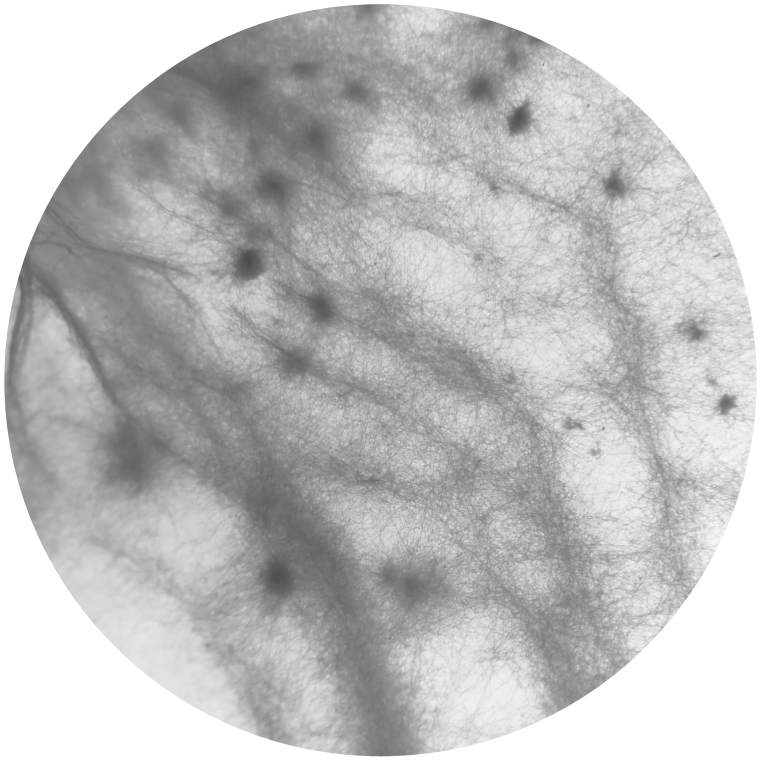

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Research and Application of Mycelium in Architecture

MASTER'S THESIS

to achieve the university degree of

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Supervisor

Assoc. Prof. Dipl.-Ing. Dr.techn. Milena Stavrić

Institute of Architecture and Media

Graz, October 2020

AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis dissertation.

Date

Signature

"We need to have a paradigm shift in our consciousness. If we don't get our act together and come in commonality and understanding with the organisms that sustain us today, not only will we destroy those organisms, but we will destroy ourselves."

Paul Stamets, mycologist

RESEARCH AND APPLICATION OF MYCELIUM IN ARCHITECTURE

ABSTRACT

The subject of this research is exploring new possibilities of mycelium, the vegetative part of a mushroom, as a sustainable building material in architecture. This interdisciplinary subject is primarily embedded in the field of architecture and secondarily in mycology. A theoretical investigation initiated the project, whereas the experimental part combined different kinds and sizes of plant-derived waste with several mycelium types. They were cultivated in order to grow a mycelium-based material, which was formed and used as a stable building material with a wide range of applications, therefore also in architecture.

Using mycelium, many architects and designers have been developing and shaping their products. Experiments have also been made in the field of architecture creating load-bearing structures. Keeping pace with the rapidly growing movement, the output of this master's thesis is the evaluation of a new material composition in architectural structural area, examined in a limited and challenging environment conditions, while using the existing references.

The starting point is the analyses of the latest research results found in the field of mycology and current methodologies used in the field of mycelium-based design. The project is an attempt to find a viable, long term solution for the global problem of pollution and waste management, focusing mostly on the building industry and construction waste, which makes almost 30% of all generated waste in the EU. With the use of a combination of defined local agricultural by-products, the transportation costs can be minimised and the material made completely sustainable. We are faced with a serious continuing mistreatment of our environment, meaning we have to turn to alternative and natural solutions for our deeply rooted problems. Many solutions focus on the management and distribution of the existing waste, but there are also attempts to reinvent the production itself, making the waste either completely reusable, biodegradable, or ideally, non existing.

The thesis, "Research and Application of Mycelium in Architecture", was conducted in the frame of the SFB project, subproject SP9: "Material- and Structurally Informed Freeform Structures", as a part of the research basis for the project.

OVERVIEW

The introduction chapter explains where the idea for the theses comes from, which is basically a continuation of an elective course undertook during my studies.

Continuing with stating the critical points that need to be dealt with, the problems of our societal mentality and the demand for fundamental changes in our way of life. Several aspects are being discussed: anthropocene, ecocene, circular economy and the term sustainability.

The third chapter is defined by overlapping areas of interdisciplinary research, which have influenced my work process within this thesis. Starting with biological examples that have been an inspiration for many architects and artists and correlating biological terms to architecture.

An outline explains what mycelium and fungi are, their history and presence in our everyday lives. References of projects that have already been built and companies that have released mycelium-based products on the market in architecture, design and other industries. The next chapter is an overview of mycelium types used in the experiments, with a short review of each.

The practical part of the research is a compilation of experiments conducted. The initial chapter describes in detail the working procedure, continuing with different material combinations and lastly their evaluation.

Material testing is explained in the next chapter - density, compression strength, three-point flexural test and capillary water absorption, concluded by the interpretation of the gathered results.

The outlook of the thesis covers the conclusion of all the relevant aspects of the material, its potentials - which can be exploited, and limitations - that should be addressed and worked on, as well as the future steps that will come.

INDEX

1 INTRODUCTION

Fig. 1: Symposium logo

1.1 URBANA SYMBIOSIS[1]

The inspiration for this thesis came from a project previously conducted as a part of an elective course, which I had chosen during my studies. That seminar was lead in the subject of materials science and furniture design in the summer semester 2018 in the wood workshop from the Institute of Spatial Design at the TU Graz, under the initiative "natur vielfalt bauen". The interdisciplinary team consisted of two biology, Mojca Legvart and Sophia Knaus, and two architecture students, Saša Ritonja and myself. The final results of the seminar were exhibited and presented at the symposium in Montforthaus Feldkirch (Fig. 1).

> *Urbanes Wachstum, Nachverdichtungen und der gleichzeitige Wunsch nach einer klugen und energie-effizienten Ortsentwicklung bedürfen mehr denn je den Blick auf Biodiversität, Klimawandelanpassung und Lebensqualitäten. Das internationale Symposium geht Bedürfnissen und Strategien nach, stellt zukunftsweisende und innovative Projekte vor und ermöglicht einen transdisziplinären Wissens- und Erfahrungsaustausch für Expertinnen und Experten sowie Anwenderinnen und Anwender aus den Bereichen Architektur, Landschaftsarchitektur, Städtebau, Raumplanung, Bauwirtschaft und Ökologie.* [2]

Since the project served as an initial input for the following work of this thesis, the main objectives and results will be presented here.

The proposal was developed as a part of the master programme at TU Graz, under the supervision of Judith Augustinovic Dipl. Ing. Dr.techn. and Reiner Eberl. The biological input of the project was received by Martin Grube, Univ. Prof. Mag. Dr.rer.nat. of University of Graz.

In the course, existing building techniques of wild animals were researched, analysed and interpreted. From the knowledge gained, specific strategies and concepts for nesting, incubators, holes, etc. were developed and differentiated.

The *Urbana symbiosis* project aims at a necessary mutuality between nature, man and man-made space, symbolized through a construction made of mycelium and endangered wildflowers exhibited in a public space.

1 https://naturvielfaltbauen.org/wp-content/uploads/2018/07/urbana__.pdf

2 https://www.feldkirch800.at/magazin/natur-vielfalt-bauen

1.1.1 Green areas in Graz

Graz was analysed for the most important green spaces - Stadtpark, Schlossberg, Städtischer Augarten, Mur river banks and the Volksgarten. Additionally the city has many green courtyards and smaller green areas. Therefore, it cannot be stated that Graz has a lack of natural urban areas, however, the absence of insects is omnipresent.

Two basic problems were identified: firstly large green areas are concentrated mostly around the historic town core and squares and streets in the centre are without trees or other green elements. Secondly, blooming plants, which are main food source for insects, such as butterflies and bees are rarely seen.

How can we approach these problems?

We agreed that several interventions in the city would be necessary in order to connect the larger green spaces. The intention was not to design furniture, but to start from the concept of an ecosystem. The idea was to create a new ecosystem, a biotope that could be placed anywhere. It should stimulate the residents by creating awareness, be aesthetically pleasing and have a nature-protecting role.

1.1.2 Form-finding

The inspiration was found in Graz, in the vicinity of the Universalmuseum Joanneum - a round green area enclosed by a tall metal fence (Fig. 2). An idea of an area with different types of blooming plants came to mind, which would have a function of an insect habitat. It could be an independent part of nature in the city.

In the beginning, the concept was to design a shape that could be placed in a garden, but would also be a part of a greater scheme across the city. In further studies, the focus shifted to green areas i.e., parks in Graz. Biotopes could be placed in these kinds of urban spaces - unlike on a balcony - because the necessary ground is already available. Since the cylindrical shape, like the one in Joanneumsviertel, turned to be unfavourable for our concept we chose a dome shape, a kind of a green igloo, that will become completely overgrown with climbing plants. A self sufficient ecosystem becomes an oasis for insects, chaotic on the inside, without any human intervention needed. The issue with this approach is that it is a closed off system and separation is exactly opposite of growth. If nature is to spread punctually from small sources closed systems are not the solution. A closed fence becomes a spatial structure.

The chain wire fence was taken as a motive, being suitable for climbing plants. In order to create a three-dimensional construction, we began with the rhombus shape, developing into an octahedron, which enables stacking of individual elements (Fig. 3). By using the modular construction, the scale of the intervention can go from only several parts to reaching bigger structures such as pavilion.

Fig. 2: Fenced biotope

Fig. 3: Idea for a structure

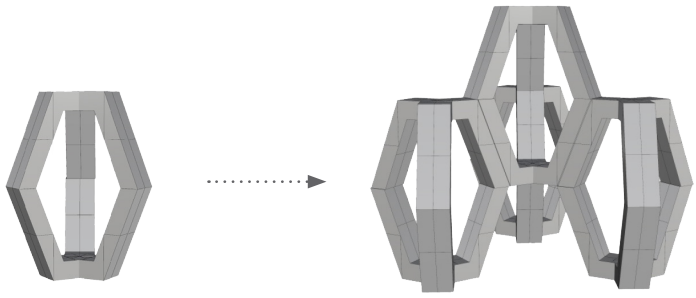


Fig. 4: Single element - mid size assembly

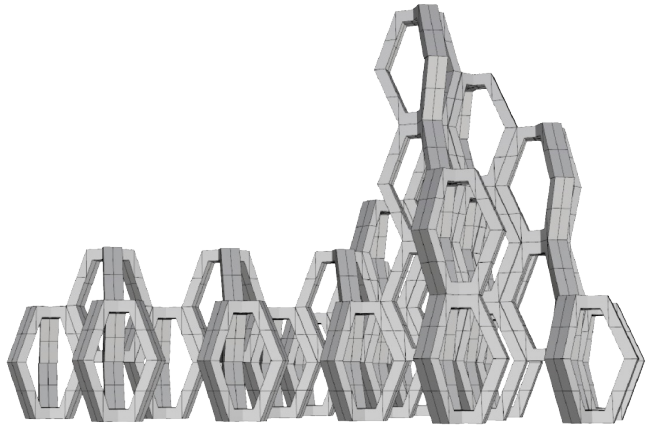


Fig. 5: Bigger public structure

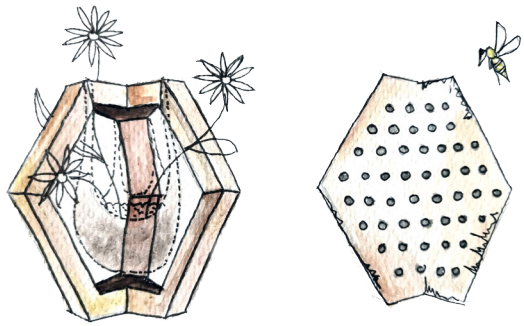


Fig. 6: Module sketch

As for the material, conventional building materials such as steel or wood (with steel connections) would be possible, however, it would be contradicting the initial idea. Subsequently, soil as a building material came in question because it is an essential growing medium for plants, a sculptural shape made of soil to build and plant on. Due to lack of implementation options (such as getting soil in shape and secondly keeping it in the desired shape), it remained unfortunately only an abstract idea during the course of the development process. Another plan arose from the idea of building with soil, something 100% naturally cultivated but temporary, that would later degrade, thus closing the life circle. This is how mycelium became our material of choice.

1.1.3 Form | Scale | Material

Although mycelium has uses in architecture, art and design, the exact potential of its capabilities remains vague. During our research, we learned about some of the material properties one of them being decisive for out concept - mycelium can be used in a similar manner as a clay brick.

Regarding the production scale, it made sense to work with an efficient and comfortable dimension, easy to develop, shape and produce in large quantities. Since the concept involves meadow flowers (Fig. 6), the needed dimensions of individual parts matched the height of the mentioned plants - roughly 40 x 40 x 50 cm (Fig. 4).

With this sizing and form, it could be possible to have a unit on one's balcony. The modular nature of the project suggests stacking and arranging individual parts, which

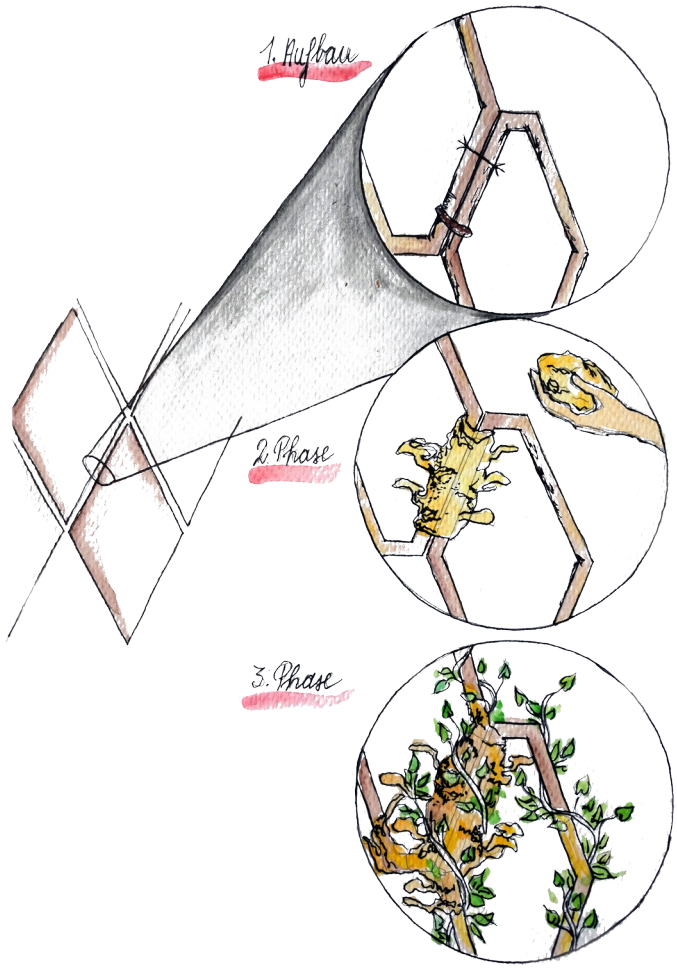


Fig. 7: Connection scheme

Fig. 8: Mojca Legvart, Feldkirch, 2018

can create larger dimensions in public spaces. (Fig. 5) The modularity has the advantage of producing the same basic part and arranging it to fit the needed form, customizing it to individual site plans.

The stacking and binding of individual parts remains unclear, because of the material novelty. Since the necessary binding was planned to be mycelium itself, the construction had to be executed in two steps: the load bearing construction first had to dry out and only afterwards could the second layer of the living material be applied (Fig. 7). After consulting different experts, who have already worked with mycelium, it was difficult to estimate if such a way of binding would work. That is why the project was continued by producing 1:1 prototypes. The work in progress was exhibited at the previously mentioned symposium in Feldkirch in October, 2018 (Fig. 8).

Fungi are researched in all facets of science, one of those research fields being material science. Mycelium can be moulded and formed as desired. When mixing the mycelium with substrate, its network will begin spreading, and while consuming the substrate itself, the mycelium will begin to take shape in which the substrate was placed. Once it has dried it hardens considerably. The fungal material is fire retardant by nature and can even self extinguish. It can withstand pressure up to 30 000 times higher than its own mass. If it contains air pockets, it will remain afloat in water. It is light, hard and tough. But its best characteristic is the material's minimal impact on the environment. Mycelium is a renewable resource and completely biodegradable. It also absorbs carbon dioxide from the soil.

2 CHALLENGES

The environment became globally unstable in the twenty-first century because of several reasons, some of them being rapid population growth, increased food and housing demand, freshwater scarcity, inadequate waste management, all of which are influenced by demographic, environmental and economic components. These elements have accumulated to the point where we, as a society, will not be able to recover from such damage. According to Stockholm Resilience Center and their study of Nine Planetary Boundaries (Fig. 9), two Boundaries - loss of biosphere integrity flow and biochemical flow, have already entered the zone of high risk and possibly irreversible environmental changes are expected to take place.[3]

2.1 ANTHROPOCENE TO ECOCENE

It is now globally accepted that we live in a geological age called the Anthropocene. As the word itself describes it, this era is defined by the human influence, especially in relation to environmental and climate changes. Its predecessor is the Holocene epoch, which began approximately 10 000 years ago.[4]

Anthropocene epoch has such a negative impact on the planet that the side-effects of the modern age are actually reverse-terraforming the Earth, meaning that irreversible damages and loss of biodiversity are taking place. This anticipates the extinction of living beings, including ourselves. High demand on resources, which are continually extracted, without enough time for them to regenerate to their full extent, or at least to the state where preservation is, leads to their depletion.

Furthermore, we are not really working globally towards a scenario where we do not get extinct as a species. Attempts such as recycling, reducing, reusing and alternative energetic concepts are important, but unfortunately not a viable long-term solution. The problem is so deeply rooted in our society and way of living that the fundamental development of humans needs to change.[5]

A shift to Ecocene is a logical proceeding, as the current state rapidly loses all potential for survival. Our development has to steer us into a prospective future, where we do not exclude ourselves from the environment we live in. This affects all levels of our living spectrum, therefore also architecture.

What does Ecocene exactly mean? Since we still live in the age of Anthropocene, a clear path and unravelling of this paradigm shift is not yet defined. But what can be said with certainty are the first steps we need to take towards it. As Rachel Armstrong, a professor

3 https://www.stockholmresilience.org/research/planetary-boundaries.html

4 http://www.anthropocene.info/index.php

5 see Armstrong 2016, 11.

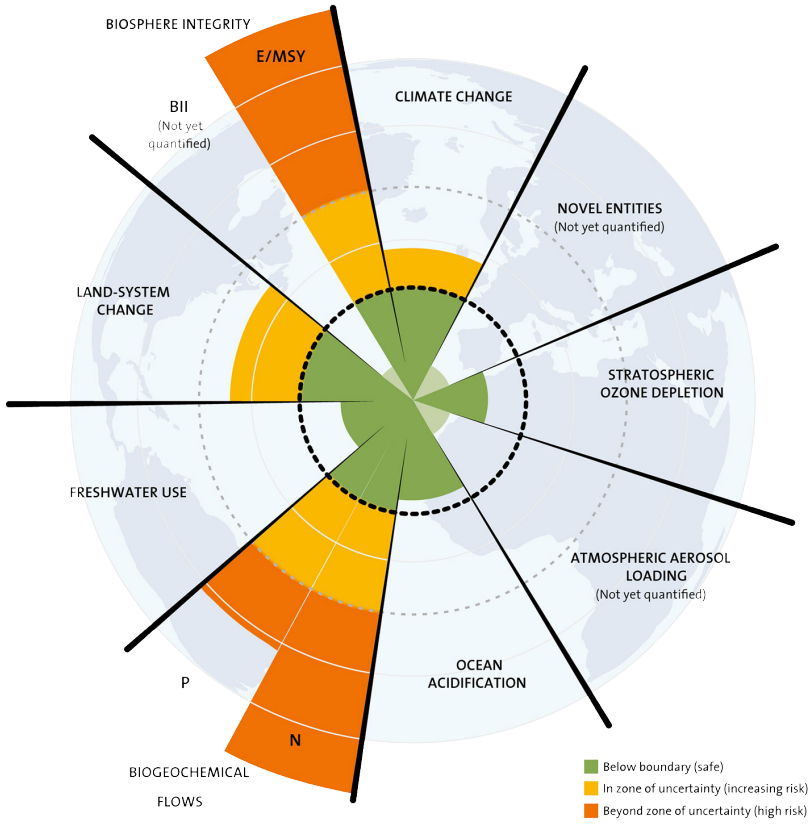
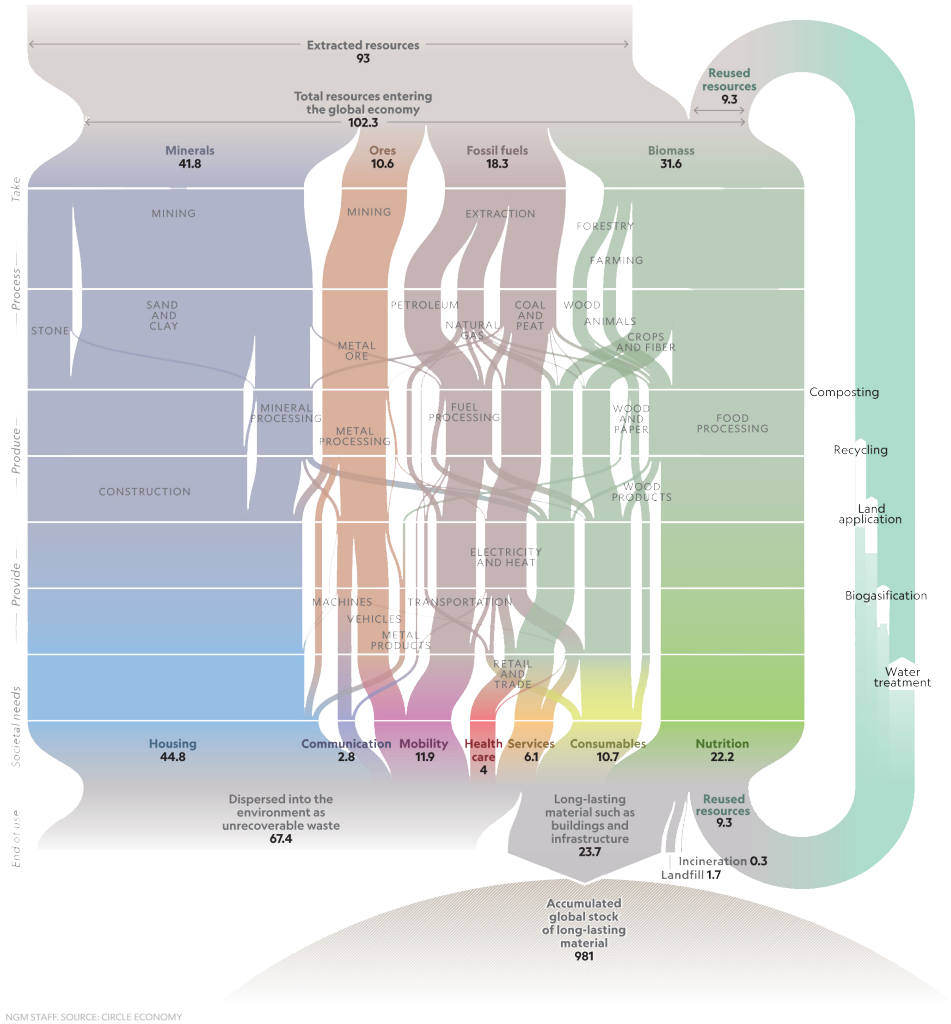


Fig. 9: Nine Planetary Boundaries

of experimental architecture at Newcastle University states, we - as architects, have to reinvent and introduce a connection between our homes and nature, rather than separating them. One has to start this process from the material itself - genuinely sustainable means connecting and crafting from nature. To do that, a proper language is needed in the same way that living organisms communicate between each other, by chemical reactions, i.e. a metabolism. A use of metabolic materials in architecture is desired, but they are still being generated and are not widely available. A paradigm of building an inert object has been present in architecture for ages; a top-down approach, which enforces a structure upon living matter. Another great advantage of metabolic materials if a possibility of growth, self-repair and response to the immediate environment.[6] These potential ideas could one day bring a radical shift in the way we build, and later on, live.

