and mycelium-based composite hybrid (RCMBC), as well as the region of its production, the last phase of this thesis was to propose a final design and production strategy. China has a restriction on the use of recycled concrete aggregates in structural capacities, which limits the use cases of the product to partition walls. Given the goal of combining these materials was to allow their technical properties to complement each other, these properties must be reconsidered in this context. A good partition wall must be durable, aesthetically pleasing and soundproofed.

Since the base design already takes advantage of the mechanical strength and durability of concrete, emphasis should be placed on maximizing the efficiency of the mycelium-based composite's sound absorption rather than its thermal capacity. The problem with relying on the interior section of an ICMU for its acoustic properties is that it is blocked from absorbing noise by the concrete. As established in Section 2.2, concrete largely reflects sound, which is beneficial in reducing the sound travelling from one room to another to the other, however it wastes the potential of the MBC to absorb the sound on the same side as the source. This blocked access to the material can be fixed by either increasing the porosity of the recycled concrete (e.g. removing sand from the mixture to create a permeable material),[246] or by cutting slits into the block façade. The second move holds the advantage of both breaking up the flat surface of the concrete and providing direct access to the sound absorption available through the mycelium-based composite

Through this small adjustment to the design, the RCMBC product revealed itself to be an Acoustical Concrete Masonry Unit (ACMU) (Figure 4.8).[247] ACMUs are often used in schools (e.g. gymnasiums and auditoriums), manufacturing facilities or other similarly programmed and designed buildings where internal sound mitigation is desired.[248] They are designed with twin slots that open to the cavities within the unit, turning each cavity into a Helmholtz resonator.[249] The bottleneck design results in a viscous loss of sound energy at the neck, neck edges and front wall of the resonator, while the cavity results in a thermal loss of sound energy (Figure 4.7).[250] Since a Helmholtz resonator is most effective when the design is in tune with a specific noise frequency,[251] a fibrous material is often included within the cavity against the opening to aid in dampening a wider variety of noises.[252]

The RCMBC acoustical masonry unit should be designed to match these specifications to optimize noise reduction while still maintaining the standard dimensions and installation methods as a standard cavity CMU (203 x 203 x 406mm). These dimensions allow the unit to be used in any interior application where concrete blocks would typically be used, offering improved sound dampening, a subtle visual patterened texture across the installed surface and a reduced embodied carbon. Maintaining the standard CMU dimensions would help ease its public integration while maintaining the characteristics of its innovation – its low complexity, subtle implication of innovation and compatibility with existing systems.

246 Fediuk et al., "Acoustic Properties of Innovative Concretes," January 14, 2021.
247 Concrete Masonry and Hardscapes Association, "Noise Control With Concrete Masonry."
248 Concrete Masonry and Hardscapes Association, "Concrete Masonry Unit Shapes, Sizes, Properties, and Specifications."
249 Colinwell, Acoustic Masonry | Hear the Difference.
250 Komkin, Mironov, and Bykov, "Sound Absorption by a Helmholtz Resonator," 385.
251 Komkin, Mironov, and Bykov, 385.
252 Concrete Masonry and Hardscapes Association, "Noise Control With Concrete Masonry."

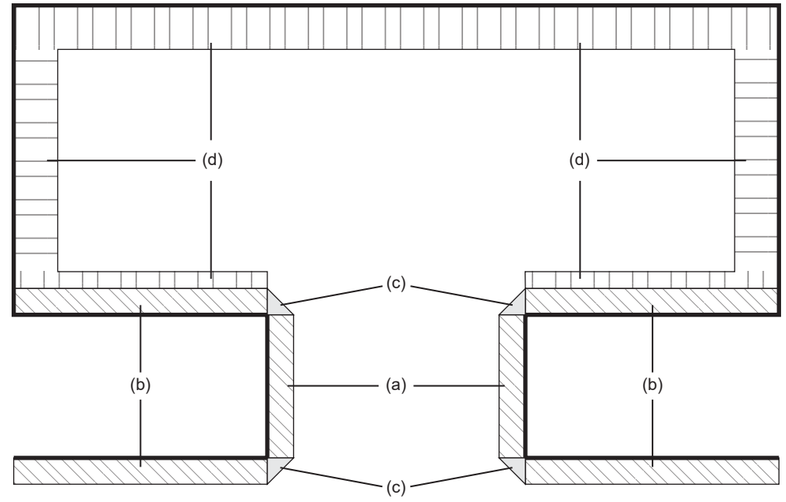


Figure 4.7: Sound energy loss in a Helmholtz resonator.

