A SUSTAINABLE ALTERNATIVE TO ARCHITECTURAL MATERIALS: Mycelium-based Bio-Composites

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Abstract: In the history of architecture, technologies adapted from other disciplines have created new paradigms for design and production. During the first Industrial Revolution, for instance, developments in mechanical and material engineering, and the introduction of wrought-iron, steel, and concrete, led to revolutionary changes in architecture. In the nineteenth and twentieth centuries, electrical engineering and electronics had a similar groundbreaking effect on architecture and design. It seems that regarding the necessities and problems that exist in the 21st century, such as dependency on fossil fuels for construction that lead to carbon emission, the abundance of solid and liquid waste and unjustifiable costs, another change in the paradigm of construction is required. One possible way to address these issues is to return to nature and take advantage of biomaterials. This research studies the integration of mycelium-based bio-composites into the field of architecture. Mycelium is the vegetative part of mushrooms by which they absorb nutrients from the soil. When treated, mycelium results in a foam-like composite material that is lightweight, and biodegradable. Over the past couple of years, designers started to use mycelium-based composites in several applications ranging from product design and furniture to building panels and masonry blocks. In this research, the aim is to explore novel methods to use mycelium-based bio-composites in temporary and/or low-rise constructions. The focus of the research is on enhancing the material properties by investigating the factors that affect the nature and growth of the cultivated mycelium-based bio-composites and exploring novel structural systems based on the constraints and affordances of mycelium-based bio-composites, using computational form-finding techniques, generative design and optimization methods. In this paper, the initial incentives for conducting the research and the proposed methodology are discussed.

Keywords: Biomaterials, bio design, mycelium, bio-composites, masonry

INTRODUCTION

Material thinking is important for architecture, as it is through materials that design ideas are converted to physical artifacts. This process requires accessible, cost-effective and sustainable solutions. The industrialization of materials initiated three revolutionary changes in architecture during the last centuries, towards a less sustainable building industry. In the 18th century, the invention of the steam engine allowed people to use machines as their agents for the industry. During the last decades of the nineteenth century, the use of electrical power initiated a second change, and in the mid-twentieth century, the invention of computers and digital technologies revolutionized the industry for the third time (Hebel and Heisel 2017). After the industrial revolution, the main structure of buildings changed from masonry to steel frame after mass production of materials, such as concrete and steel, afforded the possibility to raise taller buildings thanks to the invention of mechanical tools like pumps and elevators.

Industrial solutions for architecture, engineering and construction (AEC) cannot change the method of thinking and only modify traditional ways temporarily. They may provide a remedy for problems of the current century such as air pollution, global warming and landfill waste. However, architecture requires a shift to be reactive and to adapt to the environment. Materials, as the backbone of the AEC industry, would play a critical role in this shift. The current approach of production, utilization and disposal can be shifted to production, utilization, recycling and reutilization. Nature provides optimal and sustainable answers using limited resources. Therefore, researchers from biology, material science, as well as designers and architects can collaborate to explore ways to convert materials from nature to the building industry for more sustainable alternatives.

This paper first presents a background study on biomaterials in architecture, specifically focusing on mycelium and its applications in design and architecture. Then, the proposed methodology for the Ph.D. study to integrate mycelium-based bio-composites to architecture is presented.

1. BIOMATERIALS

1.1. BIOMATERIALS IN ARCHITECTURE

Park and Bechthold (2013) suggest that the fourth revolutionary change in the building industry may happen soon with a return to nature. According to Flynn (2016), such a shift in architecture, to what she calls "living architecture" requires modern thinking and technologies. Nature's answer to the problem of materials is the use of biomaterials. Biomaterials are materials derived from living organisms whose mechanical properties are often outstanding, in comparison to the weak constituents from which they are assembled (Zolotovsky 2018). These materials are generally sustainable because they use little amount of energy to perform their function and produce the least amount of waste (Vincent 2012). However, there are some challenges for utilizing biomaterials in the building industry: They require processing, as many of them cannot be used as raw materials, and their large-scale applications are still underdeveloped (Derme et al. 2016). To develop biomaterials for the built environment, novel technologies that can enhance their properties with the least modification needed in their natural behavior are required. The methods used for developing matter to be used as bio-based materials are different: some require ordinary processes such as baking, molding and mixing, while others will require more radical ones like cultivating, breeding, raising or farming (Hebel and Heisel 2017). Girometta et al. (2019) consider materials that contain at least one component that is biologically produced and that are completely biodegradable as bio-based composites (Girometta et al. 2019). These materials are usually durable, with superior mechanical properties, generated by "soft living tissues" (Zolotovsky 2018). The most important features of biomaterials are their multifunctionality, hierarchy, and the ability to self-assemble and self-heal. Motivations to integrate bio-based materials with design and architecture arise from the fascinating opportunities for diverse forms of expressions that can be achieved, and the possibility to reimagine the paradigms of production towards more sustainable solutions (Karana et al. 2018).