6 see Armstrong , TED, 2009.



NGM STAFF. SOURCE: CIRCLE ECONOMY

Fig. 10: An x-ray of our global economy

2.2 CIRCULAR ECONOMY

The economical aspect also plays an important role, as we are currently finding ourselves in the so-called linear system. It relies on the extraction of raw materials, transforming them and disposing of them once their life cycle ends. This is obviously very harmful for the environment, because only a small percentage of those products are actually recycled.

Circular economy is defined by the absolute reusing of disposed materials, with radical changes in the production itself taking place, thus preventing the existence of waste. This does not mean that the products become obsolete, it means that the interpretation and understanding of waste is redefined. As soon as one attributes an economic value to a certain product, its value is recovered and it therefore continues its journey as a part of a life cycle in this kind of economy. In order to achieve such understanding, the public awareness of the cycle and its meaning is necessary. Reusing and recycling are still an important part of this economy, but other factors have to be included in order to maintain the circular model.

Everything in nature works in cycles, from plants, animals, humans, "waste", soil, and so on. The problem escalated when population growth reached exponential numbers; that's exactly the point where linearity lost its sense. The diagram, an x-ray of our global economy (Fig. 10), shows four types of raw materials that are being extracted: minerals, ores, fossil fuels and biomass. They are then vertically divided into categories, which represent areas of human needs. As seen on the bottom left side of the graph, the majority of the materials flow into construction, then housing; 44.8 billion tons. This is not that surprising, because our current societal needs follow the universal trend of population growth, but it shows the great deal of responsibility we carry, especially as architects and constructors.

The somewhat discouraging number is the one accumulated through composting, recycling, land application, biogasification and water treatment , which totals in only 9.3 billion tons of reused resources. It shows how insufficient our attempts are, when compared to the rest of the world's waste.[7]

From this point of view, realising the magnitude of the problem that we are facing as a planet, some measures have to be taken in order to maintain the balance between nature and the built environment. A certain amount of critical thinking and social responsibility is needed in the production as well as consumption process.

Besides circular economy, there are other schools of thoughts, which have been developing concepts on the same premises, as stated in the Ellen MacArthur Foundation. As there are many other examples like industrial ecology, blue economy or Regenerative design, the relevant ones will be mentioned here.

7 see Kunzig 2020.

The first one is “cradle to cradle” concept, developed by a German chemist Michael Braungart and an American architect Bill McDonough. This theory divides all material into two categories: biological and technical. It takes the natural process of a biological metabolism and transferred it to a “technical metabolism”, where a flow of industrial materials takes place. Both of those metabolisms have their nutrients, which are designed for continuous recovery. It eliminates the concept of waste, maximises the use of renewable energy and respects human and natural systems.

Performance economy was established by the architect Walter Stahel, as a vision of an economy in loops, with its influence on job creation, economic competitiveness, resource saving and waste elimination. He founded the Product Life Institute in Geneva over 25 years ago, which follows four main objectives: product life extension, long-life goods, reconditioning activities and waste prevention. It also favours selling services than goods.

Biomimicry is an approach often promoted by Janine Benyus, which imitates some successful examples from nature and applies them on human problems. The concept is built around three assumptions: nature as model - by researching systems and processes in nature for solving obstacles in human life, nature as measure - the sustainability of innovation is judged by ecological standards, and nature as mentor - aims towards learning, rather than extracting from nature.

Natural capitalism describes the overlapping of business and environmental interests under one global economy. It perceives the dependency between the production of human capital and the flow of natural capital. This idea relies on four principles: a radical increase of natural production by changes in design and technology, shift to biologically inspired models, moving to a “service-and-flow” business model - providing value in a flow of services, rather than the traditional sale of goods, and reinvesting in natural capital - regenerating natural resources before they become obsolete.[8]

2.3 THE “S” WORD

Sustainability is a term which has been used in almost every aspect of commercial practices; from sustainable fashion, food industry, politics, economy, consulting, investment, accounting, building, architecture, etc. It’s so widely spread that it became meaningless and somewhat irrelevant.

In architecture, it is misleading in a way that it describes buildings with green roofs, the usage of solar panels and similar practices. Sustainable does not mean optimising the energy flow in the building while using natural resources or materials - this still operates on the premise of resource consumption. It should mean rethinking the foundation of the design process, while learning from nature by applying the same principles. Our built environment is therefore becoming a hybrid between nature and architecture. Even though sustainable architecture nowadays aims toward a “zero-energy” future, that process still involves resource extraction - it’s buying time to some extent, but not a permanent solution.

8 https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought

3 TRANS-DISCIPLINARY RESEARCH

3.1 ARCHITECTURE AND BIOLOGY

This chapter focuses primarily on the correlation between architecture and biology, which have been mutually beneficial throughout history. Architects have always searched for their inspiration in nature, sometimes borrowing natural forms as their own, or looking at the material itself, obtaining ideas just by understanding natural processes. This kind of intertwined exchange of information goes both ways, as both of these disciplines use theoretical input, as well as mutual practical knowledge.

Biologists have developed theories by observing tensegrity structures designed byBuckminster Fuller and Kenneth Snelson.[9] Donald Ingber, a cell biologist, interpreted Fuller's tensegrity concept as a system of energy in a non-static space, influencing his understanding of how cells are structured in a nanometer scale. Similarly as in tensegrity structures, tension within the cellular system is transported continuously through the cell in a way that an increased tension in one member results in increased tension with all the other members.[10] Correspondingly, biology models of self-organized systems have influenced architectural design in terms of hierarchy of single elements and have brought inventive forms and structures.

Ernst Haeckel was a scientist and an artist, who was fascinated with diverse forms found in skeletons of marine organisms, radiolarians (Fig. 11). The invention of improved microscopes have made his research possible. His drawings were considered to have a high aesthetic value, which reached a wide audience at the time and even influenced architectural design (Fig. 12).[11]

9 see Sabin/Jones 2018, 40.

10 see Ingber 1998, 48-57.

11 see Gruber 2016, 22.

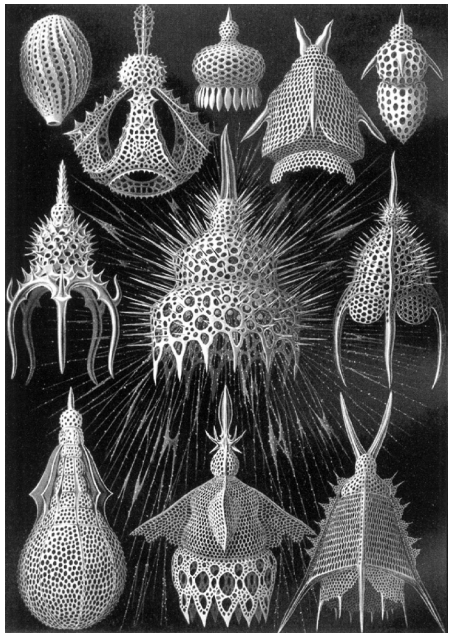


Fig. 11: Radiolaria, Ernst Haeckel

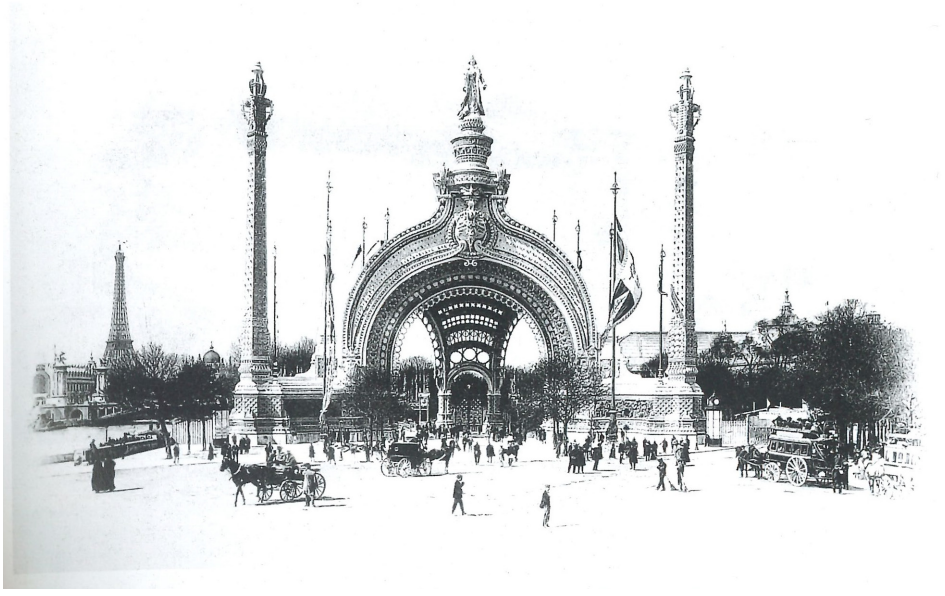


Fig. 12: Design for the World exhibition in Paris, René Binet, 1900

Fig. 13: Silk Pavilion, Mediated Matter Group, 2013

Borrowing ideas, finding inspiration and comparison of analogies in different fields are, nowadays, more important than ever. As we all face similar challenges in life and share the same existential threats as a society, we have to seek solutions that are applicable on every level of human existence. In order to do so, sharing information and knowledge is an imperative for technological and societal growth. There is always one side of an interdisciplinary collaboration which delivers the research, whereas the other one delivers the application.

Rather than producing objects as direct solutions for a certain problem/demand, an exchange platform of creative thoughts and ideas is developed, where both sides have a chance to express radical and alternative models suited for a specific cause. These kinds of research models are also focused on one, or more, goals, but the methods they use towards achieving them usually employ a dynamic correspondence between the object and its context. Meaning, they search for factors which can be used from the environment itself in order to optimize the design.

There are several recognized institutions and labs that engage in this sort of exchange when designing new concepts. By using novel approaches and techniques from a certain field, adaptations and experiments are implemented, starting from small scale tests, until building the actual design. They underline sustainability and merging of nature with architecture.

One of those institutions is the Mediated Matter Group at the Massachusetts Institute of Technology, led by Neri Oxman. By studying animal behaviour and then using it for the design fabrication, she developed a new approach. The Silk Pavilion was designed in that manner (Fig. 13). Silkworms were put on a predefined geometry and finished the outer layer of the pavilion by naturally producing silk.[12]

12 see Brownell/Swackhamer 2015, 128.

Another example of comprehensive interdisciplinary output is the Research Pavilion (Fig. 14). The Institute for Computational Design (ICD, led by Achim Menges) and the Institute of Building Structures and Structural Design (ITKE, led by Jan Knippers) at the University of Stuttgart collaborated in designing a bionic fibre-woven pavilion. The multidisciplinary team of biologists, architects, palaeontologists and engineers researched natural fibre composite shells and implemented their expertise by designing robotic fabrication methods for polymer structures. The net formation mimics strength-toweight ratio of a spider web, the pneumatic arrangement soap bubbles and geodesics mimics radiolaria.[13]

Radiant Soil is Philip Beesley's project finished in 2013 (Fig. 15). It is an interactive system where visitors interact with the space trough movement. It responds to the proximity of people by lighting itself, releasing odours and generating air circulation. That way, a dialogue between nature and people is continuously created. Deliberately designed to look fragile, the project opposes conventional robust architecture. It represents biological needs that are often ignored by architecture and embellishes the problem of static, rigid buildings closed of from their environment.[14]

There are two approaches architects take when working with nature. The first one is *representation*, which means translating natural shapes and applying them into a design. This is often associated with terms biomorphism and biomimicry. For instance, an ornamental adaptation used purely for aesthetic purposes. One can easily differentiate the source, regarding material and execution, and representation of the formal. The other approach, engagement directly interacts with natural substances, i.e. living beings. Newer designs are created by mimicking a certain behaviour of an organism. Bioengineering is a relevant term in this kind of process.[15]

13 see Sabin/Jones 2018, 25-26.

14 see Brownell/Swackhamer 2015, 102.

15 Ibid., 22.

Fig. 14: ICD/ITKE Research Pavilion, 2013-14

Fig. 15: Radiant Soil, Philip Beesley, 2013

3.2 LIFE CRITERIA

Life has many forms and definitions. In biology, the definition of life has a list of certain criteria that need to be fulfilled. Those are globally accepted and they unify the concept of a living organism. Those criteria are: order, energy processing, homoeostasis - metabolism, growth and development, reactions to the environment, evolutionary adaptation and propagation.[16] All of these factors are intertwined in a way that they influence each other, e.g. growth is possible through metabolic activities, reacting to the environment influences the orientation of growth, etc.[17]

How many of these aspects of life can be found, or translated, into architecture?

Other biological characteristics of living beings, which are not necessarily interpreted as a basic criteria of life can be, however, connected to architecture. Terms such as resilience, adaptation, intelligence, and self-healing are one of the many biological terms architects tend to incorporate in their designs and visions. However, most of these designs aiming to achieve living, moving architecture remain as a vision, similarly as Ron Heron's concept of the Walking City, developed in the 60s (Fig. 16).

Metabolism in architecture exists as a movement in post-war Japan, which is characterized by mega-structures built to mimic biological growth (Fig. 17). Other than the iterative stacking of single modules that remind of cell organization within a tissue, these structures have very little in common with the way how metabolism actually works. However, changing the scale from objects to materials when defining metabolism in architecture brings relevance to other fields of research. Metabolic materials are, according to Rachel Armstrong, materials which can directly respond to their environment through chemical reactions:

> *"Metabolic materials are a technology that acts as a chemical interface or language through which artificial structures such as, architecture, can connect with natural systems."*[18]

They function through transforming one group of substances into another, thereby producing or absorbing energy. These materials offer a medium through which an chemical exchange of information between architecture and the environment takes place[11]. Even though such materials are still being researched, an application in architecture is plausible, e.g. in façades which could adapt themselves according to the needed requirements, with changes occurring naturally, i.e. through chemical reactions.

16 see Campbell 2000, 5.

17 see Gruber 2016, 21.

18 Armstrong, TED, 2009.

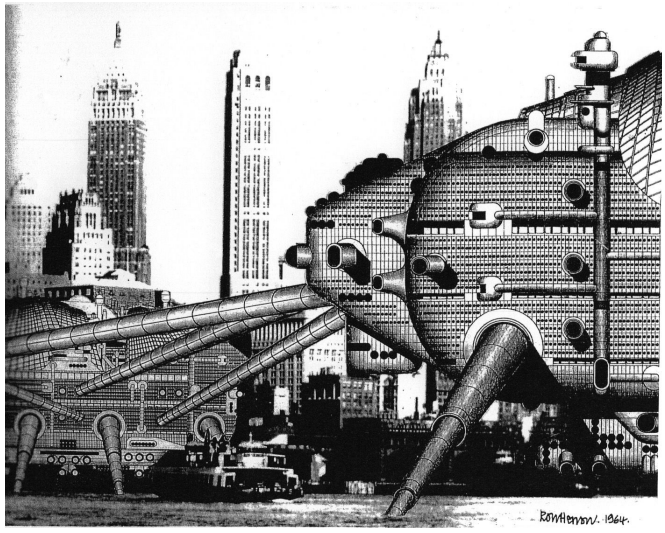


Fig. 16: The Walking City, Archigram, 1964

Fig. 17: Nakagin Capsule Tower, Tokyo, 1970

Fig. 18: Urban growth of New Delhi, 2019

Fig. 19: Auerworld Palace, 1998

Fig. 20: Fab Tree Hab

In biology, growth is defined as division of cells. It happens by changing their size and numbers. Biological growth is present on many scales besides the cellular one. Molecules, tissues, organs, organisms, whole populations, ecosystems, evolution and eventually, biosphere, are all defined by it. A big advantage of biological growth is the differentiation of cells, meaning, specific types of cells can be developed according to a certain deficit or need.[19]

An analogy of cells in architecture could be single building elements, e.g. bricks. While the process of building takes place, an object is "growing". Bricks are stacked on each other, and the object is increasing in volume. Similarly as cells form a tissue, bricks form a wall. This analogy could work if the process of expansion had the same method. Cells are multiplied by division, but bricks are assembled by addition.

Material growth in architecture is questionable. Wood expands and shrinks depending on the humidity, whereby clay shrinks during its drying process. But both of these processes are actually a minimal increase, i.e. decrease in volume.

Growth of buildings can be defined during the building process, because it is visually noticeable in a very short span of time. But once the construction is finished, growth stops and is somewhat limited by the geometry, if further expansion is needed. The only exception would be structuralist building system, where growth is limitless through continuous stacking of modular units in all directions. This could be described as growth in architecture if it, again, was not based on addition of building elements.

If these ideas and principles are transferred to an even bigger scale, one can discuss urban growth. It is not only defined by addition of single elements, i.e. buildings, but also by infrastructure, which through their interconnections, in a way, function as an organism. This is usually seen in the rapidly growing cities in developing countries (Fig. 18). One can even expand this scale and consider cities and regions as tissues and organs, which finally form an organism called the Earth.

Where do these growth patterns/principles find their common language?

Biological growth can also be a direct part of architecture. Starting from a simple comparison of a hedge having the function of a fence, or a tree providing shelter (Fig. 19), manipulating plant growth in a way it forms furniture (John Kurbsack, 1922), and even houses, where Mitchell Joachim (Terreform ONE) envisions a future where we could pre-grow entire cities in 7-10 years, by just using native trees to grow homes (Fig. 20). They do not only fit into the environment, but are actually a part of it. A prefabricated CNC scaffold is integrated into growth where a living structure is brought into shape.[20]

19 see Imhof/Gruber 2016, 30.

20 https://terreform.com/fab-tree-hab

Openness in biology means exchange of information, resources and energy. In architecture, these processes are very similar - opening or closing a door, window etc., there is a clear physical border. These borders do not have to be so straightforward - they can become more subtle by architectural means - e.g. ornaments with a function of a semi-closed wall (Fig. 21), also by nature having a role of an architectural border - Blur Building, generating fog as a result of natural and man made forces (Fig. 22), creating vague external boundaries.

Propagation as such does not yet exist in architecture, i.e. in technology. Not in the terms of self-replicating or reproducing, as it appears in nature. If this term is to be applied in architecture, it can be defined by features and typologies. This is not directly a material process, but a process of passing on information and knowledge. A start towards propagating in architecture could be seen in automated production. For instance, 3D printing is a method of applying material in layers, where same objects can be replicated.[21]

Evolutionary development, or adaptation, can be understood as a never-ending design process, where the concepts get constantly modified, by learning from the flaws that have been made.

Design in nature is based on evolution and natural selection. It is a very slow and limited process, which changes and adapts continuously. Organisms inherit some capabilities, memorising and adapting the enormous amount of information, which always being filtered. There is no such thing as a finished product in nature, which is tested and then abandoned or considered for further development; the continuous process keeps upgrading and renewing, always collecting and assessing information ("conservative development").

Design in technology is revolutionary and creative, not necessarily being a continuation of something already done before. Its growth is exponential i.e. faster with every year that comes. It exceeds the limitations of natural design (evolution).[22]

21 see Gruber 2011, 154-155.

22 Ibid., 108-109.

Fig. 21: Islamic cemetery, Altach, 2019

Fig. 22: The Blur Building, Swiss Expo, 2002

4 MYCELIUM

Fig. 23: Prototaxites, the prehistoric fungi

4.1 THE KINGDOM OF FUNGI

One billion years ago, in the Precambrian era, a supercontinent called Rodinia existed. Due to tectonic plate movement, new continents emerged along, resulting in a diverse topography. At the end of the ice age the Megagea glaciers left a barren landscape of rocks and deserts.

Roughly 500 million years ago an explosion prompted an emergence of microbes and microorganisms such as bacteria and early fungi. Natural selection narrowed down both fungi and bacterial species. The fungi survived by adapting to life on mineral surfaces, creating in turn first mineral-rich soil. The spores produced a type of acid which could penetrate hard rocks.

When a group of sea algae migrated through fresh water onto land, they came in contact with the fungi and started exchanging nutrients. Since algae were able to produce glucose via photosynthesis, they could exchange sugar for mineral nutrients, thus starting a symbiotic relationship between fungi and plants. The exchanged nutrients enabled ideal living conditions and flourishing of life. The fungi enabled the evolution of other species meaning the whole network can be traced back to fungi.

Fungi consist of thread-like cells, hyphae. The stems and the caps which they are known for are only a small part of the whole organism or the fruiting body which is responsible for production and distribution of spores. Most fungi are microscopically small and do not produce the fruiting body. The primary part of the fungi organism is the vegetative part, called mycelium. It is a threading form of hyphae, which is intertwined with the substrate, usually soil or wood. Mycelium penetrates landscapes and holds the soil together hence preventing erosion. It is very tough and durable and the reason behind its robustness is the cellular wall of the hyphae made out of chitin and polysaccharides. Mycelium is a fast growing decomposer, it dissolving organic material and enabling access to nutrients for other organisms. The biggest living fungi organism located in Malheur National Forest, Oregon, USA and its network is estimated 900 ha.[23] [24]

23 see Stamets, TED, 2008.

24 https://naturvielfaltbauen.org/wp-content/uploads/2018/07/urbana__.pdf

4.2 GROWTH PHASES

Broadly speaking, mycelium is a fungal root system, i.e. a vegetative part of mushrooms, which consists of branching hyphae (Fig. 24). Mycelial growth can basically be described as hyphal penetration of a substrate. A spore inoculated on a nutrient forms a tube which experiences exponential non-photosynthetic growth.[25] By inoculating a suitable substrate, one can differentiate three growth phases:

1. Lag phase - this is the part where there is zero to little population growth, while the mycelium cells get used to their new environment. This phase is individually determined for each species, but the shorter the lag phase, the faster the growth is.
2. Exponential phase - if the conditions remain favourable after the lag phase, increase of biomass takes effect, as well as cell number. This it the optimal period for mycelial growth and it's desired to last for as long as possible.
3. Stationary phase - this phase occurs once the nutrients are exhausted. The growth stops, but the fungi remain in a "hibernation" state. However, if the nutrients get completely exhausted or deficient humidity takes place, the organism dies.[26]

4.3 MYCELIUM TYPES

During the practical part of my research, I chose to work with several mycelium types. The idea behind it was solely to see if some mycelium strains grow better, faster or denser on different substrate types, under same conditions and after the same preparation method. The chosen mycelium strains will be presented and compared according to their growing habits, appearance in their natural habitat and lastly, my personal experience with each strain.

25 see Prosser 1993, 513.

26 see Jones et al. 2017, 245.

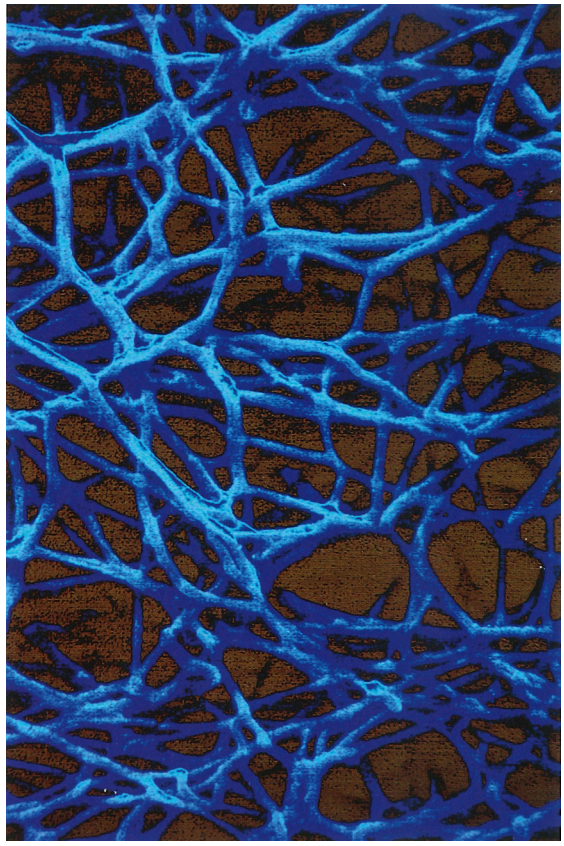


Fig. 24: Mycelium close-up

4.3.1 *Ganoderma lucidum*

Commonly known as reishi (Japanese for "divine" or "spiritual mushroom") and ling chi, ling chih, ling zhi (Chinese for "tree of life mushroom") - also called the mushroom of immortality. Often mentioned in Chinese, Korean and Japanese art (Fig. 25), reishi is traditionally related to royalty, health, wisdom, sexual prowess, happiness and is generally considered a good omen.