(a) viscous loss at the wall of the neck.
(b) viscous loss at the front wall of the resonator.
(c) visocous losses at the edge of the neck.
(d) thermal loss in the resonator cavity.

Adapted from Komkin, Mironov and Bykov (2016)

The production of the recycled concrete blocks and MBC acoustic panelling would need to be done separately, with the MBC panels transported to the CMU production facility to be installed within the blocks. The production process for a recycled CMU begins by mixing recycled concrete aggregate, sand and the binding cementitious materials (50% cement and 50% blast furnace slag as an alternative solution to get the best combined sustainable, mechanical and durable results from the recycled concrete)[253] with water. The mixture would then be molded in a block machine, with the slits in the façade incorporated into the reusable formwork.[254] The block machine would ensure the recycled concrete is firmly compressed and vibrated within the formwork – once compressed the masonry unit would be left to cure and harden in a low-pressure kiln.[255]

The MBC panels would undergo a similar production process as was used in this thesis. Ideally, this process would use a substrate of hardwood sawdust from construction waste (plus a nutrient such as wheat bran) as a bulk substrate, but the existing substrate formula from an oyster mushroom farm would also suffice. Once inoculated the bulk substrate would be pressed into a 203 x 105 x 38mm formwork, and the mycelium would be left to colonize in a sanitized environment for 2-4 weeks. The product would then be ceased at 180°C for 2 hours, rotating every 20 minutes. This low ceasing temperature means the oyster mushroom farm does not require an unreasonable investment in heating equipment. Following this process the MBC panels can be transported to the recycled CMU facility to be installed in the blocks. While ideally care would be taken to avoid scraping the outer layer of mycelium growth when friction fitting the materials, these sides will be pressed firmly against concrete, therefore so long as the structural integrity of the panel is not compromised, some material damage would be tolerable.

From a cost perspective, the proposed material substitutions make the RCMBC ACMU a more enticing product than a standard acoustic masonry unit. As noted above and in Section 2.1.1.2, the natural aggregates used in concrete are far more detrimental to the environment than a recycled concrete aggregate due to its intensive excavation process and subsequent transportation. This process contributes to it being a more expensive material. The opposite is true with recycled concrete – in many cases it is cheaper to recycle concrete than it is to send it to the landfill, and the resultant crush can be up to 50% less expensive than standard virgin aggregates.[256] Given that aggregate is the main ingredient in concrete, this can greatly reduce the cost of the product. A standard concrete mix will typically cost $289-300 (CAD) per cubic meter,[257] but recycled concrete goes for approximately $155.[258] Cost savings can also be found in the selected acoustic material. A material such as mineral wool can cost approximately $530 per cubic meter[259] while hardwood sawdust (the bulk material of this selected mycelium-based composite) sells for $9.55 for the same volume.[260] Of course, hardwood sawdust is not the only material required for MBC production. Buying liquid culture for oyster mushrooms can cost as much as $10 per 10cc when buying retail in Canada,[261] however considering the popularity of oyster mushroom production in China, the discounts involved in industrial bulk shipments, and the mycelium's ability to grow and develop quickly for months within a nutritious substrate, the

253 Berndt, "Properties of Sustainable Concrete," 2613.
254 Nitterhouse Masonry, "CMU Manufacturing Process."
255 Nitterhouse Masonry, "CMU Manufacturing Process."
256 recycledconcre, *3 Advantages of Using Recycled Concrete Products.*
257 Canada Building Materials, "Western Price List - Canada Building Materials."
258 Tomlinson Group, "INTERLOCKING CONCRETE BLOCKS."
259 B, "Cost of Soundproof Insulation in Ontario."
260 Malwood Sawmills, "Mulch, Shavings & Sawdust."
261 Nature Lion, *Liquid Cultures | Best Varieties Of Mushrooms.*