1.2. CLASSIFICATION FOR BIOMATERIALS

Materials in this area can be categorized according to their operating system. Some materials are used in the process of fabrication and when the project is finished, they are killed or at least, hibernated. The other set of materials respond to the environment after the production and behave as a part of the living body and an element of final architecture. The last group is the ones that are full of living organisms interacting with the environment and reacting with stimuli, activating the architecture completely. In literature, these three groups are called "bio-based materials", "bio-responsive materials" and "bio-active materials," respectively (Zolotovsky 2018; Lu et al. 2016). For example, bacterial cellulose (figure 1-A), crustacean-

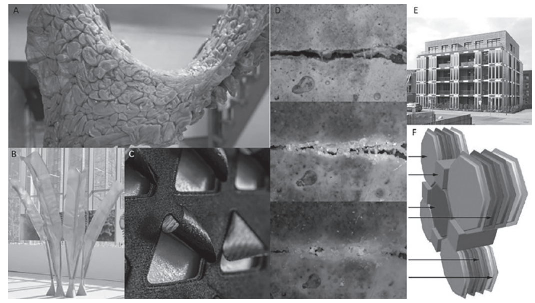

Figure 1: A. Structure made of bacterial cellulose (Derme et al., 2016), B. Structure made of crustacean polysaccharides (Mogas-Soldevila et al., 2015) C. Sweat-reacting bio-actuators (http://digicult.it), D. Self-healing bio-concretes (Delft University), E. BIQ house (http://thenextgreen.ca) and F. Water walls concept (Cohen, Flynn, and Matossian 2012)

based polysaccharides (figure 1-B) and wood foam can be mentioned as instances for "bio-based materials." Living bio-actuators (figure 1-C) and self-healing Bio-concretes (figure 1-D) are examples of "bio-responsive materials." BIQ House (figure 1-E) and PBR façade that use algae in their envelope, Living Architecture blocks and Water Walls (figure 1-F) that use microbes and algae to purify air and water and to generate electricity, fall into the category of "bio-active materials."

2. FUNGAL SOLUTION

One of the natural matters that can be cultivated and can substitute current construction materials is mycelium-based bio-composites. Mycelium is the root network of fungi, a fast-growing matrix that acts as a natural binder consisting of *hyphae*. It consumes organic waste and produces biodegradable bio-composites. Mycelium-based bio-composites have been explored particularly to produce new materials for packaging, thermal and acoustic insulation and a broad variety of design objects and furniture. Scholars from several disciplines, such as mechanical and industrial engineering, industrial design, chemistry, and biology, have conducted research on this new material, however, there is little literature on the use of mycelium-based bio-composites in the AEC industry. The purpose of current research is to assess the abilities of mycelium and the opportunities it offers for conversion to the architectural context as a building material, and to define frameworks for using this new bio-derived material in this field.

2.1. MYCELIUM

Mycelium is the vegetative part of fungi made of a mass of hyphae. Hyphae is the long, branching filamentous structure, acting as the growth agent in fungi. Each hypha consists of one or more cells which advance the growth process by division and has an average diameter of 4-6 micrometers. Mycelium, with enzymes secreted from hyphae, break down the biopolymers to simpler bodies and then absorb them by active transport, which is an action at the cellular scale of living organisms to digest carbon-based nutrients. This process lets the hyphae grow out of the substrate into the air, creating a "fluffy or compact layer covering the substrate, called fungal skin" (Appels et al. 2019). Thus, fungal colonies made of mycelium can be found inside or on the surface of organic substrates such as soil, sawdust, paper and any other carbon-based matter. The primary uses of mycelium in nature are related to its ability to decompose organic waste, due to the existence of carbon in organic matter.