Because it's distinguished for its health-simulating properties, reishi has been researched in numerous studies for tumour treatment in breast and prostate cancer [27], management of histamine-mediated allergic responses [28], sleep deprivation [29] and many other fields of research.

Reishi is widely spread throughout the world; the species belongs to the wood-decaying fungi, saprophytes growing on tree trunks of oak, beech, elm and even palm tree. The shape of its fruiting body is similar to a growing kidney, with a cap that can reach 5-20 cm in diameter. Its shiny surface seems as if it has been lacquered, whereby its colour varies from red, brown, black, yellow and white on the underside. [30]

There have also been numerous studies on mycelial growth of *Ganoderma lucidum*, where a positive correlation between the mushroom yield and lignocellulosic substrates has been defined; thereby a preference of high amount of cellulose and lignin in substrates.

27 see Sliva et al.2002, 603-12.

28 see Powell 2004.

29 see Jia et al. 2005, 43-47.

30 see Stamets 2005, 231-233.

Fig. 25: Chen Hongshou: Man holding
Lingzhi mushroom, 17th century

Fig. 26: Sample inoculated with *Ganoderma lucidum*

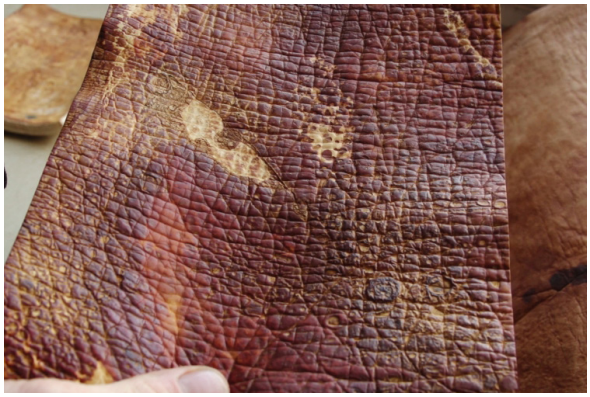


Fig. 27: Leather piece grown from reishi

Fig. 28: Fruiting body

Fig. 29: Mycelium brick, Philip Ross

Mycelium application in architecture, art and design has gained in relevance in the last 10 years. One of the pioneers who started forming mycelium (especially *Ganoderma lucidum*) into bricks (Fig. 29) and assembling them as arches is Philip Ross, the founder of "Mycoworks", located in San Francisco. Ross started with seminars and workshops under the title "(...) mushroom building bricks that are stronger than concrete"25 in 2012, whereas today he specialises in fabricating leather grown from reishi (Fig. 27). It is primarily used and tested to be applied in fashion industry, because its tensile strength matches that of animal leather (it reaches 10 MPa until the material breaks). Additional and significant advantage of the material is that it can be grown in two weeks with very little resources.[31]

After consulting with microbiologists, the benefits of reishi have peaked my interest because of the hydrophobic properties of its fruiting body[32], therefore also its mycelium. However, during my practical work with this particular mycelium strain, I have come across some difficulties in terms of easy contamination. Since my work was conducted in a semi-sterile environment, the source of the repetitive bacterial infections can not be determined with complete certainty. Therefore, only a couple of samples, which were successfully grown, were tested for their qualities, which will be described in the chapter Material Testing (7). A big visual feature of reishi is the reddish colour of its skin (Fig. 26), which matches the colour of the fruiting body emerging from one of the grown samples (Fig. 28). Its protective layer has a certain thickness when compared to other mycelium types, creating a feeling of compactness of the composite.

31 https://www.madewithreishi.com/

32 see Balzamo et al. 2019.

Fig. 30: *Hericium erinaceus* in nature

Fig. 31: *Pleurotur djamor* in nature

Fig. 32: Pom pom - grown sample

Fig. 33: Pink oyster - grown sample

4.3.2 *Hericium erinaceus*

This mushroom has several other names, which closely relate to its unusual appearance (Fig. 30); Lion's mane, hedgehog mushroom, old man's beard, monkey's head, pom pom or yamabushitake (Japanese for "mountain-priest mushroom").

It grows up to 40 cm in diameter by forming cascading white threads. It is distributed from North America, Europe to China and Japan, where it prefers growing on dried or dead tree trunks of oak, walnut, beech and maple, so it is considered a saprotroph. However, it is not that common to come across it in nature.[33]

Pom pom is also researched for its countless medicinal and pharmaceutical properties for anti-dementia effects[34], anti-tumour and immune-modulating activities, neuroprotective activity, antimicrobal activity, antioxidant and anti-ageing activities[35], etc.

While working with this mycelium strain, I noticed a relatively slow growth process on both beech and oak sawdust substrate (Fig. 32). After the drying process, the samples exhibited sufficient stiffness, but the outer protective layer did not developed as much as expected. Even without the protective layer, the samples were densely compacted so no crumbling of the substrate appeared.

4.3.3 *Pleurotus djamor*

The pink oyster, is a close relative of Pleurotus ostreatus, popular for its pink colour (Fig. 31). Even though it shares many characteristics with the pearl oyster mushroom, while working with this strain, several differences were noticed. Two substrate types were inoculated, beech and oak sawdust. The growth of this mycelium was extremely slow compared to all the other strains used within the experiments (Fig. 33). The samples with oak got partially contaminated. The samples with beech sawdust were growing for more than seven weeks and were dehydrated afterwards. There was no outer skin layer which would unify the sample in one piece, so the final product had an appearance of sawdust glued together in one piece with no visible mycelium. The substrate was not densely bound together, so pieces of sawdust started falling off as soon as the sample was being handled. For these reasons, further work with this mycelium strain was abandoned.

33 see Stamets 2005, 245-246.

34 see Kawagishi/Zhuang/Shnidman 2004.

35 see Thongbai et al. 2015.

4.3.4 *Pleurotus ostreatus*

Common names are the oyster mushroom, tree oyster, straw mushroom, hiratake or tamogitake (Japanese). This mushroom type is very common, as it is the one of the easiest to grow. In nature, it grows on tree trunks and logs (Fig. 34), i.e. it needs a lignocellulosic substrate, but all sorts of other substrates are appealing to this mushroom; paper, straw, wood, seeds, etc. Its by-products, water, carbon dioxide, enzymes, alcohols and carbohydrates, serve as a nutritious foundation for other organisms. Because of its ability to grow on almost any substrate, it has a great potential of reducing poverty, by recycling worthless waste and producing food. Caps of the fruiting body reach 5-20 cm in diameter, colour can be influenced by temperature and other growing conditions.[36]

This mycelium type was most frequently used for my experiments, exactly because of its ability to grow on a wide range of substrates. I rarely encountered contamination during my work with this mycelium type, even though the environment was relatively clean. The initial idea behind my experiments was to make a broad comparison between several mycelium strains regarding their growth speed on different substrates, as well as slightly adjusted growing conditions. When all these parameters are taken in consideration, a very wide spectrum of samples and combinations is created, which would need a very long time to be properly grown and tested. That's why this exploration got reduced to only this mycelium type, with an exception of several samples with *Ganoderma lucidum* strain. The samples inoculated with *Pleurotus ostreatus* take around two weeks to grow; the first week in a plastic mould, and the second one unmoulded to have enough oxygen on the surface to grow its white protective skin. When compared to reishi, the outer layer of oyster has a more fluffy, feathery feature, whereas reishi produces a tougher, skin-like growth.

36 see Stamets 2005, 279-280.

Fig. 34: Oyster mushroom

4.4 REFERENCES - MYCELIUM WORLDWIDE

Many architects and designers have already been implementing mycelium qualities in their designs during the last decade. Because of its ability to bind the substrate it grows on, unifying it into one piece, its application is very wide. From solid, to foam and leather, there are a couple of leading companies which found their place in the sustainable production market. This map is an overview of some of the production, projects and labs, which have been active in this practice, located throughout the world. Since their products found their application in various fields, from fashion industry, plant-based meat, to interior design, the ones mentioned in the next chapter will mostly relate to architecture.

1 USA: Mycoworks (San Francisco), Ecovative (New York), Bolt Threads (San Francisco), MycoTechnology (Aurora); Hy-Fi (MoMA, New York)

MYCO WORKS

MycoTechnology

BOLT THREADS

ECOVATIVE DESIGN

2 UNITED KINGDOM: Sebastian Cox (mycelium + timber), Aleksi Vesaluoma (Brunel University)

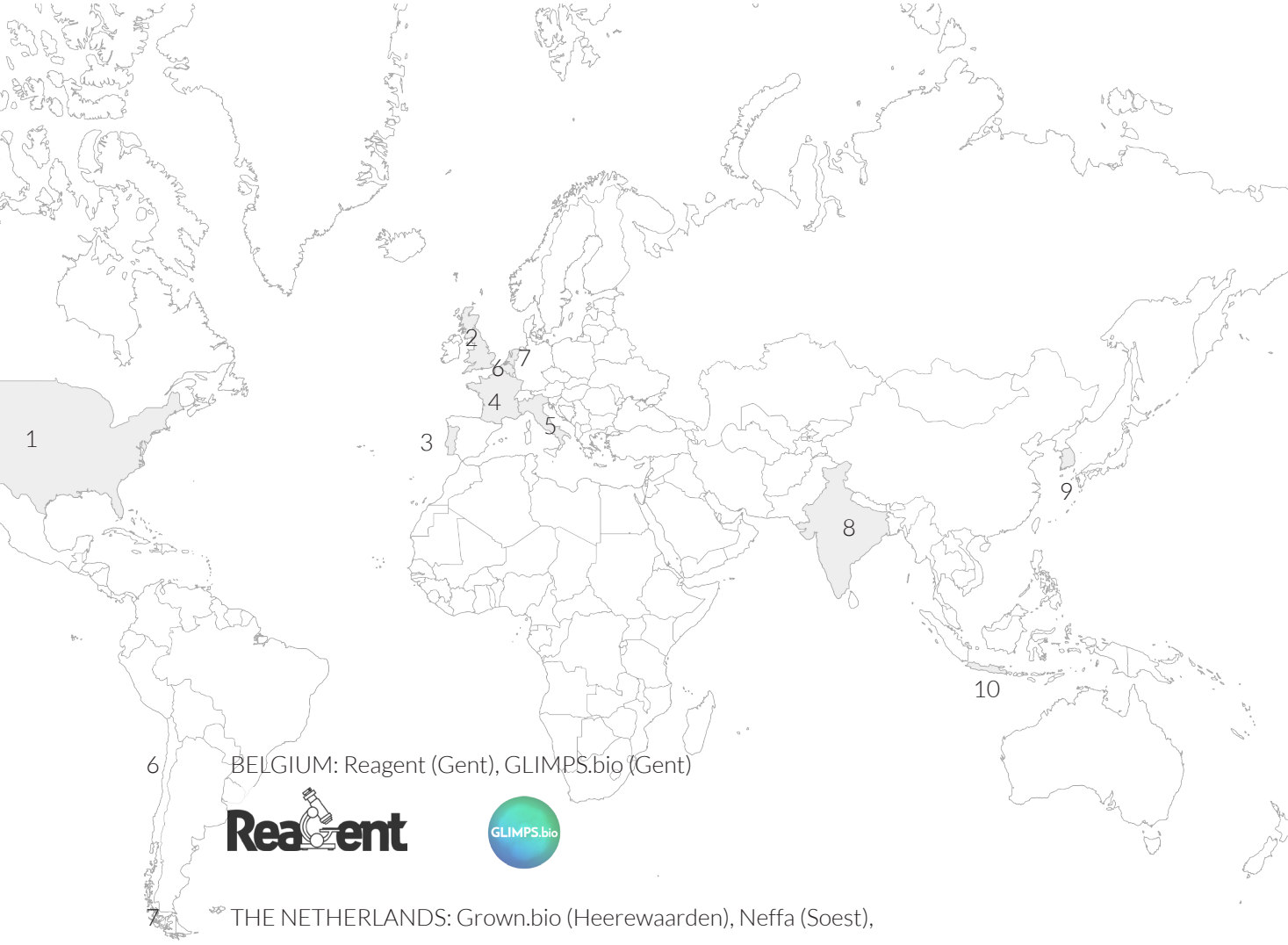
3 PORTUGAL: Critical Concrete (Porto)

CRITICAL CONCRETE

4 FRANCE: Myceluim chair by Eric Klarenbeek (Centre Pompidou)

5 ITALY: Mogu (Inarzo), The Circular Garden (Milan Design Week)

mogu
RADICAL BY NATURE



6 BELGIUM: Reagent (Gent), GLIMPS.bio (Gent)

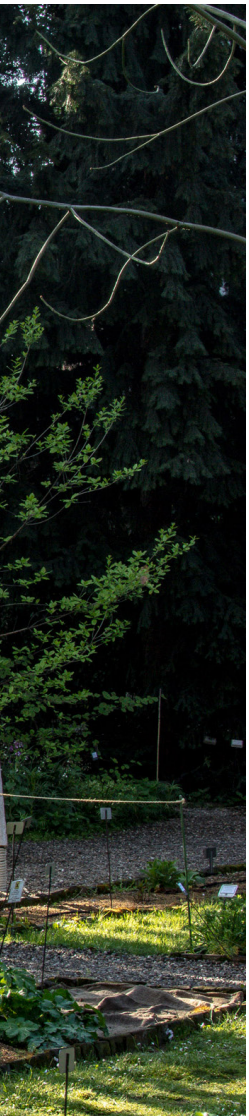
7 THE NETHERLANDS: Grown.bio (Heerewaarden), Neffa (Soest), The Growing Pavilion (Dutch Design Week)

8 INDIA: Arching Pavilion (Kerala)

9 SOUTH KOREA: MycoTree (Biennale of Architecture and Urbanism, Seoul)

10 INDONESIA: Mycoteck (Cipada, West Java)

Fig. 35: Arch assembly - The Circular Garden



4.4.1 The Circular Garden

The project was designed for the Milan Design Week in April 2019 by Carlo Ratti Associati, in Orto Botanico. The concept of circulation was implemented on the level of biodegradability of the material, which was grown over 6 weeks and afterwards disintegrated in soil once the exhibition was concluded. It is one of the few projects using mycelium on such a tremendous scale, as the mycelium arches were grown in one piece. The whole assembly consisted of 60 arches, each up to 4 meters high (Fig. 35). Each arch was constructed using reverse catenary principle, initially inspired by Antoni Gaudí.

For growing the mycelium structures, the architects collaborated with a well-known Dutch firm, Grown.bio. Spores were used as the inoculum, by being injected in the substrate, consisting of woodchips. The arches were grown two months before the exhibition. Other materials used in the project were ropes - to connect the arches and metal parts, which were recycled afterwards. The authors also argument the use of such degradable materials when building temporary structures for short-term exhibitions and festivals, such as the Milan Design Week, as a way of reducing usually generated large amounts of waste.[37]

37 https://carloratti.com/project/the-circular-garden/

4.4.2 MycoTree

MycoTree is the result of a collaboration between Professorship of Sustainable Construction at the Karlsruhe Institute of Technology (KIT), the Block Research Group (BRG) at the Swiss Federal Institute of Technology (ETH) Zürich and the Future Cities Laboratory (FCL) in Singapore. It was the centerpiece of the Beyond Mining - Urban Growth exhibition at the Seoul Biennale of Architecture and Urbanism 2017 in Seoul, Korea (Fig. 36).

The mycelium strain used for this project was *Ganoderma lucidum*, as it grows quickly and sturdily in a tropical climate. The production of mycelium components was developed by the company Mycotech in Indonesia. Provided from a local food industry, wood chips, sawdust and fibrous components such as cassava roots and sugar cane were used as substrate samples. They were previously tested in order to suit the mycelium strain ensuring the maximum growth rate and its structural strength. Compressive strength tests, using a uniaxial testing machine, have shown that sugar cane and cassava roots were the best fibrous option. The composite had a density of 440 kg/m^3 with 0.61 MPa compressive strength. The inoculation rate was 5%.

To achieve an even load transfer between the single elements and accordingly to the whole structure, bamboo plates were placed on each end of the element (Fig. 39). Although mycelium composites offer a great ecological alternative to similarly evaluated materials, their structural strength is relatively low compared to conventional materials such as concrete or steel. This is the reason why geometry is crucial when achieving stability does not come solely from material properties.

The geometry was designed in a way to only transfer compression, using 3D graphic statics, developed by the Block Research Group at ETH Zürich (Fig. 41).[38] The great advantage of using this technique is that the geometry of the final product is polyhedral by construction. The spatial branching of the mycelium represents a load-bearing

38 see Akbarzadeh/Van Mele/Block 2015, 118-128.

Fig. 36: MycoTree - exhibited at the Seoul Biennale, 2017

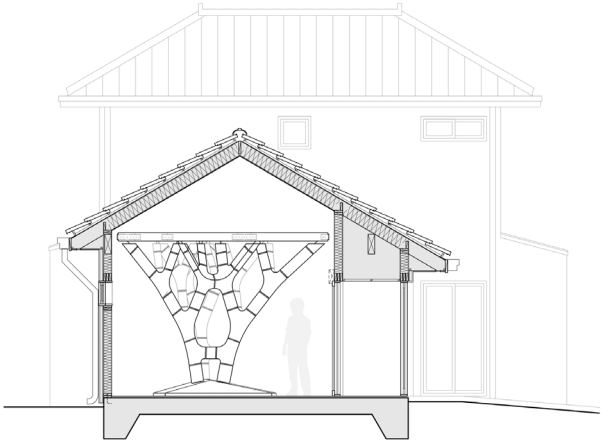


Fig. 37: MycoTree - section

Fig. 38: Filling of the digitally fabricated moulds with inoculated substrate

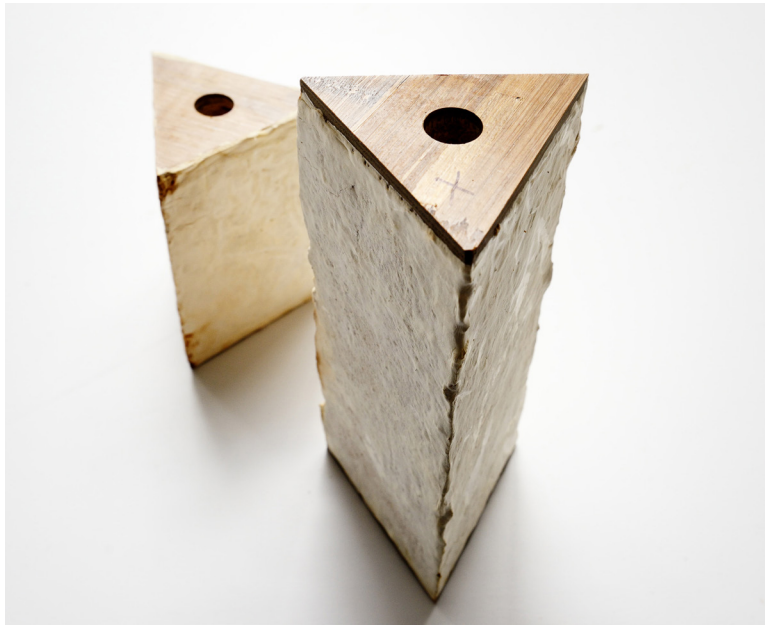


Fig. 39: Single elements with bamboo plates

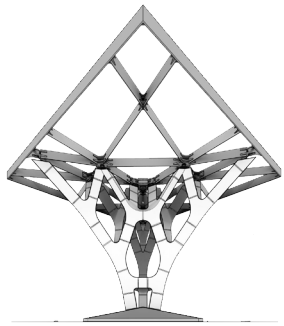


Fig. 40: Structure

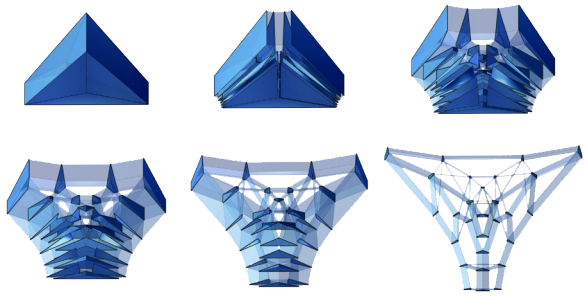


Fig. 41: Exploration of the structural geometry

element of a building, whereas the grid on the top of the structure represents the ceiling (Fig. 37), or the top floor of the building, which applies load to the mycelial structure. However, a couple of constraints were guiding the final output of the design. Each node was limited to a valency of four, to ensure effortless fabrication process and to minimize the geometry complexity. The angles between two mycelium elements had to be bigger than 30 degrees. In order to achieve continuous transitions, the distances between the node centres were limited to 40 cm. Finally, each element does not exceed 60 cm in length, to ensure no bending happens.

The fabrication process began with making the moulds for the nodes, the pieces were laser cut from reusable sheets. To avoid mechanical connections, teeth-and-slit joints were developed for simple assembly. The nodes were designed to carry their own weight through compression, whereas the grid took the tension of the whole construction. It holds the branching elements together and prevents them from falling over, its construction was manufactured by a CNC-cut 8 mm thick bamboo boards . Again, to simplify the connections between single elements, a slit-and-slot connection was chosen for the assembly.[39]

39 see Heisel et al. 2017.

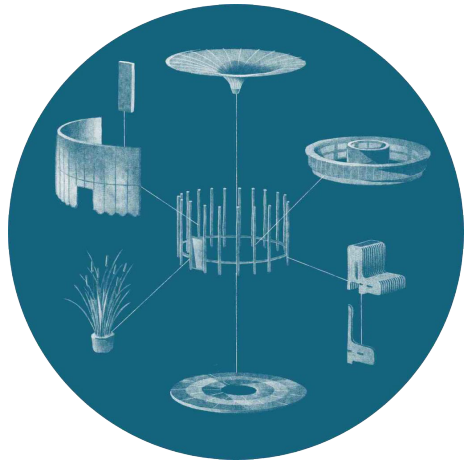


Fig. 42: Exploded image of the pavilion

4.4.3 The Growing Pavilion

This pavilion demonstrates implementation of biobased materials on every level of construction. The pavilion was built by the team of Biobased Creations of Company New Heroes, for the Dutch Design Week in 2019 and hosted more than 75,000 people in the course of ten days (Fig. 43).

To show the spectrum of the biobased materials used in this project, a material atlas was made, showing all the material research that was conducted prior to construction. The materials were categorized into several groups; natural raw materials (xyhlo mold (Aureobasidium pullulans), *Ganoderma lucidum*, hemp, cotton, aspen wood, etc.), building materials (mycelium facade panels, bio-laminate floor and furniture, ecoboard benches, cotton roof, kerto construction, xyhlo coating) . For each of the building components a life cycle analysis was made. The authors also emphasize the importance of minimizing the CO_2 emissions, whereby the pavilion itself collects the CO_2 present in the environment. It shows how construction can keep up with the challenging environmental changes we face nowadays and have a positive impact on its surroundings at the same time.

Since the structure had to fulfil the expected fire-safety regulations, the cotton roof appeared to be challenging. The cotton was water-repellent and therefore, could not absorb an impregnation agent. The firm Braindrop developed a TNF impregnating agent, which is partially biodegradable, after conducting experiments just for the cotton roof of the pavilion.

The windows were initially planned to be manufactured from a biopolymer, PLA - a plastic extracted from a natural source. However, producing the sheets in desired dimensions was not possible due to cost and time issues, so glass was chosen for the design.

The image above (Fig. 42) shows an exploded view of the pavilion, where each material component is separately displayed, showing the spectrum of all the biobased materials used in the pavilion (Fig. 44).[40]

40 https://thegrowingpavilion.com/biobased-materials/

Fig. 43: The Growing Pavilion, Dutch Design Week 2019

Fig. 44: Interior of the pavilion

4.4.4 Product range

Since there are a lot of other companies and projects that successfully manufacture and release mycelium-based products, some of them will be shortly mentioned here. The applications vary from furniture design, acoustic panels for interior use, thermal insulation, fashion, food industry and structural experiments. The fabrication process also varies from product to product, depending on the desired quality or rather the shape of the final geometry.