262 Vereb, "How to Calculate the Carbon Footprint of a Product."
263 Vereb.
264 Vereb.
265 Volk et al., "Life Cycle Assessment of Mycelium-Based Composite Materials," 2.
266 Volk et al.
267 Volk et al.
268 Jones et al., "ICE Database Educational."
269 Australia, *How to Calculate Embodied Carbon of a Concrete Mix | Fact Sheet*, 4.
270 Australia, 4.
271 Jones et al., "ICE Database Educational."
272 Jones et al.

long term cost should still remain lower than standard acoustic padding.

This paper notes that this initial cost assessment does not take into account the cost of powering concrete and mycelium production, nor shaping them into the finished product. It is acknowledged that the mycelium would require a higher labour cost in both growing the mycelium and maintaining sterile lab conditions. While the time to produce an RCMBC product would initially take more time than using standard materials due to the inoculation period, this growth can be staggered

Though great care has been taken to research, explore and develop a sustainable product, it is important to consider on a more technical level the embodied carbon of the selected materials in comparison to the standards of today's industry. In order to calculate this, the typical equation used is:

Embodied Carbon (CO_2e) = Activity Data × Emission Factor [262]

In other words, the embodied carbon of a given material is determined by the energy used over its lifetime and its emission factors, which are based on on-site fuel emissions and inderict emissions like energy and steam.[263] Some elements that can influence the activity data include the method of extraction, transportation and end-of-life disposal methods.[264] For the purpose of this material comparison the activity data will only span from cradle to gate (covering the production process).

As previously established in Section 2, a mycelium-based composite is a low carbon material. The sawdust used in the substrate is a waste material that requires no additional milling, and therefore has an insignificant environmental impact (assumed zero-burden approach for sawdust input).[265] According to a 2024 MBC life cycle analysis (LCA), the total energy required to produce a 1 kg sawdust-mycelium block is approximately 7.26 MJ, and the total emission factor calculated for that 1kg of material was 0.6417 CO_2e.[266] Comparatively, an alternative acoustic pad material like mineral wool requires approximately 13.8661 MJ to produce and holds an embodied carbon of 1.3122 CO_2e per kilogram.[267] That means replacing the acoustic pad material with mycelium reduces its embodied carbon by half.

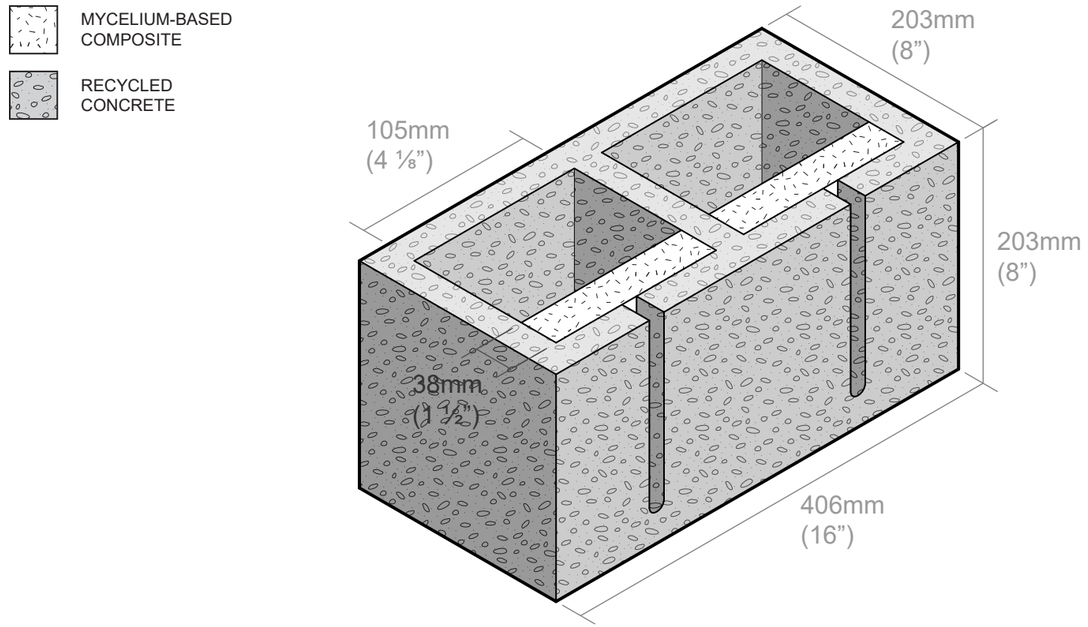
Naturally, these acoustic pads would have a minimal impact when compared to the concrete that constitutes the majority of the final RCACMU's composition. Breaking it down into their material ingredients, Original Portland Cement has an emission factor of 0.84 kg of CO_2e per kilogram[268] while fly ash has one of just 0.02 kg CO_2e/kg.[269] Course aggregates have an emission factor of 0.011 kg CO_2e/kg, which is twice the value of recycled concrete aggregates (RCA) with a factor of 0.0051 kg CO_2e/kg.[270] Looking at the finished concrete product, OPC concrete has an emission factor of 0.103 kg CO_2e/kg.[271] Substituting approximately 40% of the cement with fly ash and considering the impact of replacing a standard aggregate with RCA, the emission factor is then reduced to 0.049 kg CO_2e/kg[272] - again, approximately a 50 % reduction from using standard materials.