The filamentous mode of growth in mycelium leads to colonization of substrates and provides a large surface to volume ratio resulting in better uptake of nutrients. Complex structures in organic waste such as wood, straw, and hemp must be degraded into smaller and simpler ones, before being able to be taken up to serve as an energy source. For this purpose, fungi, through the hyphae, secrete a multitude of enzymes (Wösten 2019). This feature of mycelium enhances biodegradability. This is of high importance for industrial production. In the current era, with rapid population growth, intensified agriculture, and industrialization fast and low-cost manufacturing processes lead to constant growth of production, consumption, and accumulation of waste. Alternative building materials that are biodegradable and derived from renewable resources are valuable (Attias et al. 2017), and mycelium is a potential alternative.

2.2. MYCELIUM-BASED MATERIALS

There are two main groups of mycelium-based materials: Pure mycelium and mycelium-based bio-composites. Pure mycelium is the result of complete degradation of the substrate. It is also obtainable by "removing the fungal skin from the substrate" (Appels et al. 2019). Mycelium-based bio-composites, on the other hand, are the result of hibernation or killing of mycelium in its growth process. During colonization of the substrate, fungal growth can be stopped by drying or heating the material. Drying the mycelium, leads to its hibernation which means the fungi is ready to restart growth when environmental conditions allow it and heating will stop the fungi growth permanently. The result of either of these processes is a mycelium-based bio-composite. During the growth process, the fungus cements the substrate, which is partially replaced by the tenacious biomass of the fungus itself. Composites can be shaped to produce insulating panels, packaging materials, bricks, or new-design objects (Girometta et al. 2019). The properties of both pure and composite mycelium are dependent on the fungal species, substrates, growth conditions, processing of material, and the additives (Jones et al. 2017; Appels et al. 2019).

Existing literature about the tests conducted on the mycelium-based materials (Appels et al. 2019; Bruscato et al. 2019; Sun et al. 2019; Ghazvinian et al. 2019; Zhang et al. 2019; Yang et al. 2017; Attias et al. 2017; Haneef et al. 2017; Islam et al. 2017) shows how the conditions of cultivation, hibernation/killing, molding, and the characteristics of species and substrates used to affect the results. The consensus about the characteristics of mycelium-based materials is that they have a relatively low density compared to plastics, relatively low compressive strength compared to conventional masonry materials, lack of strength in tension and dependency on the curing process for durability and appearance. The most important feature of this material is its biodegradability. This feature allows the mycelium to fulfill the principle of the circular economy, which requires waste materials to re-enter into a production process rather than being discarded, and the final product must be combustible or compostable (Girometta et al. 2019).

2.3. MYCELIUM-BASED MATERIALS IN INDUSTRIES

Mycelium has been used for more than a century as versatile and highly productive cell factories. It means; they are used to produce enzymes and small molecule compounds, such as antibiotics and organic acids (Wösten 2019). Early explorations in the use of fungi as biomaterials began during the 1990s by the Japanese scientist Shigeru Yamanaka, who explored using mycelium to produce paper and building materials (Girometta 2019). Then, Stamets (2005) proposed using mycelium to filtrate and purify soil and water from microorganisms and chemicals by mycelial mats. In recent years, scholars and industrial teams started using mycelium in product design, fashion, and architecture.

Companies MycoWorks[1] and Mogu[2], using pure mycelium, started to produce synthetic leather to replace animal leather for sustainable purposes (figure 2-A). The synthetic leather derived from mycelium is flexible, durable and waterproof, and thus can be used to form several shapes such as belts, shoes, wallets, and other accessories in fashion the context. Ecovative[3], the first start-up company (established 2007) designated to research the utilization of mycelium in industry, in a collaboration with Dell[4] and some wineries around the US, started to produce cushions of mycelium to protect hardware and wine bottles in their delivery services to reduce the impact of plastic packaging on the environment (figure 2-B). The project, "Future of Plastics"