The first company, Ecovative, was founded in 2007 in New York, and offers numerous, very different products. Starting from the most "conventional" amongst all of the mycelium-based products, MycoComposite™ (Fig. 48) is a "patented biomaterials platform utilizing mycelium as a self-assembling biological binder for agricultural byproducts".[41] It is used as a packaging material, substituting Styrofoam, used by IKEA, Dell, Biomason, Gunlocke and Sealed Air. The next product they released is MycoFlex™ (Fig. 47), which has a performance of a foam and finds its use in the production of mycelium leather, skin care and apparel.[42] One of their most interesting products, Atlast™ (Fig. 46), is an alternative way of producing bacon in only a couple of days.[43]

An Italian company called Mogu, focused its expertise in fabricating acoustic wall panels (Fig. 50) and flooring tiles.[44] Further on, quite a few artists and designers experimented in growing their own furniture, by casting or 3D printing. Eric Klarenbeek, one of the movement´s pioneer, successfully 3D-printed a chair (Fig. 49), which is now a part of the permanent exhibition in Centre Pompidou.[45]

As previously mentioned, Philip Ross was one of the first inventors to release mycelium leather on the market, but there are also other companies whose products found their place in fashion industry, e.g. Neffa [46], founded by Aniela Hoitink, who has grown an entire dress (Fig. 45) out of circular mycelium pieces grown together.

41 https://ecovativedesign.com/mycocomposite

42 https://ecovativedesign.com/mycoflex

43 https://www.atlastfood.co/method

44 https://mogu.bio/

45 https://www.ericklarenbeek.com/

46 https://neffa.nl/

Fig. 45: Mycelium dress, Neffa

Fig. 46: Atlast™, Ecovative

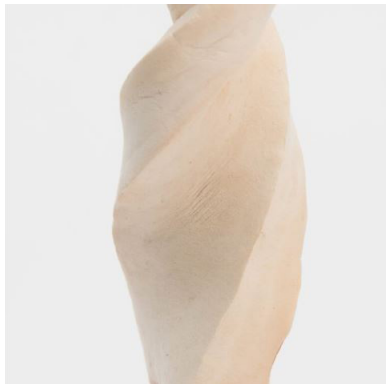


Fig. 47: MycoFlex™, Ecovative

Fig. 48: MycoComposite™, Ecovative

Fig. 49: Mycelium chair, Eric Klarenbeek

Fig. 50: Acoustic wall panels, Mogu

5 EXPERIMENTS

These sets of practical experiments served as a learning experience for myself and gaining practical skills to successfully handle mycelium. Even though there are a lot of online resources, such as do it yourself manuals and videos, which make working with mycelium look very simple and straightforward, there are still a lot of mistakes one can make if not getting properly informed. A consultation with microbiologists, biologists, mycologists or mycelium enthusiasts offers a great deal of helpful tips, which can later on be adapted to suit ones individual needs. Once a basic knowledge of working with these organisms is gained, a whole new spectrum of possibilities opens up and new experiments can be explored.

Through my learning process, I was able to visit a couple of experts in the field of microbiology and plant sciences. As these learning skills and experiments happened simultaneously during a certain period of my studies, I am going to start this chapter by explaining the basic working steps, the necessary equipment and working environment, which I had an opportunity to learn about at the University of Belgrade, department of Industrial Microbiology at the Faculty of Agriculture. Further on, a more detailed manual of my working procedure is being explained, as I needed to adapt the conventional working method to my available working space. Later on, I am going to explain the specific sets of experiments, which were conducted chronologically.

In order to better understand the circular process of fabricating mycelium composites, a growth process diagram displayed (Fig. 51).

Mushrooms reproduce by spreading spores, which are visible as dust to the naked eye. Spores can germinate if a specific set of conditions get fulfilled, such as right temperature, enough moisture and sufficient nutrients. As they germinate, they form thin threads of cells, which are called hyphae; connections between them are created as they spread, until they form a mycelial mat. If the right conditions prevail, spores can transform into mycelium (1). Mushrooms are grown either from tissue, or from spores. If grown from tissue, it's important to extract it from a fresh mushroom. If fresh mushrooms are not available, spawn or spores (5) can be purchased.[47]

Once a piece of tissue is extracted, it can be put in a growth medium on a petri dish (2). The growth expands on the medium after some time (3) and once it reaches the desired growth phase, a piece is cut from the petri dish and used for inoculation. If producing spawn, grains, such as rye (4), are sterilized and used as a substrate. When mycelium takes over the substrate, the grains are sold and ready for further inoculation (5).

For my experiments, I bought mycelium spawn from a local provider in Graz. The further steps of the growth cycle are described in the following chapter, Mycelium manual.

47 see Stamets 2005, 12.

GROWTH PROCESS

1 mycelium
2 hyphae extraction
3 mycelium cultivation
4 inoculating rye grain
5 inoculated spawn
6 humid substrate
7 mixing process
8 mould
9 unmoulding
10 drying process
11 decomposition

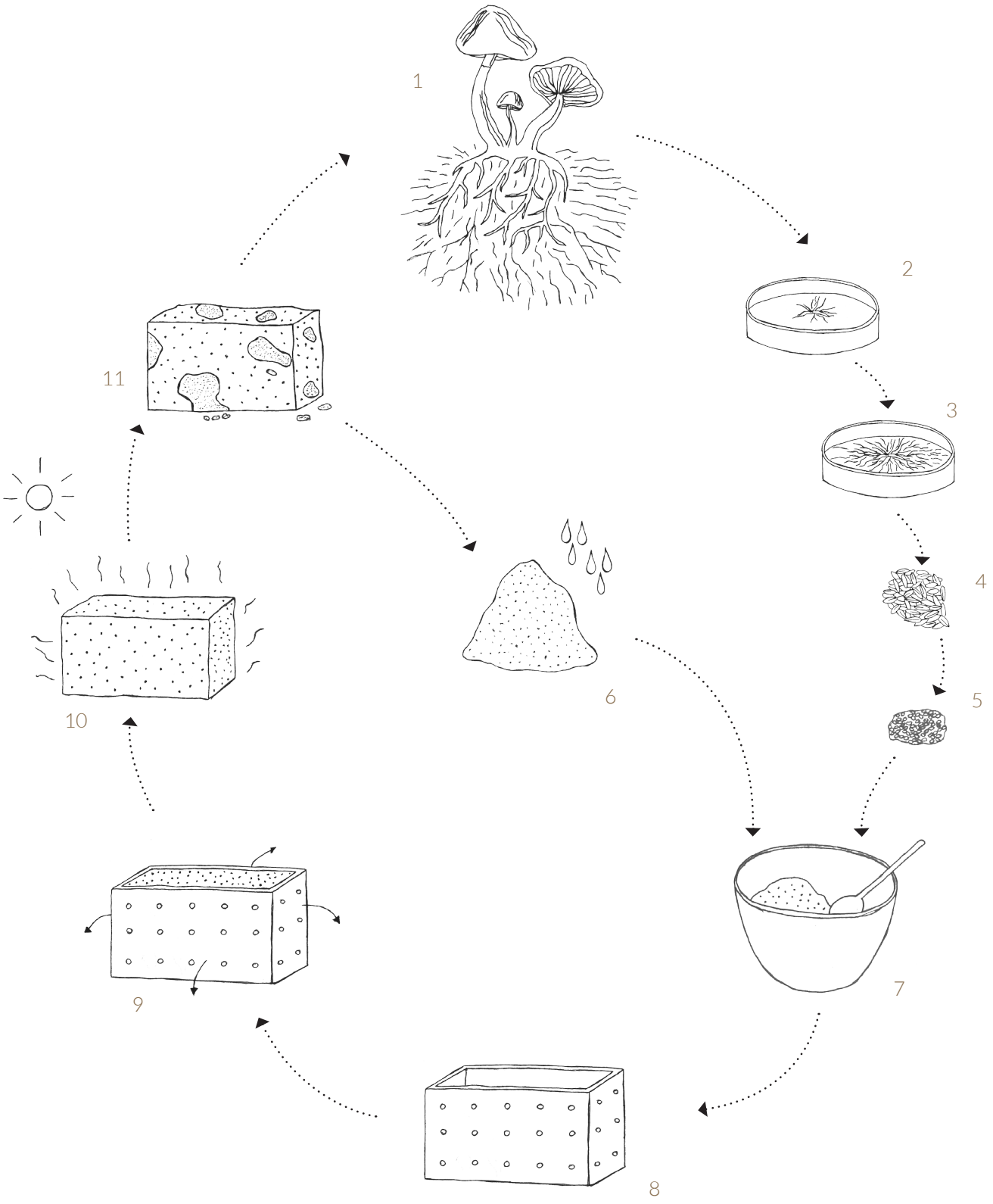


Fig. 51: Growth process diagram

Fig. 52: Some of the available substrates: sawdust, hay, wheat bran, coffee grounds, paper

Fig. 53: Unbleached paper pulp

5.1 MYCELIUM MANUAL

5.1.1 Substrate choosing

The choosing of the right substrate for a mycelium composite is usually tied to the selected strain type. As in nature, some mushrooms tend to grow under or on specific types of trees, which means that the growth can be optimised by choosing the right substrate type. Ideally, lignocellulosic biomass - dry plant matter (Fig. 53). However, many mushrooms are also suitable for growing on unconventional substrates (not found in nature), such as coffee grounds, flour or different kinds of agricultural waste (Fig. 52). Even though one can generalize and inoculate any suitable substrate type with every mycelium strain, the right lignin : cellulose ratio can benefit the growth.

5.1.2 Substrate scale

If using bigger pieces, e.g. hay (Fig. 57), it is better to make them small so that the biggest pieces do not exceed 3 cm. This is helpful because the roughness of that kind of substrate contradicts the desired stiffness of the end product. It's possible to manually press the material in a certain mould where the growth will take place, but working with smaller pieces makes it more comfortable.

On the other hand, while working exclusively with tiny pieces of substrate, like coffee (Fig. 54), wheat bran (Fig. 55) or flour, there is a possibility that the substrate gets too dense and the growth stops because of insufficient oxygen flow. When talking about particle size, these have a grain size smaller than 1 mm. Mycelium needs air to breathe, so packing it tightly in a plastic bag without a filter won't work successfully. If working with such type of substrate is desired nevertheless, a promising method would be combining it with another substrate, which has slightly larger bits, e.g. wood chips; 3-7mm (Fig. 56).

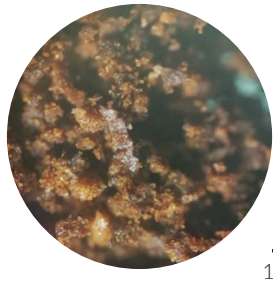


Fig. 54: Coffee grounds

Fig. 55: Wheat bran

Fig. 56: Wood chips

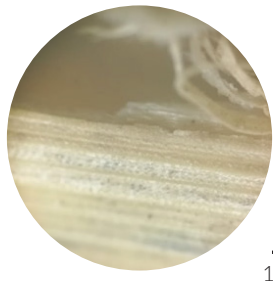


Fig. 57: Hay

Fig. 58: Soaking sawdust

Fig. 59: Substrate before sterilization

Fig. 60: Weighing the dry substrate

5.1.3 Soaking

In order to grow, just like plants, mycelium needs water. This is achieved by soaking the substrate in water overnight, or for 24 hours (Fig. 58). It gives the substrate enough time to soak up as much water as needed, as it later becomes an important factor for mycelial growth. If the organic matter remains too dry, growth will not take place. Overly moist substrates also hinders the mycelial growth, because moulds and bacteria thrive in this kind of environment. To reach the right amount of humidity will give mycelium a head start for development, before the bacteria have the chance take over.

After sufficient soaking time, excess water has to be drained. This is mostly done by putting the damp material in a cloth bag, or something similar, and compressing the material until the excess water has drained.

Any additional refinement of the substrate should be done in this stage of the process. Once the sterilization begins, the material manipulation should be reduced to a minimum. Combining of different substrates, if desired, and weighing the wet material should take place before the sterilization. This step can also be done before the soaking (Fig. 60), but ideally afterwards in order to adequately determine the mycelium rate. The rate is relevant for the inoculation, in order to know how much mycelium needs to be added later.

5.1.4 Sterilizing

The substrate is placed in glass or metal containers, or in autoclavable bags. There are special kinds of bags on the market, which are used specifically for mushroom cultivation. They are manufactured to sustain high temperatures up until 123 °C and have integrated filter strips.[48] This has a big advantage because oxygen can enter the bag without a risk of contamination from the exterior environment. An alternative solution for this would be to buy plastic bags for oven baking, which are usually available in every local grocery store. After the bag is sealed, the substrate is ready for sterilization.

A third option is to obtain, as previously mentioned, glass or metal containers. It is important to note that every piece of plastic or rubber seals has to be removed. The substrate is placed accordingly and a lid is put on top, not sealed. If a metal lid is not available, a piece of aluminium foil can substitute it.

Ideally, an autoclave is used for this process, where sterilizing takes place at 121°C for around 120 minutes.

Alternative way of sterilizing is using a pressure cooker (Fig. 59), by pouring water in the pot, approximately up until the height of the trivet and just underneath the steamer basket. The glass container or the bag with the substrate is placed in the basket and the pot is sealed. The stove should be set to achieve maximal temperature and cook. Once the pot starts releasing steam, a timer can be set.

The problem with using pressure cooker is usually its volume. There is a finite amount of water which can be put as previously explained, but it's most likely not enough to

48 https://saco2.com/zipper-filter-pp-bags-2/

last for 120 minutes. This should be tested beforehand; the approximate time of water evaporating while cooking compared to the leftover water in the pot. For instance, my cooking pot can fit around 1,2 L of water below the basket, which evaporates after cca. 40 minutes. So the technique I apply is to cook the same substrate three times for 40 minutes, each time refilling the water in the pot.

Once the sterilizing process is finished, the material has to cool down before inoculation can commence. If mycelium is introduced to the freshly cooked substrate, the heat will kill all living organisms in the spawn. Its temperature should be reduced roughly to room temperature, so the best thing to do is to let it cool on its own overnight and continue on the next day. The sterile material can be left in an unopened pot, so that way the whole container remains sterile before its further use.

5.1.5 Inoculation

The best way to secure a sterile environment, during inoculating, is to work in laminar flow cabinet (Fig. 72). The sterile cabinet ensures optimal conditions during blending the substrate with mycelium, filling the moulds and securing them for their growing period.

If a laminar flow cabinet is not available, a simple alternative is a working surface sterilized with ethanol (70%), trying to bypass contamination that might later hinder the growing process.

Another way is to build the “sterile box” with smooth sides (e.g. plastic, metal or glass) that can be disinfected effortlessly with ethanol. This method offers a semi-control over bacteria and possible contaminats flying around the air. Similar to the laminar flow cabinet, the box should have a small opening at the bottom of the front side for handling the material. Every piece of equipment needed in the box needs to be disinfected (with ethanol), like mycelium bags, mixing containers and tools like spoons and scalpels.

Every time before reaching in the box, hands must be sprayed with ethanol for disinfection purposes. Use of gloves is encouraged, but when reaching outside the box they should be replaced or sprayed. Another thing to point out is that a surface becomes sterile, once the ethanol dries out. Soaking the apparatus in alcohol and starting straight away while it is still wet does not mean that the risk of contamination is evaded.

Working in this kind of environment does not guarantee a successful outcome, but with practice, the success rates rise. Not everything can be cleaned perfectly, but the better it gets, the higher the chances are for mycelium to stay unspoiled. Once everything is clean and placed in the box, the inoculation can begin. The next few steps describe the preparation of a 10 x 10 x 10 cm sample in a plastic mould.

The usual amount of mycelium varies from 3-10 %, but using more is going to accelerate the growth. One 10 x 10 x 10 cm mould fits approximately 500 g of wet sawdust (Fig. 62), according to which is the mycelium amount calculated. After weighing the mycelium, the spawn is separated and evenly distributed throughout the substrate.

The bottom of the mould is filled and then firmly pressed with a spoon or fingers. This procedure is repeated layer by layer (Fig. 63). Attention should be brought to the corners of the mould, as they tend to stay loose if not compressed properly. When done, the mould is closed by gluing its lid with a tape.

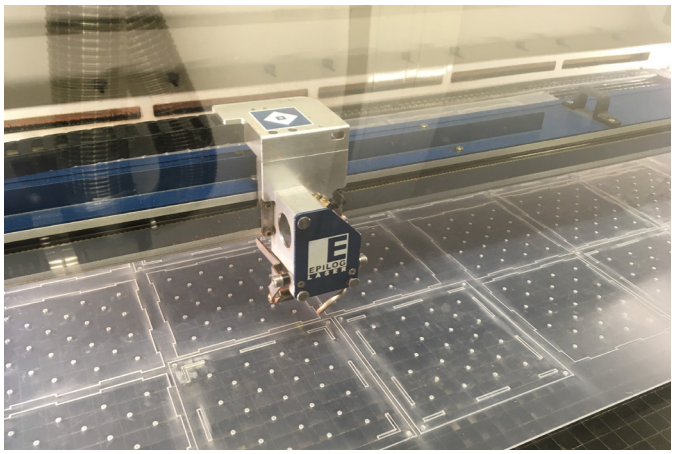


Fig. 61: Lasercutting the mould pieces

Fig. 62: Weighing the sterilized substrate

Fig. 63: Filling mould with inoculated mixture

Fig. 64: Mould removal

Fig. 65: Drying process

5.1.6 Storing and drying

The closed mould is relocated to a clean and safe growing environment, e.g. a microfilter bag (Fig. 66). The moulds need to be placed in a completely dark area, with room temperature varying between 22-25°C. In the initial growing phase, mycelium produces heat while digesting the substrate, which is why the temperature needs to be monitored so that it does not exceed 26°C. If that does happen, the mycelium basically "cooks itself" and dies. Even though the mycelium grows rapidly with higher temperatures (up to some point), there is also a higher chance of contamination. So the safe way to handle the process is to let it grow at its own pace at a lower temperature (22-24°C).

It is difficult to estimate how long it takes until the mycelium digests its nourishment, because depends highly on the substrate, strain type and amount of mycelium used. For instance, for the previously mentioned 10x10x10 cm brick, growing 15% of *Ganoderma lucidum* on wood chips at the recommended temperature should not take more than two weeks. The best indicator is when the surface of the brick becomes completely white (Fig. 67). It is also recommended to make punctures in the mould to allow oxygen to penetrate the form. After a week, the mould can be removed (Fig. 64) while the bounded substrate still remains in the microfilter bag, so that the mycelium grows its outer protective skin, and the cube becomes completely white.

Once the object becomes completely overgrown with mycelium, it is safe to unmould it and dry it out in a drying cabinet. Putting the brick on a heating source also works really well, as well as putting it in a warm and sunny place indoors. Baking it in an oven for 3-4 hours at 50-80°C also works well. As there will be some humidity left in the brick, even after long baking, the brick should be turned over every 1-2 days, so no mould grows underneath it.

Fig. 66: Growth in the microfilter bag

Fig. 67: White surface indicates sufficient growth

Fig. 68: Autoclave

Fig. 69: Placing the substrate before sterilization

Fig. 70: Working environment

5.2 UNIVERSITY IN BELGRADE

As previously mentioned, the learning experience and the knowledge I gained after spending some time at the University in Belgrade played a very important role in the practical part of my research, i.e. all the experiments conducted afterwards. During that period, I had the opportunity to enhance my self-thought techniques to the level of basic understanding of each step, through a microbiologist perspective. Thanks to Anita Klaus and her colleagues at the department of Industrial Microbiology, I was able to continue my experiments with mycelium, resulting with a much higher success rate and was able to try out other new material combinations. The procedure of the work conducted at the University was very similar to the one explained in detail in the previous chapters.

Fig. 71: Weighed substrate after soaking

Fig. 72: Laminar flow cabinet

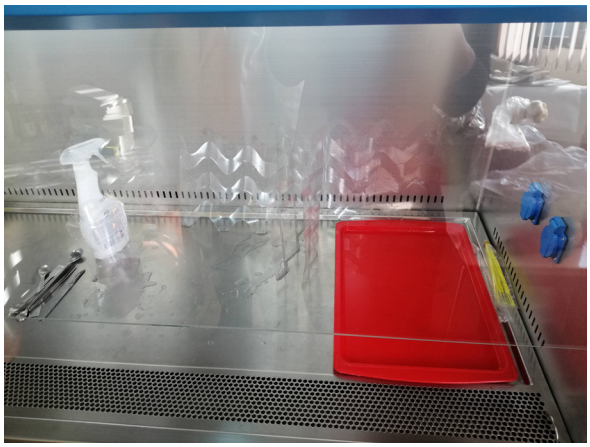


Fig. 73: Cleaning the moulds with ethanol

Fig. 74: Mould filling

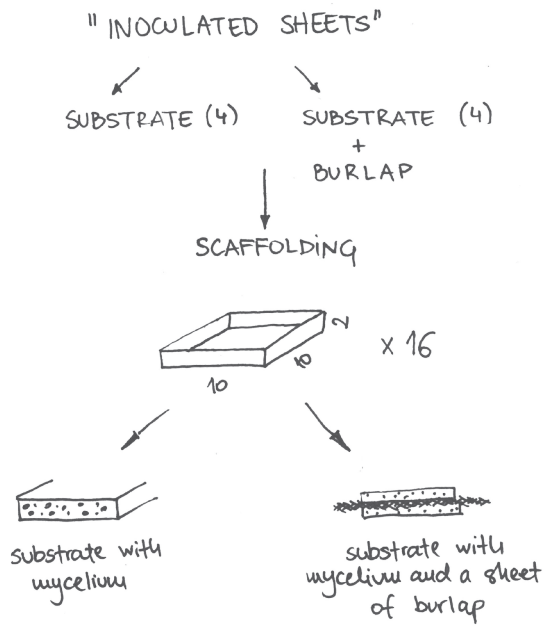
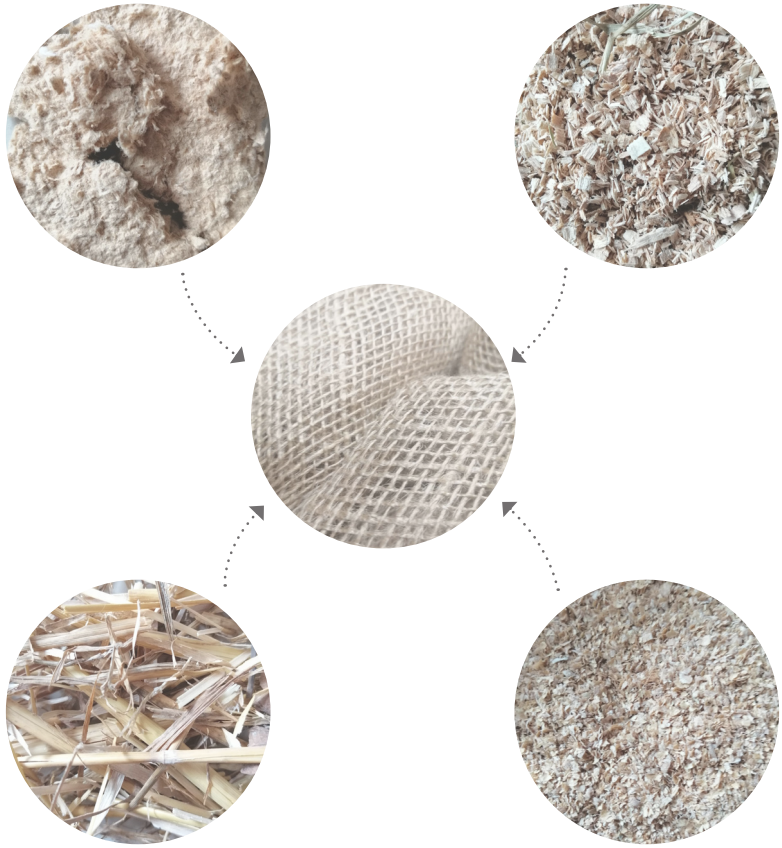


Fig. 75: Inoculation scheme

5.3 SUBSTRATE AND GROWTH EXAMINATION

The first experiments of different substrates inoculated with the same mycelium type have been done in moulds 10 x 10 x 2 cm. Initially, the substrate choosing was determined by the materials which were available at the moment, such as hay, beech sawdust, wheat bran and unbleached cellulose (Table 1). Each combination was repeated in 4 moulds; two of them consisting only of the substrate and mycelium, and the other two in combination with a burlap sheet mixed with the substrate (Fig. 75). Burlap was added to the experiment because the idea of mycelium possibly digesting this natural fabric seemed promising for further exploration. The 16 moulds were inoculated with *Pleurotus ostreatus*.