Overall, the material substitutions made in this final designed RCACMU would result in 50% less embodied carbon while still maintaining enough compressive force to perform practically as an interior wall. If this new product was chosen as standard for interior walls in office buildings, gymnasiums, warehouses, shopping centers, etc., this could significantly impact China's in-use cement stocks as well as improve overall experience and quality of life within the spaces they define.

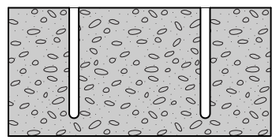
Existing products following similar specifications have been tested for the effectiveness of their sound transmission. A relevant precedent was Colinwell's EchoCheck Acoustic Blocks. Their design also consists of a recycled concrete block fitted with an acoustic pad (unspecified material). Its EC215 variant's dimensions closely match a standard cavity CMU.[273] Their blocks were tested in accordance with ASTM C423 and BS EN ISO 354:2003 to provide an average sound absorption coefficient (the rate of efficiency of a material to absorb sound) of 0.65 α.[274] In comparison, a poured concrete wall (rough) has an average of 0.05 α[275] and a standard concrete block (rough) has an average of 0.34 α.[276] This difference showcases the impact the block cavity can make on sound absorption alone, and proves ACMUs to be almost twice as effective. If it is assumed that the acoustic pad used within the EC215 has a similar sound absorption coefficient to mineral wool (0.8 α)[277], and the MBC to have an estimated sound absorption coefficient of 0.36 α,[278] then the design proposed by this thesis would not be equally as effective as what is currently available in the market. However, its use of local materials and production facilities, its low carbon footprint, environmental mindfulness and its contribution to the expansion of mycelium-based composite applications make this proposed design worthy of practical application.

The following drawings present the proposed RCMBC ACMU design and installation orientations.

273 Colinwell, Acoustic Masonry | Hear the Difference, 8.
274 Colinwell, Acoustic Masonry | Hear the Difference, 8.
275 JCW Acoustic Supplies, "Sound Absorption Coefficient Chart."
276 JCW Acoustic Supplies.
277 Scheers, Determination of the Sound Absorption of Mineral Wool, 10.
278 Walter and Gürsoy, "Sound Absorption Properties of Mycelium-Based Composites," 18.



NOTE: Designed in accordance with ASTM C90


ELEVATION
1:10

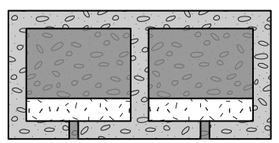

PLAN
1:10

Figure 4.8: Final Design Proposal of RCMBC Acoustic Concrete Masonry Unit.