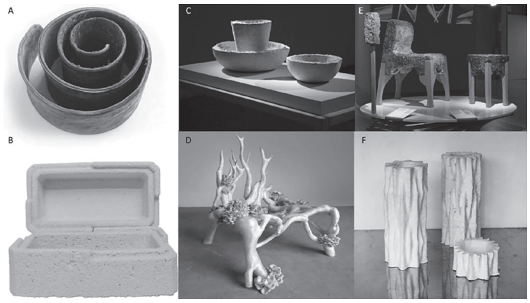

Figure 2: A. Synthetic mycelium-based leather (http://mycoworks.com), B. Mycelium-based foam packaging (http://ecovative.com), C. Mycelium-based kitchenware (http://corpuscoli.com), D. Mycelium-based furniture (http://ericklarenbeek.com), E. Mycelium-based furniture (http://thisisalive.com) and F. Mycelium-based vases (blast-studio.com)

by Officina Corpuscoli[5], proposed utensils made of mycelium to be used and then biodegraded (figure 2-C). Living Studio[6] proposed using mycelium to cultivate fungal cutlery, as a substitute for disposable plastic cutlery, that can be composted after use. Companies like Krown[7], Terreform One[8], Balst studio[9] and GenSpace[10] started to produce light, and biodegradable furniture using mycelium-based bio-composites. Product designers Phil Ross, Erik Klarenbeek, and Jonas Edvard also make use of mycelium as part of their furniture designs (figure 2-D, E, F).

Regarding the characteristics such as efficient insulation performance, fire-resistance, and air purification, mycelium-based materials are proposed to replace chemical, petroleum-based materials used for insulation in buildings (figure 3-A). Companies Mogu and Biohm[11] are pioneers in this path. They argue that their method can reduce the environmental impact of the construction process and carbon footprint. Mogu introduced wall and ceiling panels with mycelium, that are either bare or covered by resin-like coatings to be used as insulators on the building envelope.

Beyond the mentioned uses of mycelium material, efforts have been made to also use mycelium as *skeleton* in architecture. One of the most well-known works in architecture where mycelium is used as a building material, is the Hy-Fi Tower designed by David Benjamin from Living Studio[12] and engineered by ARUP[13] (figure 3-B). The tower, designed and built as part of MoMa PS1 2014, was 13 meters in height. It was made from approximately 10000 mycelium bricks that were derived from the fungal products of the company Ecovative. After hosting events in MoMa PS1 2014 for three months, it was disassembled, broken and mixed with soil to be composted. This project shows the durability, resistance and workability of mycelium. Phil Ross, an artist from MycoWorks, in his Mycotecture pavilion (figure 3-C), also used mycelium-based bio-composites as bricks. The pavilion is small-scale, and functions as a teahouse. In another project, Block Research Group[14] designed and built MycoTree, a spatial branching structure, using mycelium-based bio-composites (figure 3-D) that were shaped using special molds designed by a 3D graphic statics method. The intention in this project was to find forms that allow the material to bear compression-only loads because mycelium-based bio composites have better load bearing capacity in compression. In other words, using computational form-finding methods, they compensated weaknesses of the material for structural use (Hebel and Heisel 2017). The pavilion was designed for the 2017 Seoul biennale of architecture and urbanism. The Shell Mycelium by Yassin Areddia and Beetles 3.3 was another effort to use mycelium for designing and building a pavilion (figure 3-E). Their intention was to show mycelium as a reliable substitute for concrete in small-scale and temporary construction projects. Pointing on unused stadiums and pavilions built by concrete for events such as exhibitions and Olympics, they designed and built the pavilion for Kuchi Muziris Biennale 2016 in India. In another innovative application with mycelium, modular columns were designed and cultivated (figure 3-F). Also, minimal surfaces were formed by mycelium cultivation (figure 3-G). These experiments were proposed to explore the formal possibilities for mycelium-based materials (Gruber and Imhof 2017).