The substrate was soaked in water overnight. Hay had to be cut in smaller pieces, which would not exceed 3 cm in length, because the airiness of the material contradicts with the wanted density of the sample. As for the other materials, their natural composition was sufficient for the testing. After the preparation, the substrate was placed in glass containers and sterilized in a pressure cooker for at least 20 minutes. Since the material had to cool down to room temperature, further steps continued the next day.

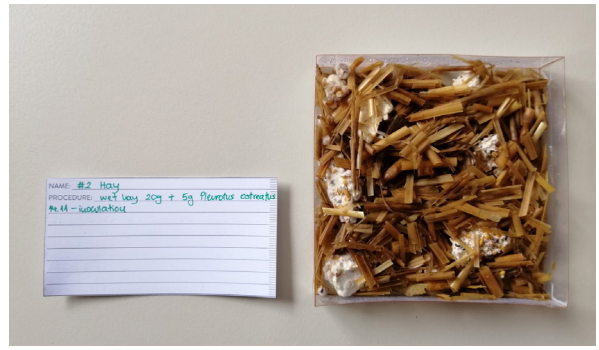


	HAY	WHEAT BRAN	PAPER PULP	BEECH SAWDUST
substrate	#1	#5	#9	#13
substrate	#2	#6	#10	#14
substrate + burlap	#3	#7	#11	#15
substrate + burlap	#4	#8	#12	#16

Table 1: Substrate and composition naming

day 3

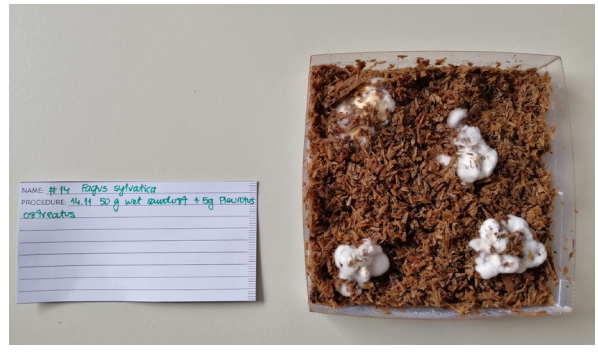
hay



wheat bran

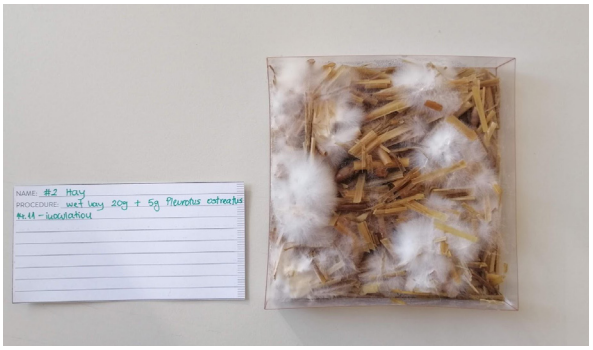
paper pulp

sawdust



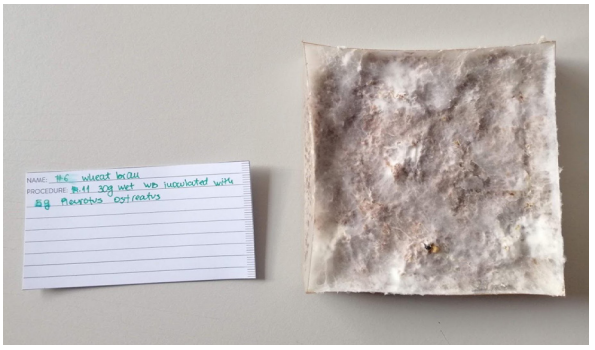
day 5

day 19

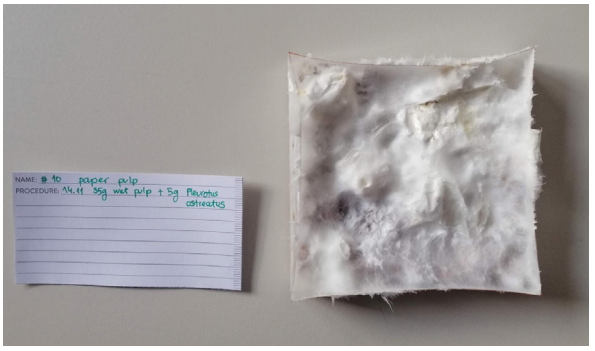

NAME: #2 Hay
PROCEDURE: wet hay 20g + 5g Pleurotus ostreatus
#4.11 - inoculation


NAME: #2 Hay
PROCEDURE: wet hay 20g + 5g Pleurotus ostreatus
#4.11 - inoculation


NAME: #6 wheat bran
PROCEDURE: #4.11 30g wet wb inoculated with
5g Pleurotus ostreatus


NAME: #6 wheat bran
PROCEDURE: #4.11 30g wet wb inoculated with
5g Pleurotus ostreatus


NAME: # 10 paper pulp
PROCEDURE: 14.11 35g wet pulp + 5g Pleurotus
ostreatus


NAME: # 10 paper pulp
PROCEDURE: 14.11 35g wet pulp + 5g Pleurotus
ostreatus


NAME: # 14 Fagus sylvatica
PROCEDURE: 14.11 50 g wet sawdust + 5g Pleurotus
ostreatus

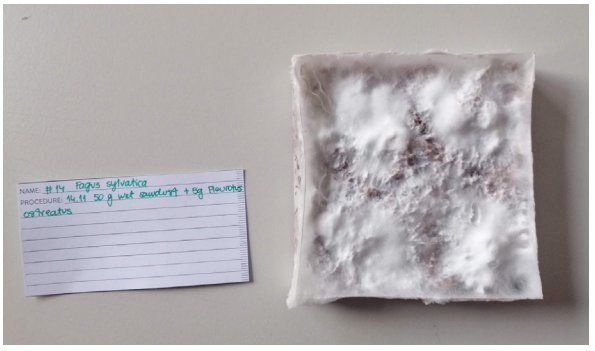

NAME: # 14 Fagus sylvatica
PROCEDURE: 14.11 50 g wet sawdust + 5g Pleurotus
ostreatus

Fig. 76: Sawdust - day 3

Fig. 77: Sawdust - day 5

Fig. 78: Sawdust - day 19

Fig. 79: Hay - day 5

Fig. 80: Paper pulp - day 5

Fig. 81: Hay on burlap - day 5

Inoculation was conducted in a “sterile” environment, in a diy sterile box. Each sample was inoculated with roughly 5g of *Pleurotus ostreatus*. The moulds were not sealed with a lid, because greater surface contact with oxygen accelerates growth. To keep the sterile conditions for as long as possible, aluminium foil was used to cover the moulds, without directly touching the substrate. The foil was punctured to allow necessary oxygen exchange. The samples were placed on trays which were put away in a dark chamber.

Besides successfully grown samples, a detailed growth documentation was recorded. It shows variations of growth patterns and speed of the same mycelium strain, and its preferred nutrition. On the other hand, the more the aluminium foil had to be removed to allow the documentation to take place, the greater the chance was for bacteria to enter, and consequently, contaminate the sample.

As seen in the displayed documentation, the initial growth was noticeable already after a couple of days. Since the mycelium was not mixed homogeneously in the sample, the growth starting at the core (mycelium grains) spread until it covered the whole surface of the sample. Since the plastic used for the moulds was transparent, the growth on the covered sides was visibly smaller. As a consequence, the samples were unmoulded after 20 days, the plastic was removed and the sample was turned around and covered again in a piece of aluminium foil, in order to get white and equal growth on all sides. The second growth phase (after the unmoulding) took around 10 days. The samples were finally dried on a heating source.

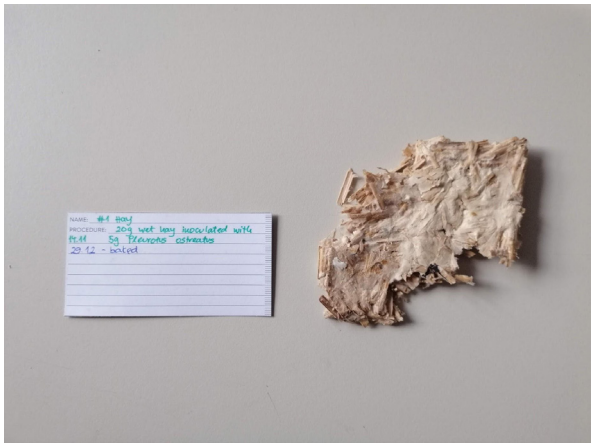


Fig. 82: Hay

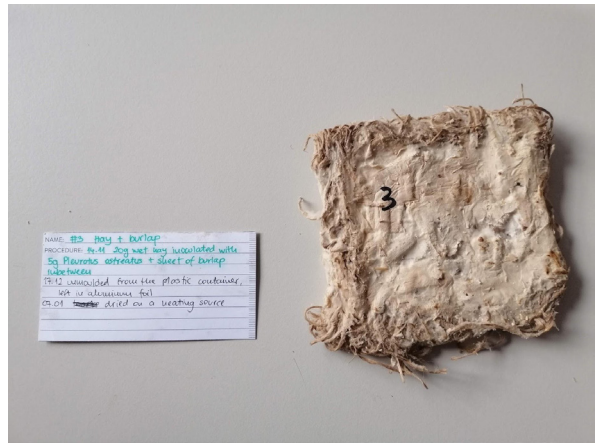


Fig. 83: Hay + burlap

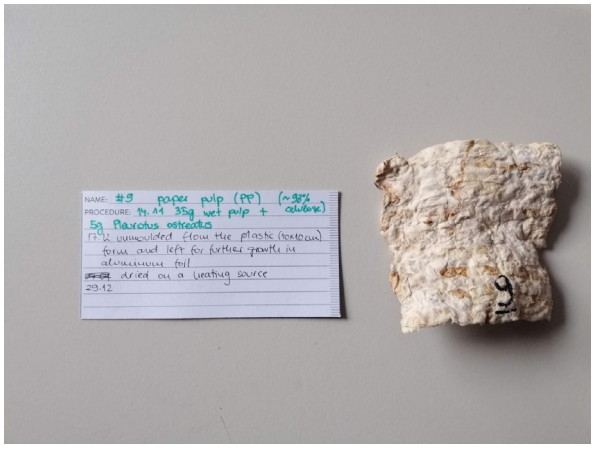


Fig. 84: Paper pulp

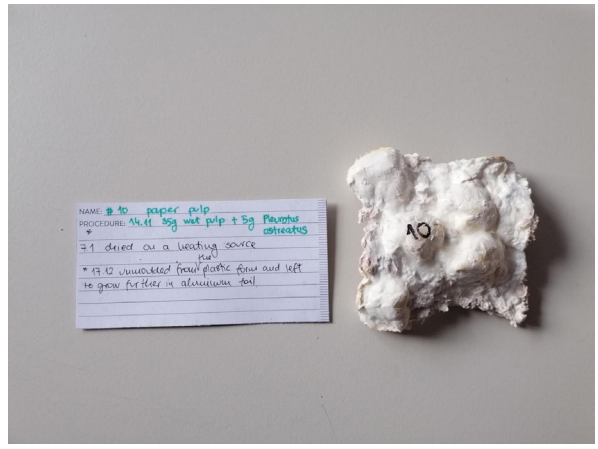


Fig. 85: Paper pulp

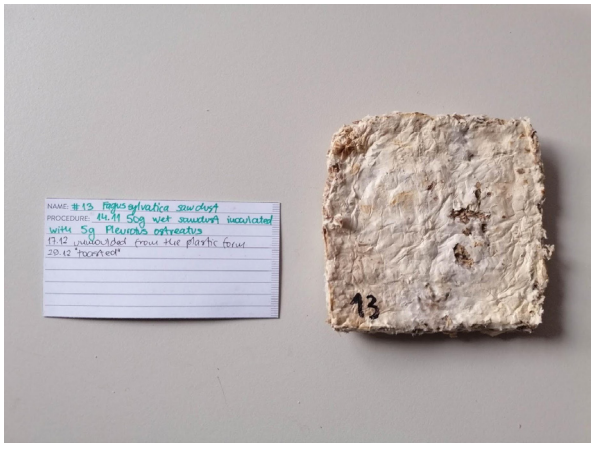


Fig. 86: Beech sawdust

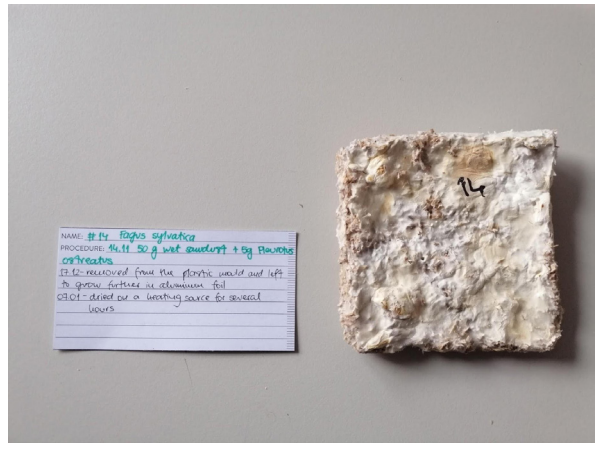


Fig. 87: Beech sawdust

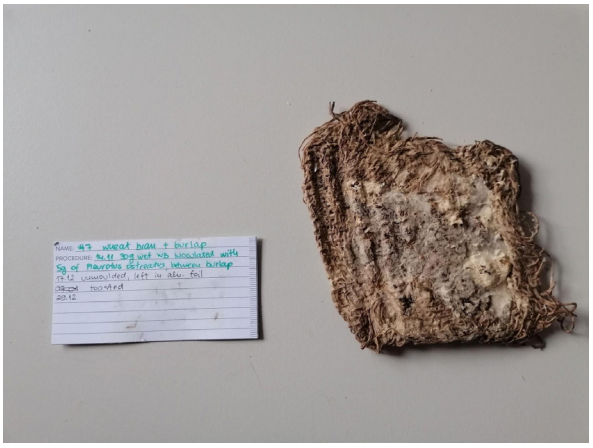


Fig. 88: Wheat bran + burlap

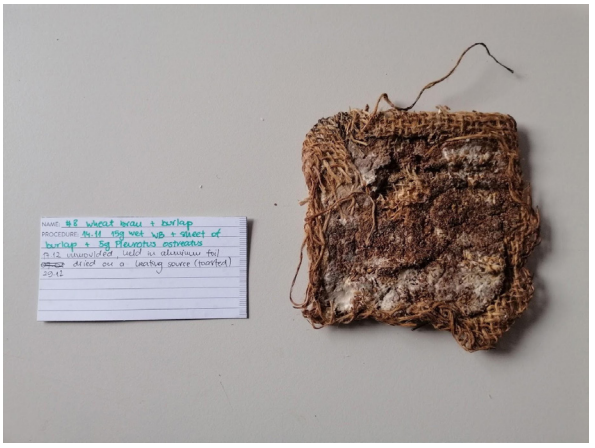


Fig. 89: Wheat bran + burlap

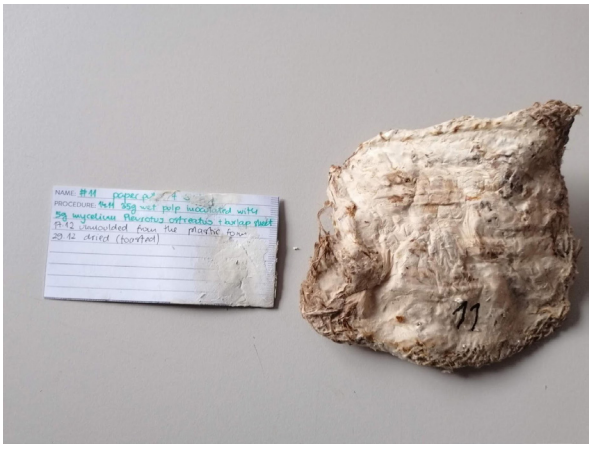


Fig. 90: Paper pulp + burlap

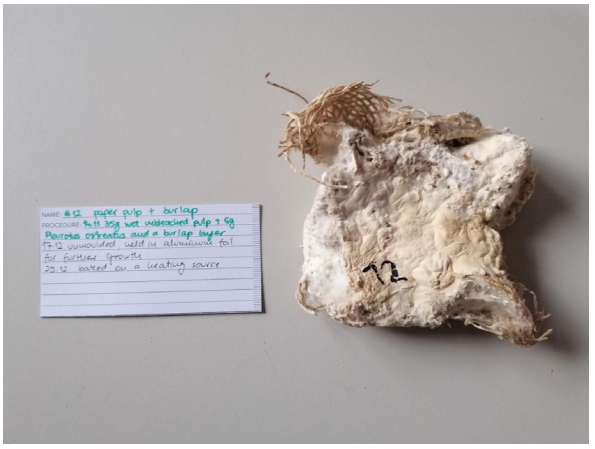


Fig. 91: Paper pulp + burlap

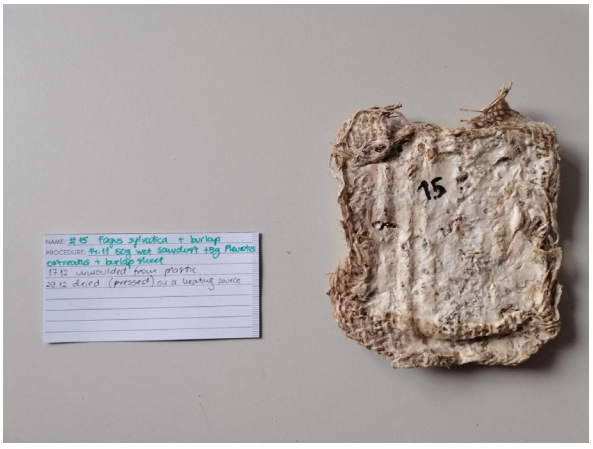


Fig. 92: Beech sawdust + burlap

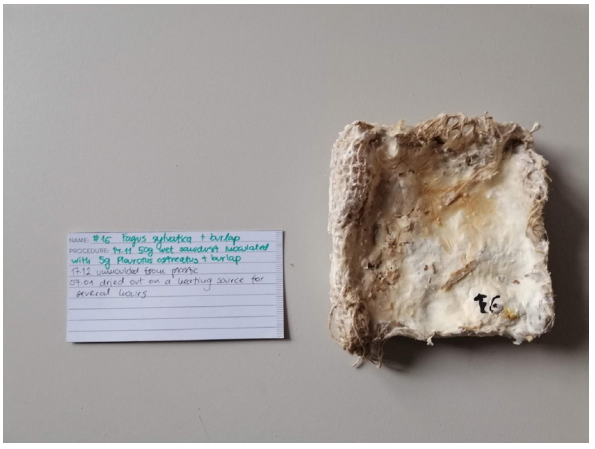


Fig. 93: Beech sawdust + burlap

5.3.1 CONCLUSION

Since the whole experiment included just the 16 samples mentioned, the conclusions stated here may be inconsistent. If the tested spectrum had more samples, the results would have been more reliable. The parameters commented here will regard breaking and shrinking, contaminations, growth density and colour as the visual aspect.

Samples #1 - #4

Pieces of hay are still noticeable, even after one month after inoculation. As the substrate was not properly compressed before inoculating, the airiness in the material is still visible, therefore prone to breaking. Shrinking is minimal, but that is also an unreliable piece of information since both of the hay samples got broken as soon as they were dried. From the four samples, two of them got contaminated. However, growth speed was tolerable, since the mycelium spread out on the surface completely in a matter of days. An evaluation of surface quality can not be made, because of the breaking (Fig. 82).

Samples #5 - #8

As the pure wheat bran examples (#5, #6) got contaminated, defining the shrinking and breaking is questionable because of the burlap piece. Nevertheless, an evaluation of the samples which are left can be stated. Even thought they had a piece of burlap in them, the samples were still very prone to breaking (Fig. 88). According to the dark colour, it can be stated that mycelium has not managed to create its coat. Probably because the substrate has not been completely grown out. To summarise, wheat bran is very unlikely to stay sterile and therefore will not be used in future testing.

Samples #9 - #12

The pieces of cellulose were randomly dispersed in the container, whereas the mycelium grew entirely in the given borders. After the drying process, the substrate shrank up to 40%, making it unpredictable if specific dimensions are to be made. However, the material became very stiff. That is why the material will definitely be used in the future. In order to anticipate, or at least reduce, the large shrinking factor, the cellulose should be dispersed all over the container and packed quite densely. The mycelium grains have to be divided throughout the substrate in a homogeneous manner. This applies for every sample, not only the ones with cellulose. The surface has an extremely white colour and a tough skin (Fig. 85). None of the samples got contaminated.

Samples#13 - #16

The material has not compressed after inoculating and became light and airy after the drying process. Shrinkage goes up to 10%, which is a relatively reliable value for future use. Similarly as with all samples, the density of the substrate particles plays a big role for the stiffness of the dried product. The outer layer of the samples has a light brown colour (Fig. 87) and the outer skin has not grown as homogeneously as in the cellulose samples.

5.4 CARDBOARD AND TEXTILES AS SCAFFOLDING

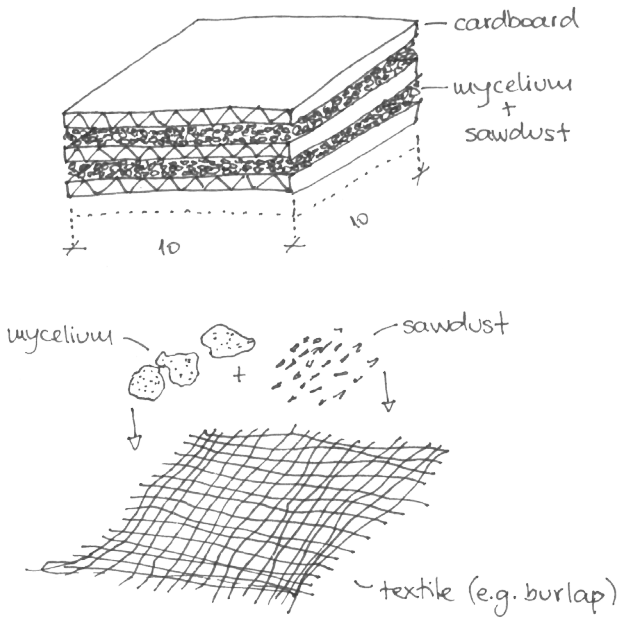


Fig. 94: Inoculation scheme - cardboard and textiles

Another approach was to go away from the relatively precise casting technique. Even though the plastic moulds can be reused, the next experiment tested the possibility of mycelium permeating and simultaneously digesting its framework (Fig. 94).

A couple of textiles were used, burlap as well. Same technique was applied as described for previous organic substrates. The piece of fabric was soaked in water overnight, then sterilized in a pressure cooker for 20 minutes, after the medium cooled down, inoculation started. Because the textile is not very nourishing, a preinoculated substrate was added to the sample. It was expected from mycelium to overgrow the inoculated substrate and the fabric, and then bend and deform them in the drying process. The experiment has not fulfilled the expectations because the fabric got too heavy from the substrate.

On the other hand, the samples with stacked cardboard pieces showed more promising results. Three types of cardboard were used: cellulose, regular and cardboard for models (Fig. 96). The pieces were cut in the same dimension (10 x 10 cm) and gently stacked on each other, with inoculated woodchips between each piece (Fig. 97), without using additional compression. Mycelium connected the layers into one solid piece with minimal deformation.