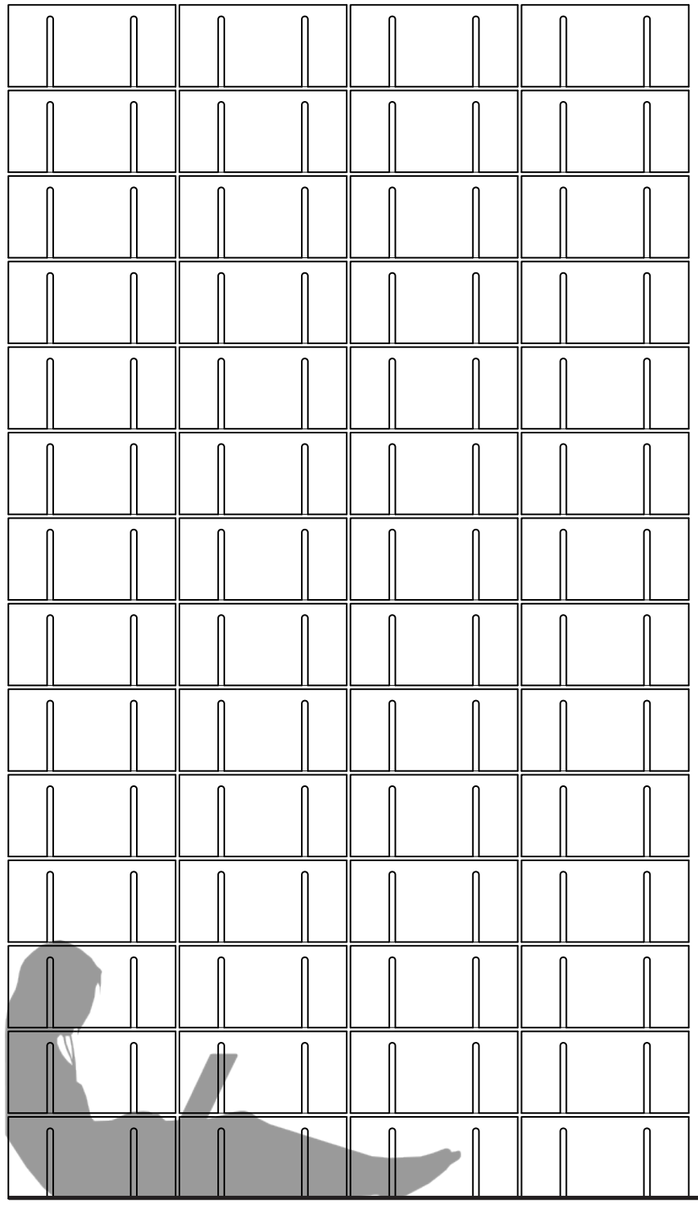


Figure 4.9: Stacked Partition Wall using RCMBC ACMU.