More recently, Perkins and Will Research Group[15], in their Tactical Mycelium exploration (figure 3-H), inspired by the Tactical Urbanist's Guide to Materials and Design, both borrowed the organic, iterative process of these projects and offered mycelium as "an alternative biomaterial for the future tactician's palette". Inspired by Antoni Gaudi's technique to build catenary arches, Carlo Ratti[16], in collaboration with Krown Biolab researchers, has grown a chain of 60 four-meter-tall arched structures with mycelium for the Milan Design Week (figure 3-I). These arched structures were grown in a six-week period to construct an archway around the Orto Botanico di Brera botanical garden in Milan and after the exhibition, were shredded and added to the soil as compost. Lastly, the Growing Pavilion (figure 3-J), designed by Pascal Leboucq in collaboration with Erik Klarenbeek as an event space is constructed with biomaterials. Among these materials, the external façade is made of panels grown from mycelium. The panels are attached to the timber frame of pavilion and can be removed and repurposed after utilization.

The studies, tests, and experiments on mycelium are currently in advance to explore other opportunities this natural material can offer for a better environment

Figure 3: A. Mycelium-based wall panels (http://mogu.com), B. Hy-fi tower (http://arup.com), C. Mycotecture Alpha teahouse (http://glasstire.com), D. Mycotree pavilion (http://block.arch.ethz.ch), E. Shell Mycelium pavilion (http://asianpaints.com), F. Mycelium-based columns (Gruber and Imhof, 2017), G. Mycelium-based minimal surface (Cruber and Imhof, 2017), H. Tactical Mycelium monolithic structure (http://jdovaults.com), I. The circular garden (http://carloratti.com) and J. Growing pavilion (http://thegrowingpavilion.com)

and future. The most important part of work with mycelium is to find out how mycelium-based materials' mechanical and chemical properties can be enhanced, and how they perform in long-term use, especially in an architectural context, under potential fatigue and humidity threats.

3. PROPOSED STUDY

In this research, the aim is to explore novel methods for using mycelium-based bio-composites in temporary and/or low-rise constructions as potential substitutes for conventional masonry construction materials. Based on the existing literature, in order to use mycelium-based bio-composites as alternative construction materials, their load-bearing capacity needs to be improved. This can be achieved by two different approaches. The first approach is to enhance material characteristics of mycelium-based composites through material cultivation processes and the second is to design structural systems based on the constraints and affordances of mycelium-based bio-composites using computational form-finding techniques, generative design, and optimization methods.

The first part of this research investigates the role of growth process for enhancing material features. Since material properties of mycelium-based composites depend on several factors, including the species of fungi and types of organic substrates used in cultivation, time and environmental conditions of growth, and the way its growth is ceased, a series of systematic tests is planned to analyze mechanical strength, in addition to the durability and environmental stability of the cultivated samples. Several samples of mycelium-based composites will be cultivated to identify the growth parameters that have a direct effect on the load-bearing capacity of the composites.

In the second part of the research, the aim is to develop digital models for compression-based structural systems based on the constraints and affordances of mycelium-based bio-composite samples that are cultivated. Using computational structural form-finding (i.e. thrust network analysis, 3D graphic statics, generative shape grammars) and simulation methods (i.e. finite element analysis), the aim is to design and cultivate/fabricate/build a series of physical prototypes in various scales using mycelium-based bio-composites and advanced computer-aided manufacturing technologies.

4. METHODOLOGY

4.1. CRITICAL REVIEW OF LITERATURE

The initial step in order to define methodology is to study the literature. A critical review is needed to identify the nature of the material and the characteristics that make it suitable for architecture. The works done in other disciplines such as mechanical and industrial engineering, industrial design, and biology, as well as design projects that use mycelium-based materials are studied. In addition, the literature related to the techniques used in architectural prototyping, design and making approaches, strategies for integrating new materials to architecture and their ability to be used for mycelium-based bio-composites are reviewed. The review resulted to define a framework for the research.

4.2. FRAMEWORK

Since biomaterials are made of living agents, both the cultivation process and the outcome are not fully predictable (Karana et al. 2018). To tackle this uncertainty, in parallel to the fulfillment of the requirements of a material, a feedback loop is needed. The feedback loop allows the researcher to cope with uncertainty. In order to explore the use of new materials in an architectural context, a recursive study among different parts of the research is necessary because 1) material explorations will inform form-finding and

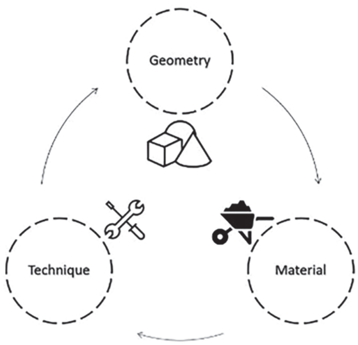

Figure 4: Trifold cycle of recursive study. (Author 2019)

simulation, and 2) changes in the material production may be necessary to improve material properties based on the findings of form-finding, simulation and prototyping stages.