Fig. 95: Inoculated textile

Fig. 96: Cardboard soaking

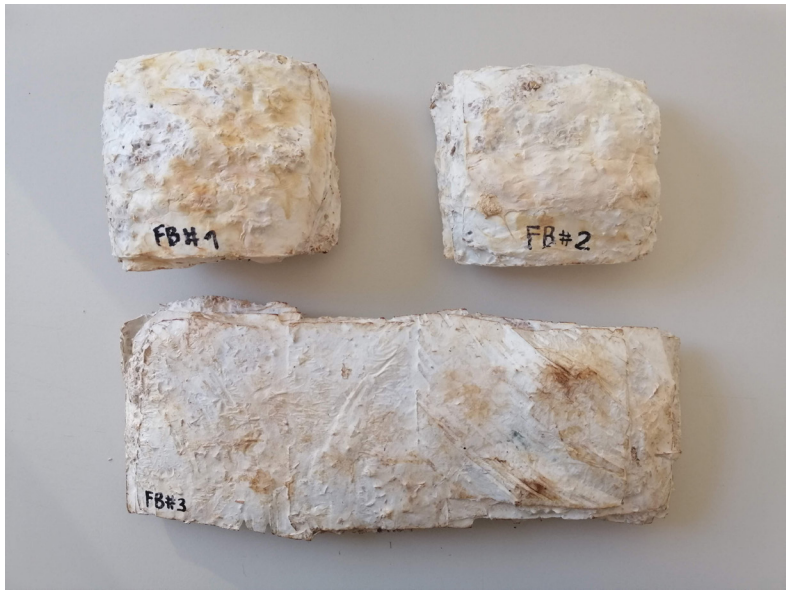


Fig. 97: Stacked cardboard pieces - dried

5.5 NOMENCLATURE

Since there is quite a large number of samples which were, and still are, being made, a certain naming method needed to be developed. Some of these are exhibited in Table 2 and 3. The system is based on several parameters, usually used in the process of making an object.

Firstly, the material preparation. The preparation varies from a homogeneous mix of one organic part with mycelium, to a blend of two or more components equally distributed into one composite. The components can also be inorganic, while at least one of the components remains organic. Additionally, the composition of one sample can be heterogeneous and depending on its inner arrangement, more than one outcome is possible.

Secondly, the number of compounds defined. Since the inorganic part may or may not be included in the sample, it comes before the organic component. There is a big variety of both of these categories, which will be discussed later on.

The third parameter is the type of the mycelium strain. They are named after both Latin names of the sampled mycelium.

Lastly, the samples are numbered chronologically, in double digits and if the parameters previously mentioned remain the same for two samples, another digit is added. Other aspects, not included in the initial naming system, are e.g. the dimension of each sample, the amount of time a substrate is being sterilized, the inoculation rate, the date of inoculation, the storage/growing conditions, the drying process, notes and, if necessary, the contamination description. An overview of some of the sample tracking is displayed in Tables 2 and 3.

To summarize all the basic parameters, a formula and a list of frequent names is listed:

MC-IM-OM-MT-NR

material composition - inorganic material - organic material - mycelium type - sample number

MATERIAL COMPOSITION

MM - mixed material, homogeneous distribution

SM - surface model; two materials are brought in contact with each other on one surface, the first one usually being organic and inoculated with mycelium, and the second one inorganic, without inoculation

LM - layered material, different from SM regarding the number of layers (more than two), usually a repetitive exchange of at least two materials, if organic all of them get inoculated

ORGANIC COMPOUNDS

FS - *Fagus sylvatica* (beech sawdust)

CS1 - white, bleached cellulose

CS2 - brown, unbleached cellulose

CS3 - washed out brown cellulose

SF - soy fibres

CO - cotton

SC - shredded cardboard

SN - shredded newspaper

CF - coffee grounds

H - hay

WB - wheat bran

INORGANIC COMPOUNDS

C - modelling clay

CP - powdered clay

S - sand

ST - stones, 5 mm

MYCELIUM STRAINS

PO - *Pleurotus ostreatus* (pearl oyster)

GL - *Ganoderma lucidum* (reishi)

HE - *Hericium erinaceus* (pom pom)

PD - *Pleurotus djamor* (pink oyster)

	Name	Dimension	Sterilization	Inoculation	Mycelium	Substrate	Storage	D
1	MM-SF-GL-01	10 x 10 x 10 cm	13.03.2020	14.03.2020	*Ganoderma lucidum*, 20%	soy fibres	mycrofilter bag, boxed, 17-23°C	sc
2	MM-FSSF-PO-01	10 x 10 x 10 cm	13.03.2020	14.03.2020	*Pleurotus ostreatus*, 20%	soy fibres, *Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	sc
3	MM-FS-PO-01	10 x 10 x 10 cm	29.03.2020	30.03.2020	*Pleurotus ostreatus*, 10%	*Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
4	MM-FS-PO-02	10 x 10 x 10 cm	29.03.2020	30.03.2020	*Pleurotus ostreatus*, 10%	*Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
5	SM-S-FS-PO-01	10 x 10 x 10 cm	29.03.2020	31.03.2020	*Pleurotus ostreatus*, 10%	sand, *Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
6	SM-ST-FS-PO-01	10 x 10 x 10 cm	02.04.2020	03.04.2020	*Pleurotus ostreatus*, 10%	stones, *Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
7	SM-C-FS-PO-01	10 x 10 x 10 cm	02.04.2020	03.04.2020	*Pleurotus ostreatus*, 10%	clay, *Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
8	MM-SC-PO-01	10 x 10 x 10 cm	02.04.2020	03.04.2020	*Pleurotus ostreatus*, 10%	cardboard, shredded	mycrofilter bag, boxed, 17-23°C	in
9	MM-SN-PO-01	16 x 4 x 4 cm	02.04.2020	03.04.2020	*Pleurotus ostreatus*, 10%	newspaper, shredded	mycrofilter bag, boxed, 17-23°C	in
10	MM-S-FS-PO-01	10 x 10 x 10 cm	07.04.2020	08.04.2020	*Pleurotus ostreatus*, 10%	sand:sawdust = 1:1	mycrofilter bag, boxed, 17-23°C	sa
11	MM-S-FS-PO-02	10 x 10 x 10 cm	07.04.2020	08.04.2020	*Pleurotus ostreatus*, 10%	sand:sawdust = 1:4	mycrofilter bag, boxed, 17-23°C	sa
12	MM-S-FS-PO-03	16 x 4 x 4 cm	07.04.2020	08.04.2020	*Pleurotus ostreatus*, 10%	sand:sawdust = 1:1	mycrofilter bag, boxed, 17-23°C	sa
13	MM-S-FS-PO-04	16 x 4 x 4 cm	07.04.2020	08.04.2020	*Pleurotus ostreatus*, 10%	sand:sawdust = 1:4	mycrofilter bag, boxed, 17-23°C	sa
14	MM-C-FS-GL-01	10 x 10 x 10 cm	09.04.2020	10.04.2020	*Ganoderma lucidum*, 10%	clay:sawdust = 1:4	mycrofilter bag, boxed, 17-23°C	w
15	MM-C-FS-GL-02	16 x 4 x 4 cm	09.04.2020	10.04.2021	*Ganoderma lucidum*, 10%	clay:sawdust = 1:4	mycrofilter bag, boxed, 17-23°C	w
16	MM-C-FS-GL-03	10 x 10 x 10 cm	16.04.2020	23.04.2020	*Ganoderma lucidum*, 10%	clay:sawdust = 1:8	mycrofilter bag, boxed, 17-23°C	w
17	MM-C-FS-GL-04	16 x 4 x 4 cm	16.04.2020	23.04.2020	*Ganoderma lucidum*, 10%	clay:sawdust = 1:8	mycrofilter bag, boxed, 17-23°C	w
18	MM-SC-PO-02	16 x 4 x 4 cm	08.04.2020	09.04.2020	*Pleurotus ostreatus*, 10%	cardboard, shredded	mycrofilter bag, boxed, 17-23°C	in
19	MM-FS-GL-01	10 x 10 x 10 cm	06.04.2020	08.04.2020	*Ganoderma lucidum*, 10%	*Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
20	MM-FS-GL-02	10 x 10 x 10 cm	06.04.2020	08.04.2020	*Ganoderma lucidum*, 10%	*Fagus sylvatica*	mycrofilter bag, boxed, 17-23°C	in
21	MM-CO-PO-01	10 x 10 x 10 cm	29.03.2020	08.04.2020	*Pleurotus ostreatus*, 10%	cotton	mycrofilter bag, boxed, 17-23°C	sr
22	MM-SC-GL-01	10 x 10 x 10 cm	08.04.2020	09.04.2020	*Ganoderma lucidum*, 10%	cardboard, shredded	mycrofilter bag, boxed, 17-23°C	no
23	MM-CS1-PO-01	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Pleurotus ostreatus*, 10%	white cellulose	mycrofilter bag, boxed, 17-23°C	
24	MM-CS1-GL-01	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	white cellulose	mycrofilter bag, boxed, 17-23°C	
25	MM-C-CS1-GL-01	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 1:1	"aquarium", 20-22°C	w
26	MM-C-CS1-GL-02	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 1:2	"aquarium", 20-22°C	w
27	MM-C-CS1-GL-03	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 1:4	"aquarium", 20-22°C	w
28	MM-C-CS1-GL-04	10 x 10 x 10 cm	22.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 1:6	"aquarium", 20-22°C	w
29	MM-C-CS1-GL-06	10 x 10 x 10 cm	22.04.2020	23.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 2:1	"aquarium", 20-22°C	no
30	MM-C-CS1-GL-07	10 x 10 x 10 cm	23.04.2020	24.04.2020	*Ganoderma lucidum*, 10%	clay:cellulose = 1:2	"aquarium", 20-22°C	bl
31	MM-CS1-PO-02	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Pleurotus ostreatus*, 10%	white cellulose	"aquarium", 20-22°C	
32	MM-CS1-GL-02	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Ganoderma lucidum*, 10%	white cellulose	"aquarium", 20-22°C	
33	MM-CS2-PO-01	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Pleurotus ostreatus*, 10%	brown cellulose	"aquarium", 20-22°C	
34	MM-CS2-GL-01	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Ganoderma lucidum*, 10%	brown cellulose	"aquarium", 20-22°C	
35	MM-CS3-PO-01	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Pleurotus ostreatus*, 10%	washed out brown cellulose	"aquarium", 20-22°C	
36	MM-CS3-GL-01	10 x 10 x 2 cm	12.05.2020	13.05.2020	*Ganoderma lucidum*, 10%	washed out brown cellulose	"aquarium", 20-22°C	co
37	MM-C-CS2-GL-01				*Ganoderma lucidum*, 10%	clay:cellulose = 1:1		
38	MM-C-CS2-GL-02				*Ganoderma lucidum*, 10%	clay:cellulose = 1:2		
39	MM-C-CS2-GL-03				*Ganoderma lucidum*, 10%	clay:cellulose = 1:4		
40	MM-C-CS2-GL-04				*Ganoderma lucidum*, 10%	clay:cellulose = 1:6		
41	MM-C-CS2-GL-05				*Ganoderma lucidum*, 10%	clay:cellulose = 1:8		
42	MM-C-CS2-GL-06				*Ganoderma lucidum*, 10%	clay:cellulose = 2:1		
43	MM-C-CS2-GL-07				*Ganoderma lucidum*, 10%	clay:cellulose = 1:2		
44 - MP	~~MM-FS-GL-03~~	10 x 10 x 10 cm	19.05.2020	20.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
45 - MP	~~MM-FS-GL-04~~	10 x 10 x 10 cm	19.05.2020	20.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
46 - MP	~~MM-FS-GL-05~~	10 x 10 x 10 cm	19.05.2020	20.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
47 - MP	~~MM-FS-GL-06~~	10 x 10 x 10 cm	19.05.2020	20.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
48 - MP	~~MM-FS-GL-07~~	10 x 10 x 10 cm	19.05.2020	20.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
49 - MP	~~MM-FS-GL-08~~	10 x 10 x 10 cm	19.05.2020	25.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
50 - MP	~~MM-FS-GL-09~~	10 x 10 x 10 cm	19.05.2020	25.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
51 - MP	~~MM-FS-GL-10~~	10 x 10 x 10 cm	19.05.2020	26.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
52 - MP	~~MM-FS-GL-11~~	10 x 10 x 10 cm	27.05.2020	29.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
53 - MP	~~MM-FS-GL-12~~	10 x 10 x 10 cm	27.05.2020	29.05.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
54 - MP	~~MM-FS-GL-13~~	10 x 10 x 10 cm	29.05.2020	02.06.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
55 - MP	~~MM-FS-GL-14~~	10 x 10 x 10 cm	29.05.2020	02.06.2020	*Ganoderma lucidum*, 10%		black box, 21°C	co
56 - MP	MM-FS-PO-03	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
57 - MP	MM-FS-PO-04	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
58 - MP	MM-FS-PO-05	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
59 - MP	MM-FS-PO-06	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
60 - MP	MM-FS-PO-07	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
61 - MP	MM-FS-PO-08	10 x 10 x 10 cm	25.05.2020	26.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
62 - MP	MM-FS-PO-09	10 x 10 x 10 cm	26.05.2020	27.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
63 - MP	MM-FS-PO-10	10 x 10 x 10 cm	26.05.2020	27.05.2020	*Pleurotus ostreatus*, 10%		black box, 21°C	
64 - MP	MM-FS-PO-11	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	
65 - MP	MM-FS-PO-12	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	

Table 2: Sample r

	Description	Notes	Contamination	Drying
:	soy fibres layered	10.04, partial contamination, relocated from mycobag to a separate chamber	green spots	-
:	soy fibres layered with inoculated beech	11.05 unmoulded		baked, 80°C for 3 hours
:	inoculated beech sawdust, homogeneously mixed	11.05 unmoulded		baked, 80°C for 3 hours
:	inoculated beech sawdust, homogeneously mixed	11.05 unmoulded		baked, 80°C for 3 hours
:	inoculated sawdust layered on sand	11.05 unmoulded		room temperature (21°C)
:	inoculated sawdust layered on black stones	11.05 unmoulded		room temperature (21°C)
:	inoculated sawdust layered on sterilized clay	11.05 unmoulded		room temperature (21°C)
:	inoculated shredded cardboard	08.05 unmoulded		room temperature (21°C), baked
:	inoculated shredded newspaper	08.05 unmoulded		room temperature (21°C), baked
:	sand and sawdust mixed, inoculated to mutual weight	outer contamination visible, cleaned with ethanol on 27.04, relocated in another microfilter bag, u	orange smudges	room temperature (21°C)
:	sand and sawdust mixed, inoculated to mutual weight	08.05 unmoulded		room temperature (21°C)
:	sand and sawdust mixed, inoculated to mutual weight	08.05 unmoulded		room temperature (21°C)
:	sand and sawdust mixed, inoculated to mutual weight	08.05 unmoulded		room temperature (21°C)
:	weight/5, multiplied by 4 parts and 10% (mycelium amount)			room temperature (21°C)
:	weight/5, multiplied by 4 parts and 10% (mycelium amount)			room temperature (21°C)
:	weight/9, multiplied by 8 parts and 10% (mycelium amount)			room temperature (21°C)
:	weight/9, multiplied by 8 parts and 10% (mycelium amount)			room temperature (21°C)
:	inoculated shredded cardboard	08.05 unmoulded		room temperature (21°C)
:	inoculated beech sawdust, homogeneously mixed	08.05 unmoulded		room temperature (21°C), baked
:	inoculated beech sawdust, homogeneously mixed	16.04 contamination, substrate was probably too wet	green smudges	-
:	small cotton pieces layered, diffucult mixing	16.04 partial contamination, relocated to the "dying chamber"	green spots	room temperature (21°C)
:	not enough material for a single cube, refill	contaminated	green smudges	-
:				
:				
:				
	weight/2, multiplied by 1 part and 10% reishi	180 mL water; 05.05 contamination, model cut in half	green-orange gradient	
	weight/3, multiplied by 2 parts and 10% reishi	water amount not measured		
	weight/5, multiplied by 4 parts and 10% reishi	515 mL water		
	weight/7, multiplied by 6 parts and 10% reishi	175 mL water		
	not enough material for a single cube	115 mL; 05.05 contamination, model cut in half	green smudges	
	black clay (schamottiert)			
		25.05 unmoulded		
		25.05 unmoulded		
		25.05 unmoulded		
		25.05 unmoulded		
		25.05 unmoulded		
	contaminated 25.05			
			green fluff	
	contaminated 29.05 - bacterial, Bacillus or Clostridium	every reishi sample got contaminated, persumably because the whole bag of strain was unclean	bacterial	
	contaminated 29.05			
	contaminated 29.05			
	contaminated 29.05			
	contaminated 04.05			
	contaminated 04.06			
	contaminated 04.06			
	contaminated 04.07			
	contaminated 04.08			
	contaminated 04.09			
	contaminated 04.10			
	contaminated 04.11			
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		09.06 unmoulded; aquarium; 15.06 turned		
		23.06 unmoulded, relocated to the aquarium		
		23.06 unmoulded, relocated to the aquarium		

66 - MP	MM-FS-PO-13	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	
67 - MP	MM-FS-PO-14	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	
68 - MP	MM-FS-PO-15	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	
69 - MP	MM-FS-PO-16	16 x 4 x 4 cm	05.06.2020	10.06.2020	*Pleurotus ostreatus*, 10% +		black box, 22°C	
70 - MP	MM-FS-PO-17	10 x 10 x 10 cm	23.06.2020	29.06.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	ca
71 - MP	MM-FS-PO-18	10 x 10 x 10 cm	23.06.2020	29.06.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	ca
72 - MP	MM-FS-PO-19	10 x 10 x 10 cm	23.06.2020	29.06.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	ca
73 - MP	MM-FS-PO-20	10 x 10 x 10 cm	23.06.2020	29.06.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	ca
74 - MP	MM-FS-PO-21	10 x 10 x 10 cm	23.06.2020	29.06.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
75	MM-CP-CS2-PO-02	10 x 10 x 2 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%	brown cellulose		42
76	MM-CP-CS2-PO-03	16 x 4 x 4 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%	brown cellulose		42
77	MM-CP-CS2-PO-04	10 x 10 x 2 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%	brown cellulose		30
78	MM-CS1-PO-03	10 x 10 x 2 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%			
79	MM-CS1-PO-04	10 x 10 x 2 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%			
80	MM-CS1-PO-05	10 x 10 x 2 cm	19.05.2020	20.05.2020	*Pleurotus ostreatus*, 10%			
81	MM-CP-FS-PO-01	10 x 10 x 2 cm	15.06.2020		*Pleurotus ostreatus*, 10%			30
82	MM-CP-CS1-PO-01	10 x 10 x 2 cm	15.06.2020		*Pleurotus ostreatus*, 10%	white cellulose		30
FRESH REISHI SPAWN FROM A NEW BAG!								
83 - MP	~~MM-FS-GL-15~~	10 x 10 x 10 cm	17.06.2020	18.06.2020	*Ganoderma lucidum*, 10%		black box, 22°C	
84 - MP	~~MM-FS-GL-16~~	10 x 10 x 10 cm	17.06.2020	18.06.2020	*Ganoderma lucidum*, 10%		black box, 22°C	
85 - MP	~~MM-FS-GL-17~~	10 x 10 x 10 cm	17.06.2020	18.06.2020	*Ganoderma lucidum*, 10%		black box, 22°C	
86 - MP	~~MM-FS-GL-18~~	10 x 10 x 10 cm	17.06.2020	18.06.2020	*Ganoderma lucidum*, 10%		black box, 22°C	
87	MM-CS1-PO-06	16 x 4 x 4 cm	29.06.2020	02.07.2020	*Pleurotus ostreatus*, 10%	white cellulose	black box, 24°C	
88	MM-CS1-PO-07	16 x 4 x 4 cm	29.06.2020	02.07.2020	*Pleurotus ostreatus*, 10%	white cellulose	black box, 24°C	
89	MM-CS1-PO-08	16 x 4 x 4 cm	29.06.2020	02.07.2020	*Pleurotus ostreatus*, 5%	white cellulose	black box, 24°C	
90	MM-CS1-FS-01	16 x 4 x 4 cm	29.06.2020	02.07.2020	*Pleurotus ostreatus*, 10%	white cellulose, sawdust	black box, 24°C	70
91	MM-CS1-FS-02	16 x 4 x 4 cm	29.06.2020	02.07.2020	*Pleurotus ostreatus*, 10%	white cellulose, sawdust	black box, 24°C	30
92	MM-FS-PO-22	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
93	MM-FS-PO-23	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
94	MM-FS-PO-24	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
95	MM-FS-PO-25	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
96	MM-FS-PO-26	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
97	MM-FS-PO-27	petridish, r=9,5 cm	29.06.2020	08.07.2020	*Pleurotus ostreatus*, 10%		black box, 24°C	
98	MM-FS-P-PO-01	petridish, r=9,5 cm	09.07.2020	14.07.2020	*Pleurotus ostreatus*, 3%	pectin, 2%	black box, 24°C	co
99	MM-FS-P-PO-02	petridish, r=9,5 cm	09.07.2020	14.07.2020	*Pleurotus ostreatus*, 3%	pectin, 10%	black box, 24°C	co
100	MM-FS-P-PO-03	petridish, r=9,5 cm	09.07.2020	14.07.2020	*Pleurotus ostreatus*, 3%	pectin, 20%	black box, 24°C	co
101	MM-FS-CP-01	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 1:8	black box, 24°C	po
102	MM-FS-CP-02	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 1:6	black box, 24°C	
103	MM-FS-CP-03	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 1:4		
104	MM-FS-CP-04	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 1:2	black box, 24°C	
105	MM-FS-CP-05	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 1:1		
106	MM-FS-CP-06	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 2:1		
107	MM-FS-CP-07	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : wood = 4:1		
108	MM-CS1-CP-01	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 1:8	black box, 24-25°C	
109	MM-CS1-CP-02	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellullose = 1:6	black box, 24-25°C	
110	MM-CS1-CP-03	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 1:4	black box, 24-25°C	
111	MM-CS1-CP-04	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 1:2	black box, 24-25°C	
112	MM-CS1-CP-05	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 1:1	black box, 24-25°C	
113	MM-CS1-CP-06	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 2:1	black box, 24-25°C	
114	MM-CS1-CP-07	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : white cellulose = 4:1	black box, 24-25°C	
115	MM-CS2-CP-01	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 1:8	black box, 24-25°C	
116	MM-CS2-CP-02	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellullose = 1:6	black box, 24-25°C	
117	MM-CS2-CP-03	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 1:4	black box, 24-25°C	
118	MM-CS2-CP-04	petridish, r=9,5 cm	16.07.2020, 2h	20.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 1:2	black box, 24-25°C	
119	MM-CS2-CP-05	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 1:1	black box, 24-25°C	
120	MM-CS2-CP-06	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 2:1	black box, 24-25°C	
121	MM-CS2-CP-07	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	powder : brown cellulose = 4:1	black box, 24-25°C	
122	MM-FS-P-PO-04	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	pectin, 2%	black box, 24-25°C	
123	MM-FS-P-PO-04	petridish, r=9,5 cm	20.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%	pectin, 10%	black box, 24-25°C	
124 - MP	MM-CS2-PO-02	16 x 4 x 4 cm	13.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%		black box, 24-25°C	
125 - MP	MM-CS2-PO-03	16 x 4 x 4 cm	13.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%		black box, 24-25°C	
126 - MP	MM-CS2-PO-04	16 x 4 x 4 cm	13.07.2020, 2h	21.07.2020	*Pleurotus ostreatus*, 10%		black box, 24-25°C	
127	MM-CS1-PO-09	truss	30 min	14.07.2020	*Pleurotus ostreatus*, 5%	white cellulose	room temp. basement	
128	MM-CS2-PO-05	truss	2h	21.07.2020	*Pleurotus ostreatus*, 5%	brown cellulose	room temp. basement	

Table 3: Sample re

	23.06 unmoulded, relocated to the aquarium		
	23.06 unmoulded, relocated to the aquarium		
	23.06 unmoulded, relocated to the aquarium		
	23.06 unmoulded, relocated to the aquarium		
capillary water absorption	07.07 unmoulded, relocated to the aquarium		
capillary water absorption	07.07 unmoulded, relocated to the aquarium		
capillary water absorption	07.07 unmoulded, relocated to the aquarium		
capillary water absorption	07.07 unmoulded, relocated to the aquarium		
	material was a bit wetter than the other; 07.07 unmolded and put in a microfilter bag; milled 16.07, sundried		
422g Claytec-Trockenlehm, 90g Cellulose, 300ml water			
422g Claytec-Trockenlehm, 90g Cellulose, 300ml water			
300g Claytec-Trockenlehm, 35g Cellulose, 150ml water			
	09.06 removed from aquarium		
	09.06 removed from aquarium		
	09.06 removed from aquarium		
300g Claytec-Trockenlehm, 125g sawdust, 75ml water			
300g Claytec-Trockenlehm, 50g Cellulose, 30ml water			
	07.07 unmoulded, relocated to the aquarium		
	07.07 unmoulded, relocated to the aquarium		
	07.07 unmoulded, relocated to the aquarium		
70% sawdust, 30% cellulose	07.07 unmoulded, relocated to the aquarium		
30% sawdust, 70% cellulose	07.07 unmoulded, relocated to the aquarium		
contaminated 20.07			
contaminated 20.07			
contaminated 20.07			
powdered black clay, schamottiert	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
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	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		
	mycelium amount - 10% from the whole weight		

5.5.1 Composite material

Because of its preparation procedure , composite material is listed in the naming system as MM (mixed material), ; two components are evenly distributed within the mixture. In this case, mycelium and substrate act as two basic parts. When growing composite materials, they keep changing their qualities until the growth reaches its final stage and gets terminated.