1:400

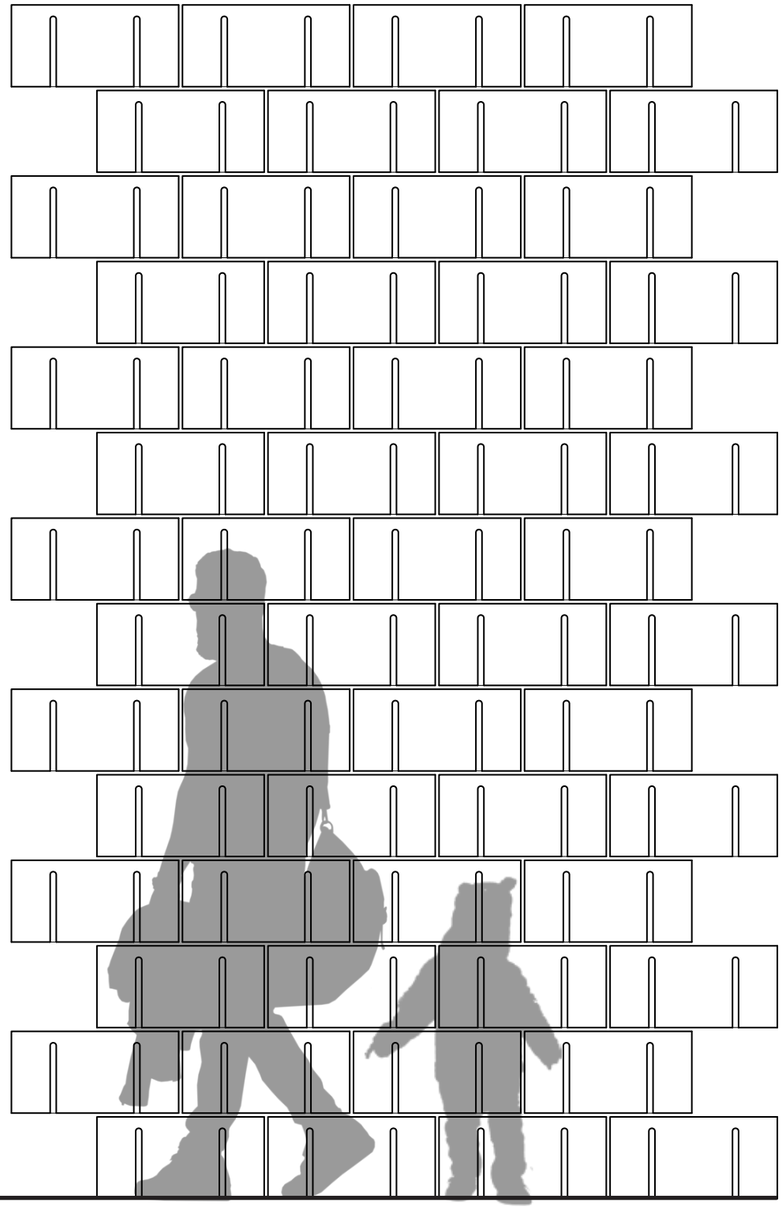


Figure 4.10: Staggered Partition Wall using RCMBC ACMU.

1:400

5

Conclusion

"As an architect, you design for the present, with an awareness of the past, for a future which is essentially unknown."

— *Norman Foster*

Through use of an integrated design methodology, this thesis was able to propose a viable sustainable product that took advantage of the strongest material properties of concrete and mycelium-based composites. By blending a holistic design approach (six principles of sustainable design), reductionist design approach (material driven design) and an exploratory approach (physical material experimentation), the idea of combining two materials on opposite ends of the sustainability spectrum was transformed from a concept to a product so plausible a similar precedent already existed in the market.

Literature Review

The first stage of the integrated design methodology served as a study of both materials for the purpose of establishing material goals for a CMBC product. By understanding the production process, innovative practices and relevant precedents, this thesis was able to identify two viable methods of material exploration – one that noted both material's reliance on formwork and another that noted the overlapping early stages of their production processes (mycelium's bi-product of water and cement's activation through hydration). The comparison of the two materials through their technical properties was difficult achieve – the properties of both materials rely heavily on their form, composition and production method. This resulted in a comparison of averages and general properties, which was useful as a reference for material aspirations and in justifying physical exploration as part of the integrated design methodology, as it sharpened expectations of what the materials were capable of. With more time, expertise and equipment, it would be useful to physically verify the technical properties for each specific studied material to better compare their strengths and weaknesses, and therefore better predict how their properties might complement each other.

A checkpoint of sustainable policies and design philosophies served as a point of reflection. Had this checkpoint been skipped, the design would have only considered sustainability from a technical perspective, discounting the larger context of the proposition. Designing for our industry's policy aspirations grounded the proposed materials in the logistics of production, and designing for the six principles broadened the scope of design from a product to an artifact that would last on this planet for several generations and thus should be considered beyond its life cycle. Should this methodology be used for future projects, the policies and philosophies could be honed to a finer point, narrowing in to ask more direct questions concerning material production and selection depending on the context of the project goal. This Section concluded with the following set of material goals that summarized the findings of the material research:

1. MBC and concrete must strike a balance between strength, durability, acoustics and thermal resistance
2. MBC and concrete must take advantage of their similar production processes to find an overlap that benefits both materials
3. Concrete use must be directed towards either 'avoiding' waste or re-using existing materials
4. Human vitality should be an underlying consideration that carries over into the design goals of the project.

Materials and Methods

This paper acknowledges that while all efforts were made to create a consistent and sanitary environment for mycelium growth, this was not studied under lab conditions and thus there is an element of human error to consider within the results of the experimentation.