The method of research can be illustrated by a three-stage cycle including material study, fabrication technique and geometric form-finding process (figure 4). This recursive process generates several alternatives for using a specific material with a technique to design a form and produces options for evaluation. By studying the material, the initial properties can be assessed, leading to identify the techniques capable of being used for the material and geometries that are possible. Then, in the fabrication stage, some more properties can be shown, such as workability. The results of fabrication addresses the pros and cons of the material, so it can be enhanced for better utilization and more design and manufacturing options.

4.3. MATERIAL EXPLORATION

The first stage of the research is material exploration. According to the nature of mycelium, the material study consists of the cultivation process and physicochemical, mechanical and environmental experiments. Several parameters in the cultivation process of mycelium-based bio-composites affect the product properties, such as species, substrates, supplements, environmental conditions, and curing processes (figure 5). In the material exploration stage, by systematically changing these parameters and conducting experiments, the desired material alternatives can be explored. One important remark about this stage is that while existing literature is informative, their results are not reliable enough for architectural use. Therefore, conducting material experiments is one of the crucial parts of the methodology.

Species of fungi used in cultivation directly influence the features of the product and the time and conditions of cultivation. More than 30 species of fungi

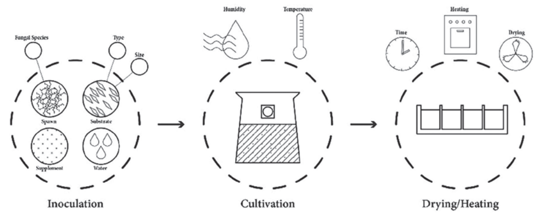

Figure 5: Influencing factors on mycelium-based bio-composites growth (Ghazvinian et al. 2019)

have been studied by scholars for producing mycelium-based materials, pure or composite, in recent years. The most influential factors for choosing the species are their availability, their growth rate, and their growth type. As a sustainable substitute for conventional materials, one of the most important factors for this material is its local availability. Transferring mushroom spawns for growing non-local species is not ideal, as there are two potential problems, namely contamination and change in the growth process due to changing the environment. Other factors related to the growth process are significant, as they optimize the time of cultivation and the texture and density of the product. For example, different hyphal types in fungi by which the species exhibit different systems of branching, lead to different structures for mycelium-based bio-composites.

The type and structure of substrates, the main part of the composites, affect the physicochemical and mechanical properties of the outcome. Substrates provide nutrition for fungal growth: The richer the substrate, the better the outcome of cultivation process. Again, one of the main criteria in choosing substrates is their availability and accessibility, without harming other industries. Researchers in this area have studied the effect of type, size and differences between dense and loose packed substrates on the characteristics of mycelium-based bio-composites. One other effective factor is the additives used with the substrate. Adding fibers to reinforce the substrate or nutritious supplements for increasing the amount of carbon and nitrogen for growth are instances of additives. Like the mixtures for concrete, mixture of mycelium species, substrate, water and the nutrient chosen for feeding the mycelium can change the features of mycelium-based bio-composites.

Environmental conditions of cultivation need to be studied as well, since it is crucial for changing the scale of production. To cultivate an integrated composite, with no fruiting bodies and empty cores, controlled conditions are needed. In smaller scales, chambers can provide a controlled environment, however, in larger scales, to build bigger blocks or monolithic structures for instance, a large-scale controlled environment is needed. The amount of light, humidity, temperature and existence of contaminant agents need to be controlled.

The drying/heating step and the curing method are also of high importance to the properties of the outcome. The length of the drying/heating process influences the degree of growth for mycelia, affecting the density and texture of the outcome. Pressing the composite, either cold or hot, increases the density and probably the compressive strength of the product. The finishing of the product is also affected by this step of the work, white-rot fungi produce white products that, after pressing, may change to a gradient of grey to brown.