Most frequently grown samples originate from the one shown in the first figure - beech sawdust with oyster mushroom (Fig. 98). The samples shown in figure 99 and 100 have an additional inorganic component - clay, but were inoculated with two different mycelium types (oyster and reishi), which is clearly visible in their surface colour.

The addition of inorganic components to the composite slow down the growth process, and introduce different properties once the growth is finished, as described in the following chapter.

5.5.2 Surface models

The goal of this experiment was to see how two materials react when they come in contact to each other. Depending on the characteristics of the inorganic part of the sample, crumbling after drying was expected, or stiffness of the organic part.

The first one of the three models showed here is named SM-ST-FS-PO-01 (Fig. 101). The original dimension was 10 x 10 x 10 cm. Pieces of black stone were put at the top and the bottom of the plastic mould. After sufficient growing time, the plastic mould was removed. Even though the stones did not have any organic components between them, mycelium grew out enough to hold them together in one solid piece. A similar activity repeated in the second model, SM-S-FS-PO-01 (Fig. 102), where sand was held together by humidity and mycelium. After both models lost their moisture content, the inorganic part crumbled away, whilst the inoculated sawdust remained.

The models were also tested for the possibility if the material could remain in shape withou the use of casts. The third model, SM-C-FS-PO-01 (Fig. 103), is a straightforward example of a binding interaction between clay and inoculated sawdust. The final model remained in one piece as expected, but the regularity of the clay surface was interrupted during unmoulding.

Fig. 98: Beech sawdust inoculated with *Pleurotus ostreatus*

Fig. 99: MM-C-CS-GL-07

Fig. 100: MM-CS1-GL-01

Fig. 101: SM-ST-FS-PO-01

Fig. 102: SM-S-FS-PO-01

Fig. 103: SM-C-FS-PO-01

6 MATERIAL TESTING

This chapter provides a detailed description and results of the material testing, which was mostly executed at the Institute of Technology and Testing of Building Materials (Institut für Materialprüfung und Baustofftechnologie) - IMBT-TVFA, TU Graz. The series of tests conducted include density, compression strength, bending tensile strength and capillary water absorption.

Most of the samples tested consisted out of beech sawdust inoculated with *Pleurotus ostreatus*, to achieve consistent results, i.e. to get an average value. The sawdust was chosen for the substrate because it is easily obtained and whose results offer a possibly wide application. Cellulose was substrate option, as it achieves better results than sawdust and demonstrates no problems during inoculation and growing phase, with very little or no contamination. However obtaining cellulose in a desired form was difficult, leading to sawdust as preferred substrate.

Other samples were grown and tested as well, showing a potential for further material exploration. A combination of two materials, both organic and inorganic was analysed in some of the tests conducted. A few of the examples were inoculated with *Ganoderma lucidum*, to test if a different strain type emphasizes some of the tested qualities.

6.1 DENSITY

The first quality tested was the material density. Before starting, the samples had to be completely dried out. This was initially attempted by baking the samples in an oven for 6 hours at 70 °C. As it turned out later in the following tests, this method proved to be insufficient. One sample was tested for compression strength (Fig. 104) in the meantime and the leftover material was damp, so another sample was cut in half to determine if it was still wet inside (Fig. 106).

The drying cabinet is a better solution for sample dehydration (Fig. 107). The temperature in the cabinet was set to 40 °C and the drying process lasted until there was no moisture left in the samples. This was carried out for a couple of days - each sample weighed until there was no difference between measurements (Table 6). Only then was final weight taken into account. Since both of the material components are naturally irregular, the final cube 10 x 10 x 10 cm was not precise enough. Each sample is slightly deformed during the drying process, due to irregular pressure from the manual filling of the moulds and the standard shrinkage factor. In order to get an average side length, each sample was measured from edge to edge and the middle of each side, resulting in 24 measurements per sample. The volume was calculated consequently, density as well (Table 4) - (Table 5).

name	average side [cm]	volume [cm^3]	weight [g]	density [g/cm^3]
MM-FS-PO-01	9,26	794,67	215,00	0,27
MM-FS-PO-02	9,29	802,20	220,00	0,27
MM-FS-PO-03	9,42	836,12	210,16	0,25
MM-FS-PO-04	9,41	832,80	212,52	0,26
MM-FS-PO-05	9,35	817,40	209,67	0,26
MM-FS-PO-06	9,42	835,01	209,28	0,25
average value	9,36	819,70	212,77	0,26

Table 4: Density - beech sawdust

name	average side [cm]	volume [cm^3]	weight [g]	density [g/cm^3]
MM-CS1-PO-01	8,74	668,01	225,00	0,34
MM-FSSF-PO-01	8,96	718,92	170,00	0,24
MM-FS-GL-01	9,30	804,36	205,00	0,25
MM-SC-PO-01	8,93	710,93	297,00	0,42
MM-S-FS-PO-01	9,73	919,75	215,00	0,23
MM-S-FS-PO-02	9,47	848,38	429,00	0,51
MM-CO-PO-01	8,82	685,35	151,00	0,22
MM-C-FS-GL-01	9,58	878,99	664,00	0,76

Table 5: Density - various samples

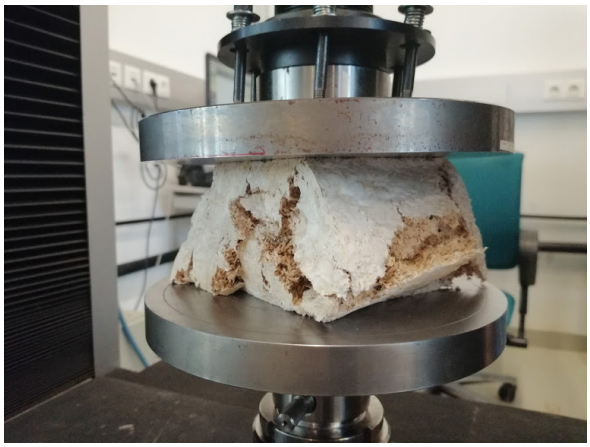


Fig. 104: Unsuccessful compression test

Fig. 105: Cutting the sample

			MM-FS-PO-03	MM-FS-PO-04	
1	container	M_2 [g]			
2	container mass + moist measurement sample	$M_1 + M_2$ [g]	287,00	300,00	
3	container mass + dry measurement sample	$M_{d1} + M_2$ [g]	210,18	212,54	
4	second weighing container mass + dry measurement sample	$M_{di} + M_2$ [g]	210,16	212,52	
5	weighing difference	3 - 4 [g]	0,02	0,02	
6	[(3 - 4)/(3 - 1)] x 100	[%]	0,01	0,01	
7	water mass (2 - 4)	[g]	76,84	87,48	
8	dry measurement sample mass (4 - 1)	M_3 [g]	210,16	212,16	
9	water content (7/8) x 100	[M - %]	36,56	41,16	
10	average water content	[M - %]		40,91	

Table 6: Drying cabinet - e

Fig. 106: Cut sample indicates insufficient drying

Fig. 107: Drying cabinet

	MM-FS-PO-05	MM-FS-PO-06	MM-FS-PO-07	MM-FS-PO-10	
	304,00	248,00	257,00	278,00	26.06.2020
	209,75	209,28	218,72	217,96	29.06.2020
	209,67	209,28	218,68	217,90	30.06.2020
	0,08	0,00	0,04	0,06	
	0,04	0,00	0,02	0,03	
	94,33	38,72	38,32	60,10	
	209,67	209,28	218,68	217,90	
	44,99	18,50	17,52	27,58	
			21,20		

et - excess water content

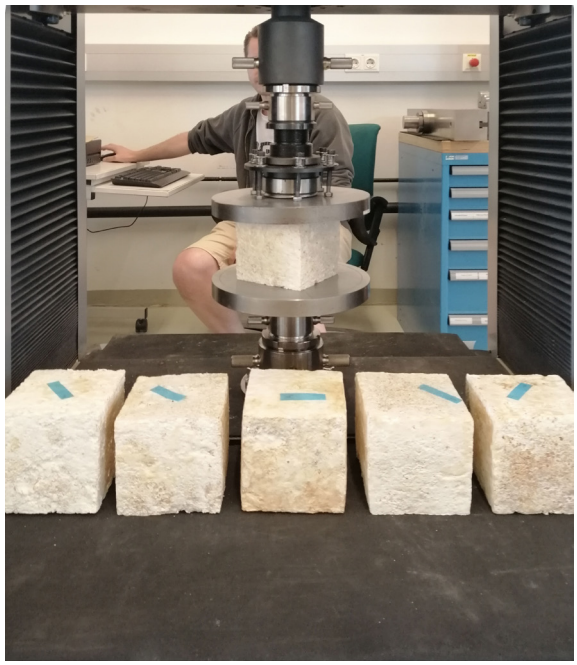


Fig. 108: Beech sawdust samples before testing

6.2 COMPRESSION STRENGTH

6.2.1 Beech sawdust samples

After defining the density of the previously mentioned samples, the same ones were tested for compression strength.

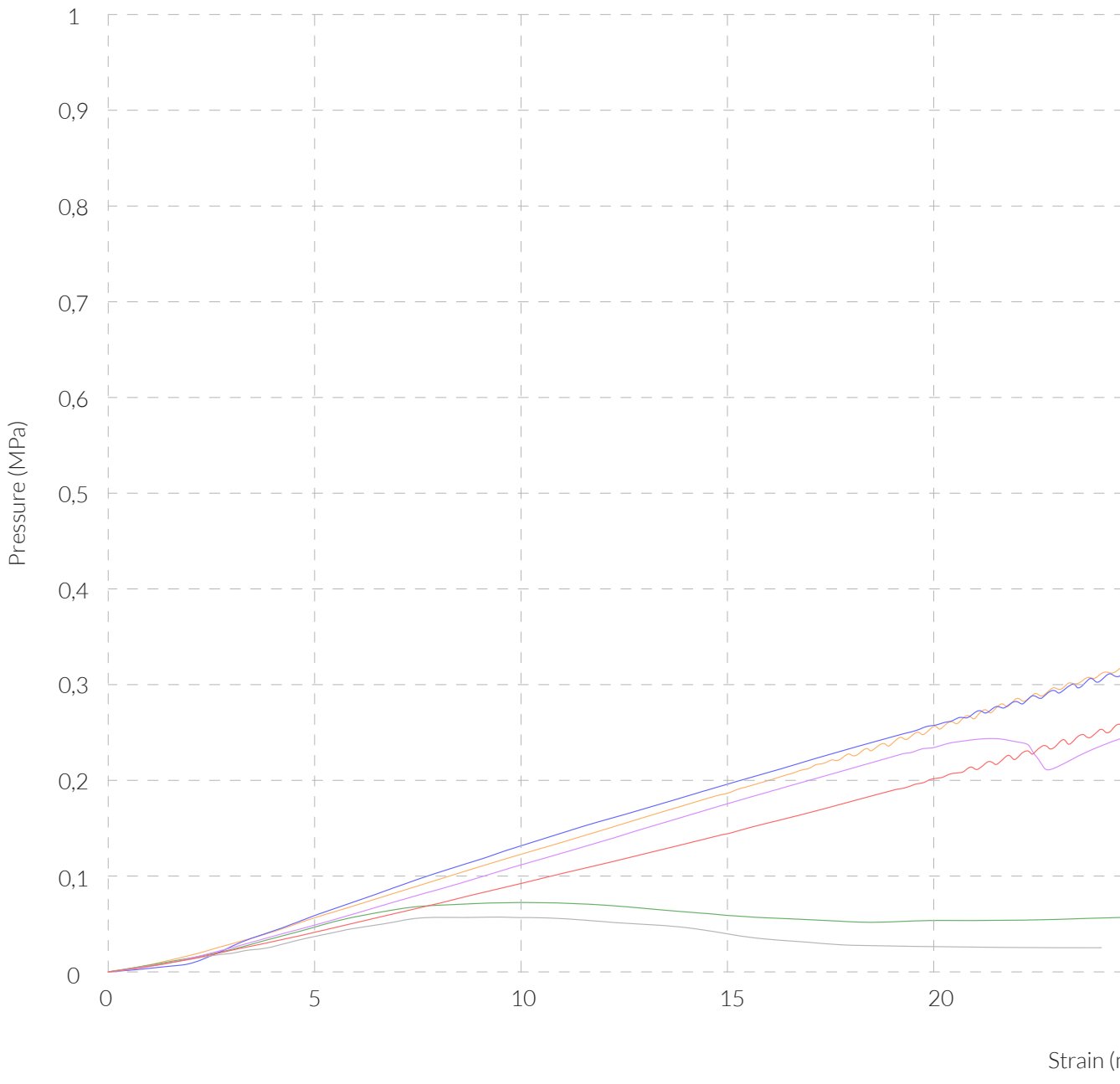
Two of the samples tested, MM-FS-PO-04 and MM-FS-PO-06 showed an error while measuring. Therefore, they will not be taken into account for the average value.

The rest of the samples showed more or less similar results, however, they can be divided into two groups: the ones baked 3 days before and the ones baked after. Two samples which were removed (MM-FS-PO-05 and MM-FS-PO-10) showed slightly lower numbers than the ones that had a couple of days more to grow. The curves on the graph are defined by three stages; first one showing mediocre endurance, the second one being the weakest stage as the sample gets soft, and finally, the recuperation phase, where the curve grows steeper than before. Considering the porosity of the material, such results were to be expected.

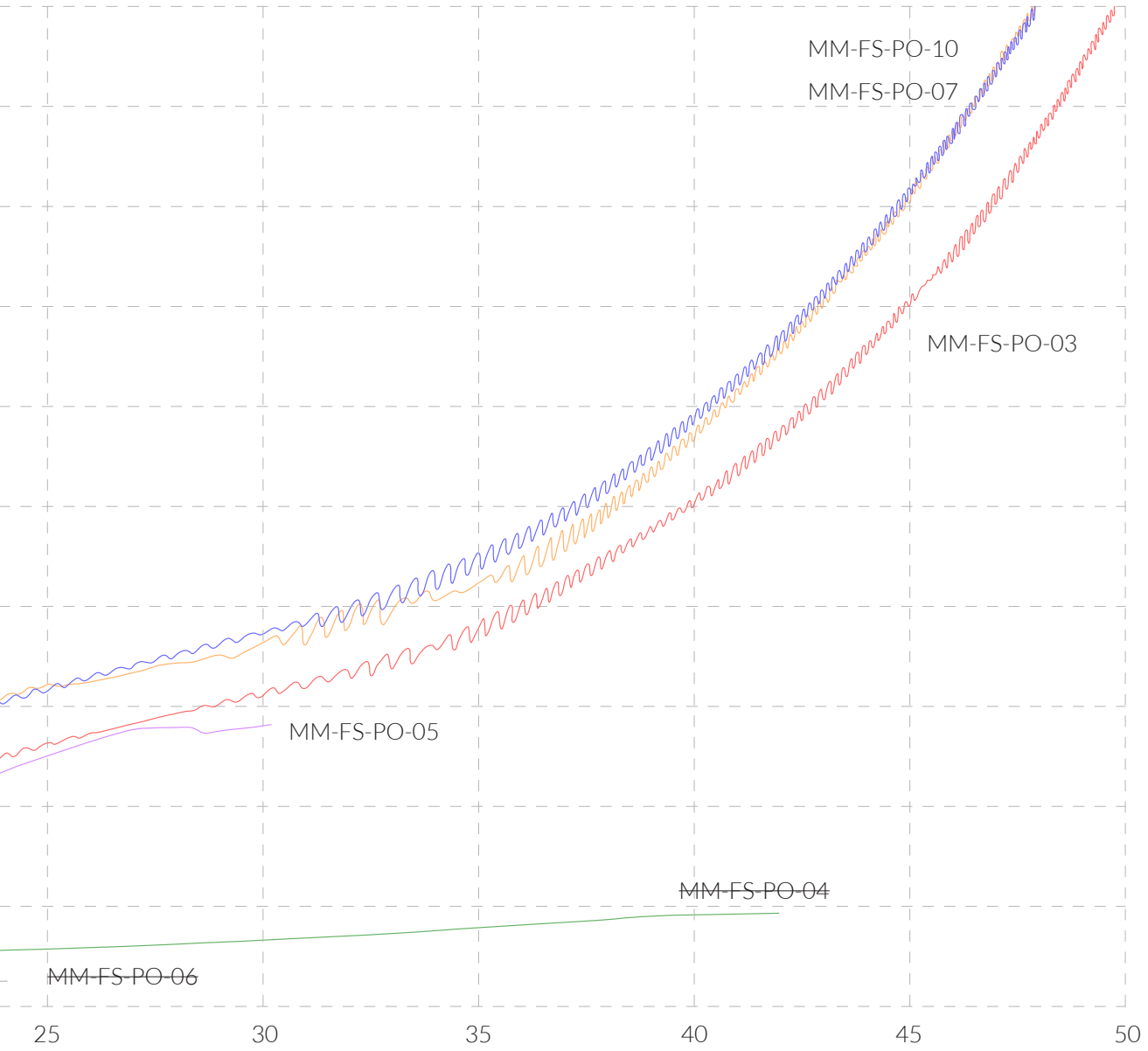
An interesting sequence to this test would be finding out how much the growth duration influences the mechanical characteristics of the samples. A series of examples where the growth gets interrupted on numerous occasions on different samples, with a couple of days between each interruption.

name	maximum_force	maximum_stress
parameter	total calculated area	total calculated area
unit	N	MPa
MM-FS-PO-03	43096,14	4,31
~~MM-FS-PO-04~~	~~941,96~~	~~0,09~~
MM-FS-PO-05	2822,56	0,28
~~MM-FS-PO-06~~	~~574,49~~	~~0,06~~
MM-FS-PO-07	42275,38	4,23
MM-FS-PO-10	24840,20	1,12
average	16812,88	2,49
standard deviation	20407,50	2,04184
area	42521,70	4,25000

Table 7: Compression strength test - beech sawdust



Graph 1: Compression s



n (mm)

on strength - beech sawdust

6.2.2 Various samples

A second set of samples consists of different combinations of organic and inorganic materials. A description of each sample is provided below, whereas the pictures of each ones are located on the next page, in the same order.

LM-FSSF-PO-01

The sample consists of horizontally stacked layers of soy fibres, between layers of sawdust. Since the sample was loaded in the same manner, it did not completely break apart like the ones which are made out of sawdust only. The layers of fibres behaved in a spring like way like, adding a certain elasticity to the sample. However, if the sample would be turned sideways, with the fibre layers standing vertically to the force flow, the results would be much different. Soy fibres to sawdust ration is 1:1, inoculated with 20% *Pleurotus ostreatus*.

MM-C-FS-GL-01

The mixture was made with one part of modelling clay to 4 parts of sawdust. Ratio was determined by volume, whereas the composite was inoculated with 10% *Ganoderma lucidum*. The amount of organic part was also influenced by the density of the clay; the idea was to introduce as much of the organic matter as possible, in order to achieve a cohesive mycelial growth on the inside, but still for the sample to exhibit the properties of clay. The sample showed similar brittleness as MM-CS1-PO-01, but somewhat lower.

MM-CS1-PO-01

The sample consists of bleached cellulose inoculated with 10% *Pleurotus ostreatus*. During the drying process, this sample the sample shrunk significantly, with some sides reducing in size up to 8,4 cm (from the original 10 cm per side). Consequently, the sample has a bigger density - 0,34 g/cm^3 - than the average sample made out of beech sawdust (0,26 g/cm^3). As previously mentioned, the sample similarly brittle as MM-CFS-GL-01, but withstands greater force.

MM-FS-GL-01

This blend consists of the same sawdust type as the ones in the previous section, but is inoculated with another mycelium strain, *Ganoderma lucidum*. When compared to previous results, it has not preformed as well. However, since this was the only sample with this strain, general conclusions can not be made.

Fig. 109: LM-FSSF-PO-01

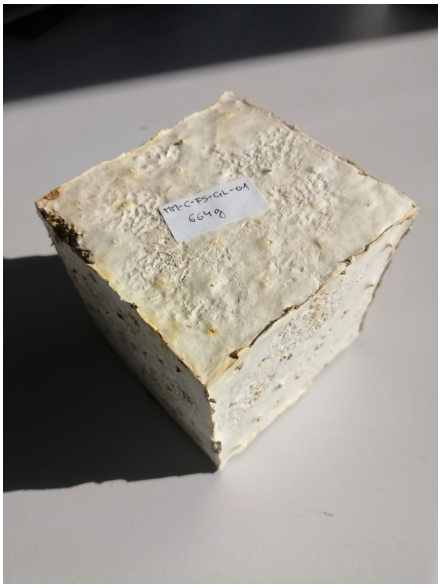


Fig. 110: MM-C-FS-GL-01

Fig. 111: MM-CS1-PO-01

Fig. 112: MM-FS-GL-01

Fig. 113: MM-SC-PO-01

Fig. 114: MM-S-FS-PO-02

Fig. 115: MM-S-FS-PO-01

Fig. 116: MM-CO-PO-01

MM-SC-PO-01

This sample preformed the best. Before inoculation with 10% *Pleurotus ostreatus* started, the cardboard was soaked in hot water and later torn to pieces, up to 35 mm big. The sample shrunk 11% when measured by the average side length and had a density of 0,42 g/cm^3, which probably contributes to the best compression strength results, as the cardboard got bound together tightly by the mycelium.

MM-S-FS-PO-01/02

Addition of sand to the mixture does not add to the mechanical strength. The two samples are differentiated by the amount of sand in the mixture; 01 has the same amount of sand as sawdust, whereby 02 has the sand to sawdust ratio 1 to 4, both determined by volume. The only advantage of these samples was the minimal, or non-existing shrinkage during the drying process.