The material goals noted that to effectively complement each other, concrete and mycelium-based composites must strike a balance between strength, durability, acoustics and thermal resistance, and production should emphasize reducing material waste. These goals guided the direction of material exploration into two paths: surface and form bonding and deconstructed bonding.

The results of the former proved that there was a negligible surface bond between the two materials. MBC did not have the structural integrity to act as a binder for concrete blocks, and concrete could not be used as an integrated formwork due to the MBC's shrinkage during both the drying and ceasing process. Should surface and form bonding between concrete and mycelium-based composites be explored further, it is recommended that rather than concrete acting as a formwork for mycelium-based composites, MBC should be grown and ceased, then used as a formwork for concrete to reduce the disparity in shrinking.

The results of the deconstructed bonding exploration revealed that cement, either dry or hydrated, does not work to strengthen mycelium-based composites. Inoculated substrate can grow to form a hybrid material around recycled concrete at a 2:1 ratio. The size of the recycled concrete impacts the structural integrity of the combined material, with a range of 3/8 – ¾" being ideal.

Under compressive forces, this combined material proved weaker than a standard MBC when handled due to the aggregate compromising the sample's structural integrity. When the sample remained intact, its compressive properties were similar to a standard MBC and the recycled concrete aggregate was therefore ineffective in providing additional strength and durability to mycelium-based composites. This study would benefit from greater access to lab equipment, firstly to ensure more consistent results between the first and second samples of the same material composition, and secondly for access to more accurate measurement tools. The machines used to measure compressive resistance were designed for concrete and therefore offered less accuracy when handling more delicate materials like MBC.

The sound absorption of a standard mycelium-based composite is greater than that of the combined recycled concrete and mycelium-based composite material. The test for acoustic properties would greatly benefit from a noise isolated environment and specialized equipment. The results gained from this thesis did serve as a guideline to determine what general strategies should be carried into product design. These findings were summarized as set of design goals:

1. Mycelium-based composites should be left without additional aggregates to maximize their structural, thermal and acoustic properties.
2. Mycelium-based composites should be grown in isolation as either a panel or a block to maximize the amount of external mycelium growth.
3. Concrete should act as a continuous support for the mycelium-based composite without intersecting it
4. Concrete should use its durability to protect and/or encase the mycelium-based compi, which is vulnerable if the substrate is exposed beyond the exterior mycelium layer.
5. The connection between the two materials should not rely on a surface bond.
6. Human vitality should be an underlying consideration in the reception and use of the product (carried over from Material Goals).

Design Proposal

Using *The Theory of Diffusion of Innovations* and The Five Material Characteristics of Innovation, the ideal base product for a concrete-mycelium material combination was determined to be an Insulated Concrete Masonry Unit (ICMU). A secondary reflection on policies and philosophies led to the conclusion that recycled concrete should be used as the base material for the masonry block, and to the discovery of China as an ideal location for the production of a recycled concrete mycelium-based composite (RCMBC) product – China has the largest in-use cement stocks in the world while also being the largest producer of oyster mushrooms. This thesis proposed the design adhere to China's use restrictions on recycled concrete, and therefore it could not be used for structural applications. The ideal application for the combined material was determined to be a partition wall.

Translating the qualities of both materials to a partition wall through the form of an ICMU led to the design of an Acoustical Concrete Masonry Unit (ACMU). This design highlights the strength and durability of concrete, a sustainable production methodology that takes advantage of existing local facilities, and a consideration for human vitality in both its form and function. The product was designed to match industry standards for a CMU to better integrate it into the existing market and installation processes that are already prevalent in the country.

Reflection

The goals of this thesis were to:

1. Represent a bridge between the past and future of the construction industry and serve as a platform for further discussion on the role of embodied carbon in the climate crisis.
2. Determine if this combination can blend the strongest technical properties of both materials and provide more structural integrity to MBCs.
3. Introduce an integrated design methodology to develop a product design based on the discoveries in goal (2) that is both practical and sustainable.

By continuously intersecting reflections on ideal policies and philosophies throughout a technically focused reductionist design methodology, this paper took a relatively unconventional approach to material exploration. It is the hope that this work might then encourage similar moments of reflection in other industry professionals that encounter it, as it is only through challenging rules of thumb that any meaningful changes can be made.