In the material exploration stage, experiments for identification of mycelium-based bio-composites as an architectural material can be divided into four major categories:

1. Physiochemical properties: Chemical structure, density, buoyancy, pH, finishing color, and other physical and chemical attributes of the material, which let the designers know the extent of the environment in which this material can be used and narrow down the line of research. Methods such as thermogravimetry, scanning electron microscopy (SEM) and Fourier-transform infrared stereoscopy (FTIR) have been used to explore the structure of the materials produced by mycelium. Studying the composition of materials informs the study about the extents of application and the competitors of the product in different industries.
2. Mechanical properties: Compressive, tensile and flexural strength tests of the material are required in order to determine design and fabrication approaches. In the case of using mycelium-based bio-composites as load-bearing elements in architecture, considering their low tensile strength, only compressive structures can be built. In order to use mycelium-based bio-composites in other ways, reinforcement is needed.
3. Durability: There is little data about the durability of mycelium-based material in the literature. As a construction material, the applicability of mycelium-based bio-composites in different environmental conditions needs to be evaluated. Conducting experimental work and efforts to improve the durability of mycelium-based bio-composites, which is highly dependent on humidity, will enhance the domain of utilization of this bio-based material.
4. Insulation: In addition to the acoustic properties of mycelium-based bio-composites, heat and electric conductivity can be utilized as an important feature in their architectural use, due to the potential insulation agency. Because of their porous nature, mycelium-based bio-composites can be used as insulation. Some of the fungal species, by creating the fungal skin, enhance the composites in fire retardancy as well, which is another positive potential for a material to be used in the building industry.

4.4. FABRICATION TECHNIQUES

In the next part of the recursive work, techniques able to be used for designing with mycelium-based bio-composites needs to be tested. Simulation and fast prototyping using computational tools and parametric software, and then physical models and prototyping, are required for this stage. The design process is an iterative process, and prototyping allows the designer to assess the results. After initial evaluations through computer simulations, physical explorations are conducted. Several approaches for making use of the new material, such as molding, aggregation, 3D printing, and laser-cutting, can be explored in order to utilize the material in the making processes. It is important to identify possible fabrication techniques for mycelium-based bio-composites and the opportunities that each of them offers for the making process.

4.5. GEOMETRY DESIGN

The other part of the cycle is the form-finding process. This stage is related to the other two parts of the cycle. The results of material exploration and the possible fabrication techniques for mycelium-based bio-composites influence the forms that can be produced. For example, using 3D graphic statics as a technique must be accompanied by using its own form-finding methods. Likewise, some materials, by their features, follow specific grammars that can be extracted by shape grammars and be used for form-finding. Thus, the outputs of other stages are required for starting form-finding and the results from this stage can feed the next cycle of material study. For instance, monolithic geometries may need more material tinkering and exploration since in large-scale moldings, curing by pressing the material is not as simple as curing in aggregation methods, since the greatest structural performance of the material is dependent on the thickness of fungal skin. In order to have more uniform mycelium-based bio-composites cores cemented by hyphae as well as skins, more studies are needed.

This recursive method of material exploration, study of techniques, and geometry design must be applied several times. This research proposes to scale-up the designed geometry in each stage from a micro-scale prototype to meso-scale ones, with macro-scale as one of the final outcomes.

CONCLUSION

The main purpose of this study is to integrate mycelium-based bio-composites to the architectural context as an alternative for conventional masonry materials to be used in low-rise/temporary constructions. Mycelium-based materials are advantageous as a sustainable material due to their green production that uses wastes from other industries to generate materials. They also do not produce waste after demolition, since they are biodegradable. Some other advantages of the material are its light weight, insulation capacity and fire retardancy. The methodology for the conversion has been explained as a recursive method simultaneously exploring material properties, fabrication techniques, and form alternatives. This needs an interdisciplinary approach from computational design, biology, engineering, and materials science disciplines. Based on the existing literature and the experiments completed, the load-bearing capacities of mycelium-based bio-composites need to be enhanced, either by improving their inherent characteristics via the material cultivation process or by employing structural systems, forms, and geometries that can compensate for these constraints in structural behavior. In the next stages of research, these two approaches will be studied.

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ENDNOTES

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