This thesis was not successful in increasing the mechanical strength of MBC through concrete; it was successful in proposing a practical application of the combined materials. Through strategies that include using local materials and production facilities, recycling as much waste as it produces and working to service human vitality, the final design of a simple ACMU is one that embodies all the principles of sustainable design.

There is much to reflect on in the design of the product itself. While the integrated design methodology was efficient at quickly narrowing potential material applications to the best use case, it was a creatively stifling process to funnel the materials through like-products for the selection of a pre-made design template. It may have been more interesting to instead deviate from this stage and instead base the final design directly from the lessons learned in the research and material exploration phases. In this way scale and material ratios could have been explored more abstractedly, leading to a more thought-provoking application that may have more efficiently communicated the metaphor of the coming together of the two opposing materials.

While this method would be more difficult to justify as a practical addition to the construction industry, and perhaps even difficult to justify sustainably, this extra push for creativity and innovation would have matched the energy required to spark new and engaing conversations about the practicality of organic materials and the controversial role of concrete. In comparison to what may have been born of this deviation, the final design presented in this thesis comes across more as an answer to an oversimplified equation, and while this answer is valid, practical and easily applicable to real world scenarios its solution does not engage with the research and exploration to the extent originally envisioned at the start of this project.

Research Outlook

The ambitious scope required by a holistic approach to design resulted in defining strict limitations to ground the study of the two chosen materials. These materials were limited to only one strain of mycelium, one type of substrate, and one type of concrete (newly produced and recycled). Mycelium-based composites were limited to one method of production, though access to a heat-press would have allowed for more ambitious explorations of the relationship between the materials. Should these two materials continue to be explored with an expanded scope, the proper lab equipment and time, this paper recommends the following research directives.

Staying within the parameters of this thesis' exploratory studies and beginning with studying surface and form bonding, it would be beneficial to vary the scale of the interlocking form of the concrete to better determine how that impacts the bond of the mycelium-based composite within the resulting block. The openings in this study ranged from 4-6 cm, therefore it is recommended to use concrete blocks with interlocking forms/openings that range from 1-3 cm and 7-10 cm. Rather than using a mushroom grow bag, the blocks should be placed within an acrylic formwork before the MBC is added. Specialized tools may be required to incorporate mycelium within tighter spaces. Once the final blocks are produced, they should be studied at both a macro level (through shear testing the materials to accurately document the impact of this change) and a micro level (by using a microscope to analyse to what degree the mycelium transferred from the substrate to the concrete, and whether different surface shapes and textures might encourage futher growth).

Deconstructed bonding requires further physical testing of both standard sawdust based mycelium composites and composites with a recycled concrete aggregate. The aggregate size should be scaled in proportion to the size of the grow container, with enough space for the innoculated substrate to envelop and secure the concrete. The sample size should be expanded to at least 6 successful samples of each material, and each should be compressed at the same right on an a more sensitive machine. These samples should also be studied on a microscopic level to determine the strain within the inoculated substrate as well as between the mycelium and the concrete. This data should then be transferred to a digital model and simulation of the compression experiments to replicate the discovered behaviour and strength of the materials and then expand on them to explore the efficiency of the material at different scales and forms.

If the research were to be expanded beyond the scope of what was presented in this thesis, it is recommended for future studies to explore which mycelium and substrate combinations provide the strongest natural bonds, then further this study in combination with concrete at various production stages. This can include casting concrete on the MBC and/or binding thinner concrete shells with MBC. Exploring the relationship between concrete and heat-pressed mycelium (which has a wood-like texture) is also recommended. Future research should also explore alternative concrete recipes and production strategies. This includes cementitious alternatives to cement, permeable concrete (this has the potential to be infused with a mycelium-infused paste) and lightweight concrete (this is better suited for binding with MBCs).

More practically, furthering the research of this thesis should focus on applying this same integrated design methodology to other biomaterials – it is crucial that the construction industry recognize the growing crisis of embodied carbon in our building materials, and work to find new low-carbon strategies that can be integrated into our existing system.

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