MM-CO-PO-01

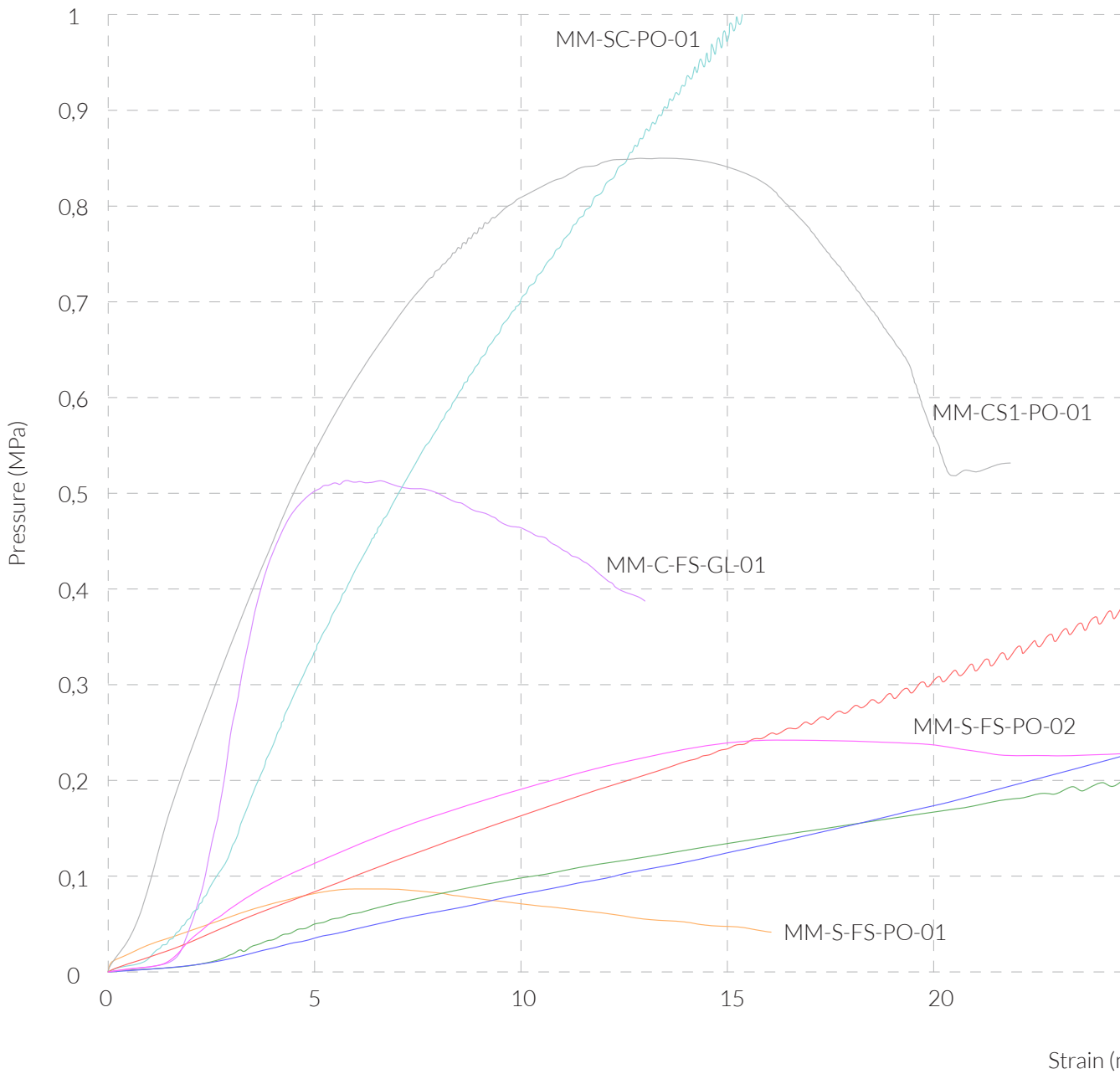
Since cotton consists of cellulose, this type of nutrition worked well for mycelium. The fibres that were used for the sample have had a significant length, and were therefore challenging to mix with the mycelium grains. The sample preformed somewhere between the one with soy fibres and sawdust, and just the sawdust. MM-CO-PO-01 exhibited the same “bouncy” quality as the sample with soy fibres, since it got compacted after testing and did not really break

After concluding the tests, a couple of broken pieces of the three samples containing sand and clay were examined under a microscope (Fig. 111-113), to see how much the mycelium penetrated through the inorganic material. Even though traces of white mycelium fibres were noticeable, a different kind of measurement is needed to determine the exact pathway of growth. However, the mycelium growth is present around sawdust. An additional factor is the location of the broken pieces within the sample, e.g. the closer it is located to the surface, the more oxygen flows in the material, therefore more growth is present.

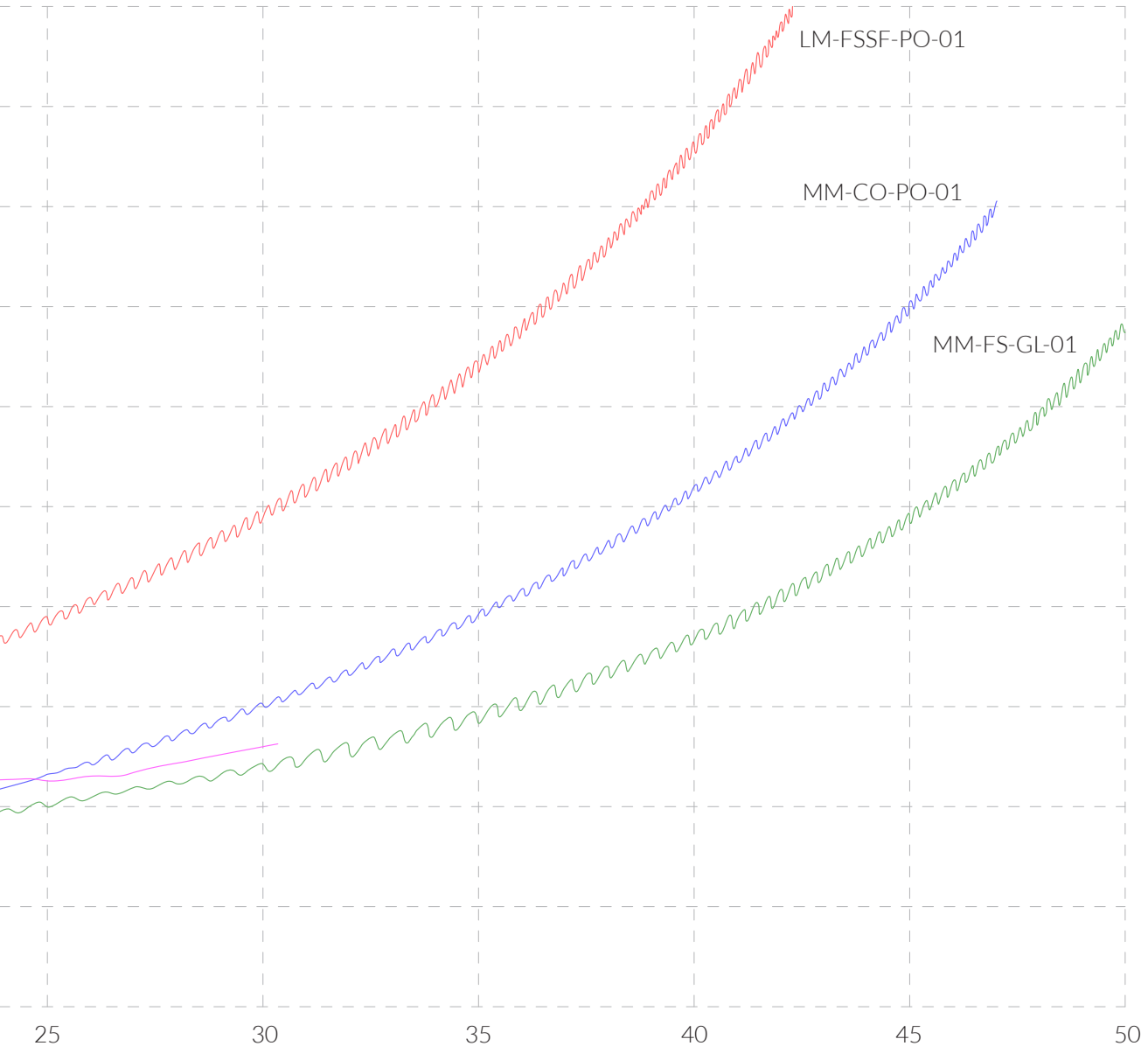
Fig. 117: LM-FSSF-PO-01 and MM-CO-PO-01 - after testing

name	maximum_force	maximum_stress
parameter	total calculated area	total calculated area
unit	N	MPa
LM-FSSF-PO-01	15737,45	1,99
MM-C-FS-GL-01	4622,05	0,51
MM-CS1-PO-01	6429,34	0,85
MM-FS-GL-01	6607,95	0,76
MM-SC-PO-01	20975,92	2,65
MM-S-FS-PO-02	2314,20	0,26
MM-S-FS-PO-01	692,27	0,09
MM-CO-PO-01	6224,60	0,80
average	7950,47	0,99
standard deviation	6896,39	0,88135
area	20283,70	2,56000

Table 8: Compression strength test - various samples



Graph 2: Compression st



n (mm)

n strength - various samples

Fig. 118: Compression strength testing - before

Fig. 119: Compression strength testing - mid

Fig. 120: MM-C-FS-GL-01

Fig. 121: MM-S-FS-PO-01

Fig. 123: Compression strength testing - after

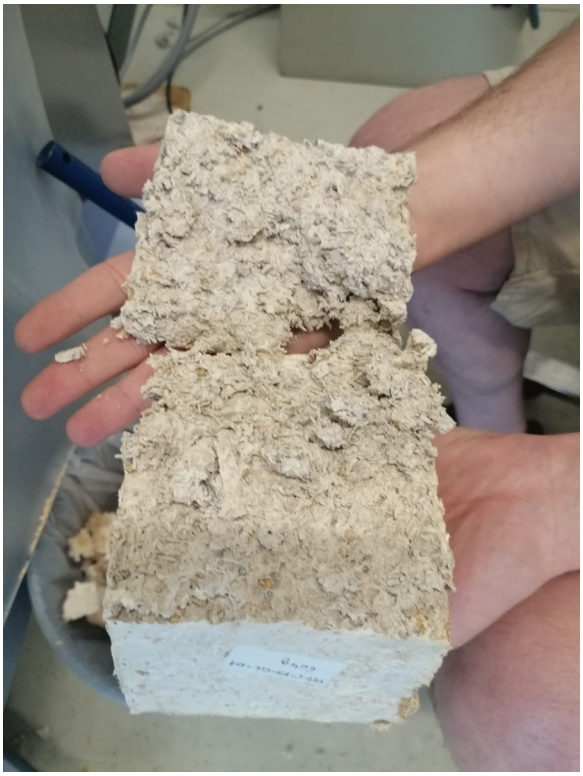


Fig. 124: After breaking - section evaluation

500 µm

Fig. 122: MM-S-FS-PO-02

500 µm

6.3 THREE-POINT FLEXURAL TEST

6.3.1 Beech sawdust samples

The first set of samples containing out of six pieces were mixed with beech sawdust. The numbers in the table below show a wide dispersion of results. They could be influenced by the difference between single elements, even though they were simultaneously inoculated and incubated for the same period of time, under the same conditions. The value between the one bearing the most, and the one bearing the least force is more than double (73,02 N and 32,54 N). A final conclusion why the results vary so much unfortunately can not be made.

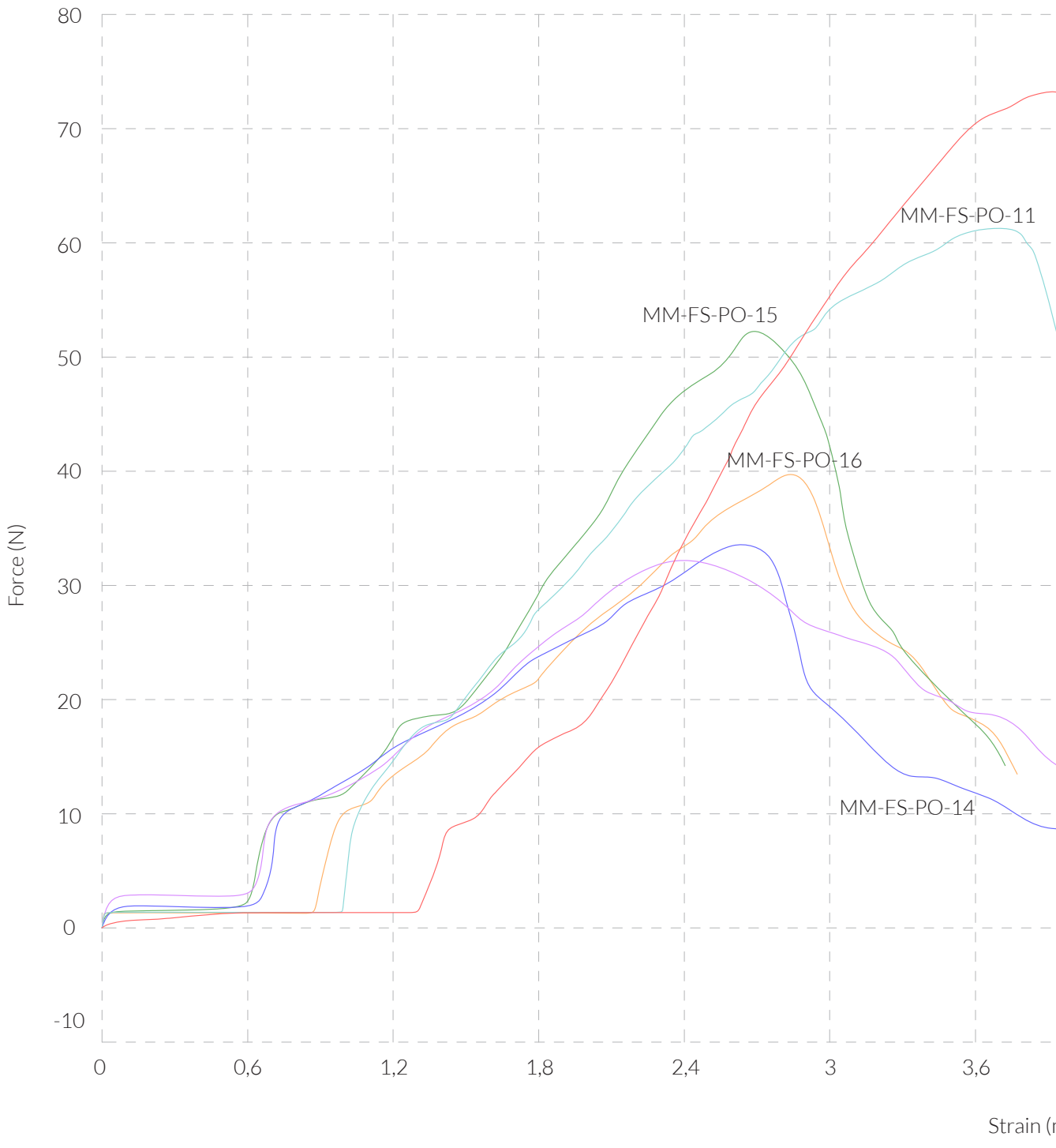
However, if the curve from the sample with the highest result, MM-FS-PO-13, is compared to an average result from the cellulose samples, they do exhibit a similar strain, whereby the sawdust sample can bear half of the force that cellulose can take.

This is also very likely influenced by the mycelium type; even though *Pleurotus ostreatus* has one of the highest growth rates, it is known that hyphal density does not exhibit same qualities in all mushrooms.

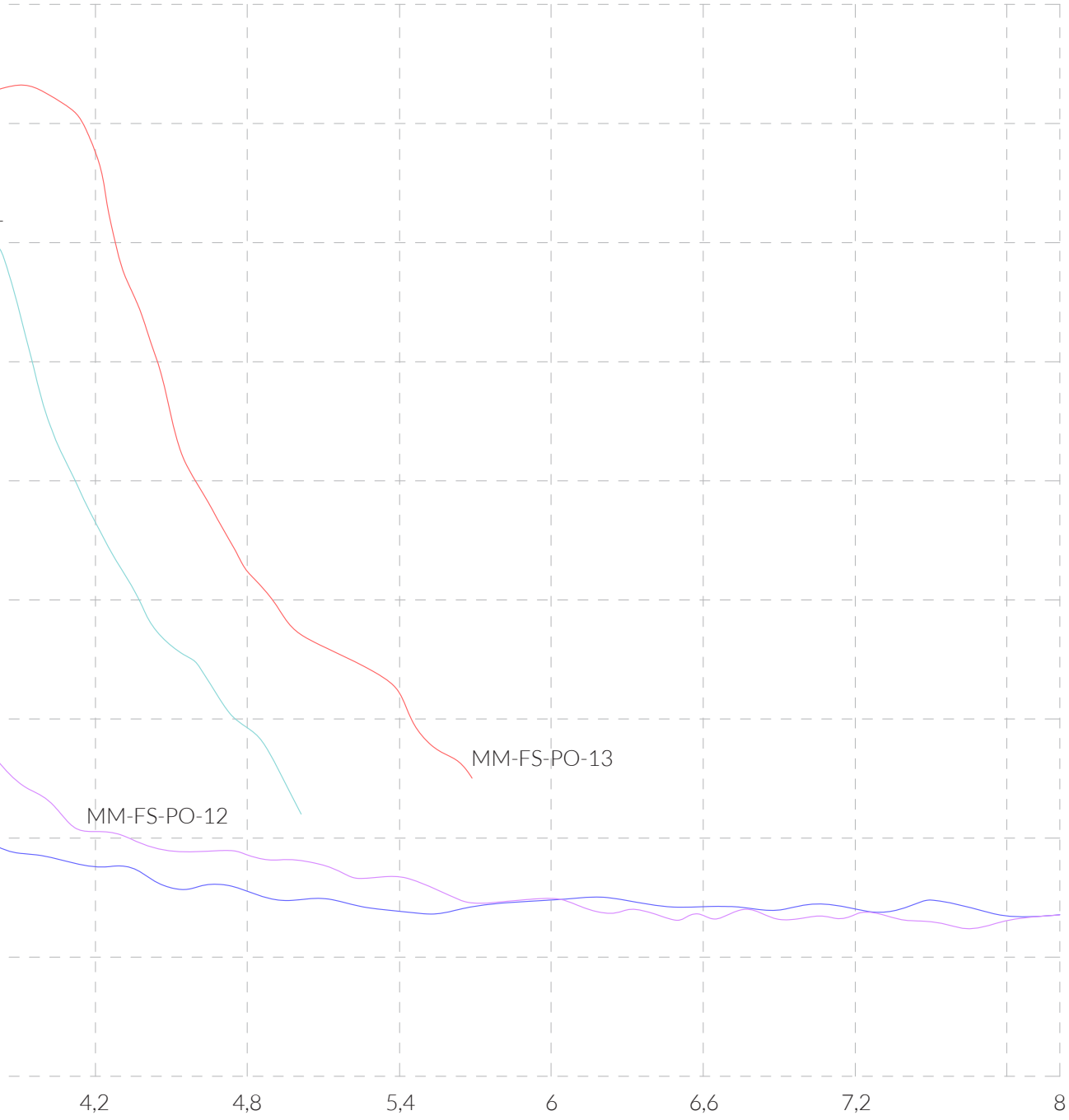
name	maximum_force	maximum_stress	maximum_distance
parameter	total calculated area	total calculated area	total calculated area
unit	N	N/mm^2	mm
MM-FS-PO-11	61,11	0,14324	3,68
MM-FS-PO-12	32,54	0,07626	2,40
MM-FS-PO-13	73,02	0,17114	3,88
MM-FS-PO-14	33,35	0,07816	2,66
MM-FS-PO-15	52,37	0,12275	2,67
MM-FS-PO-16	39,59	0,09280	2,85
average	48,66	0,11406	3,02
standard deviation	16,3627	0,03835	0,60672
area	40,4800	0,09488	1,48000

Table 9: Three-point flexural test - beech sawdust

Fig. 125: Beech sawdust samples - after testing



Graph 3: Three-point fl



n (mm)

nt flexural test - beech sawdust

6.3.2 Various samples

name	maximum_force	maximum_stress	maximum_distance
parameter	total calculated area	total calculated area	total calculated area
unit	N	N/mm^2	mm
MM-Q-GL-01	70,38	0,16496	2,84
MM-FS-GL-19	38,39	0,08997	4,52
MM-SN-PO-01	276,95	0,64909	3,65
MM-SC-PO-02	89,49	0,20973	4,23
MM-S-FS-PO-03	29,18	0,06840	1,64
MM-S-FS-PO-04	46,05	0,10792	2,74
average	91,74	0,21501	3,27
standard deviation	93,3934	0,21889	1,07249
area	247,770	0,58069	2,88000

Table 10: Three-point flexural test - various samples

Fig. 126: MM-Q-GL-01

Fig. 127: MM-FS-GL-19

Fig. 128: MM-SN-PO-01

Fig. 129: MM-SC-PO-02

Fig. 130: MM-S-FS-PO-03

Fig. 131: MM-S-FS-PO-04

Fig. 132: MM-SN-PO-01 - before breaking

Fig. 134: MM-SC-PO-02 - before breaking

Fig. 133: MM-SN-PO-01 - after breaking

Fig. 135: MM-SC-PO-02 - after breaking

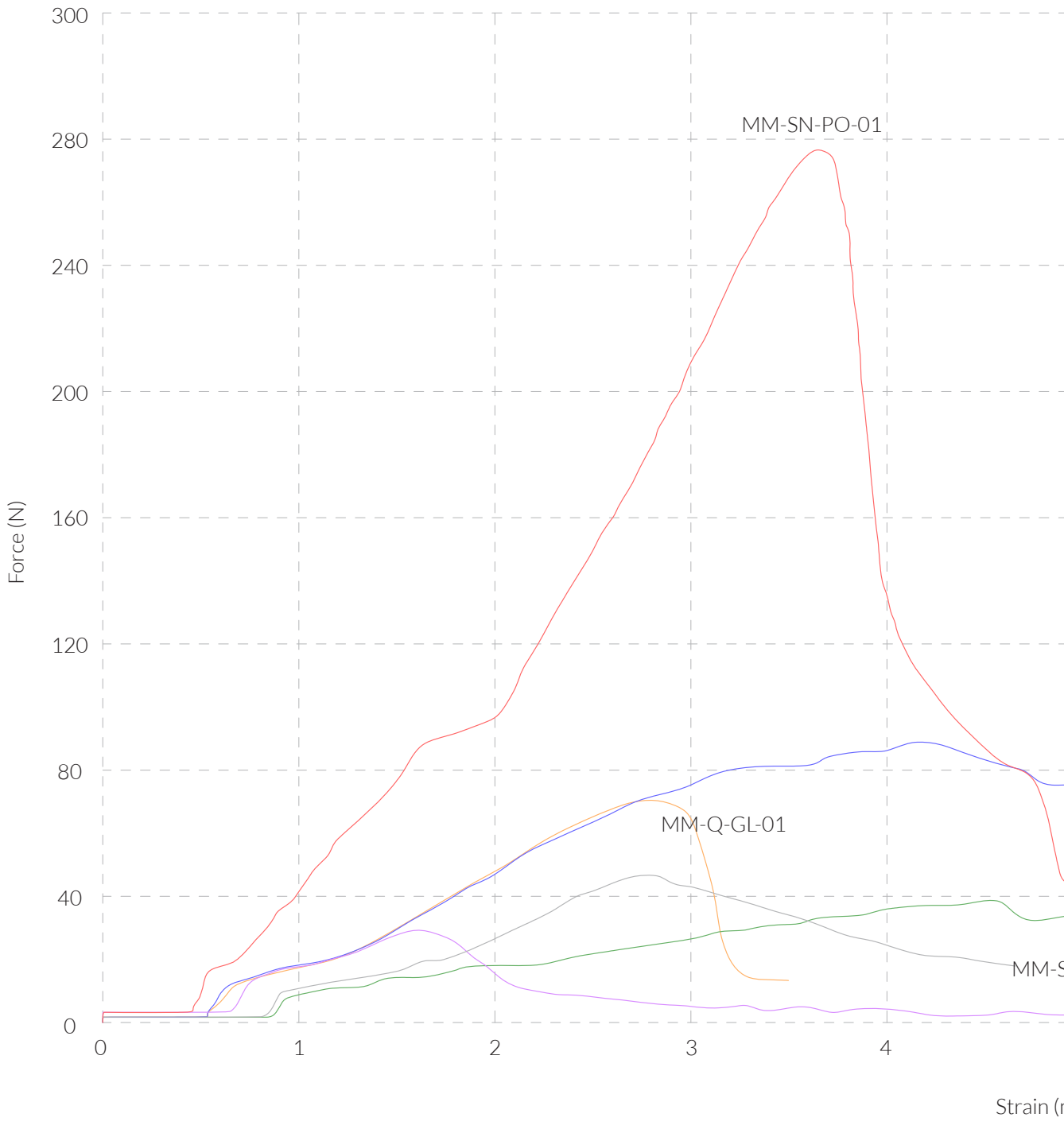
As for the tests of diverse samples, the results are, naturally, very different regarding the material, so they can only be individually analysed. Also, because of the singularity of the sample types, no general conclusions can be made. Nevertheless, a broad statement of substrate choosing is made.

The first two samples, MM-Q-GL-01 (Fig. 126) and MM-FS-GL-19 (Fig. 127) were inoculated simultaneously with the same mycelium strain, *Ganoderma lucidum*, and grown in the same conditions for a same period of time. The only difference between them is the substrate, i.e. beech and oak sawdust. The sample inoculated with oak sawdust shows significantly better results. It is also important to note that the particles of oak sawdust were smaller (1-2 mm) compared to the beech sawdust (cca. 3 mm). In order to make viable conclusions, a bigger sample number is needed. However, the difference between these two results corresponds to the dispersion of the results from the previous measuring (only beech sawdust). It would be useful to further explore this result difference, to be able to state how the mycelium strain and the substrate type affect the results.

The next sample, MM-SN-PO-01 showed by far the best results. The sample was prepared in a similar manner as the ones made with cardboard. Sheets of newspaper were soaked in water, then torn into smaller pieces by hand. Compared to the average values of beech sawdust, the sample preformed five times better.

MM-SC-PO-02, a sample with shredded cardboard, shows poorer results than the one with shredded newspaper, but performs better sawdust blend. It is difficult to define the reason behind it, but the size of the single pieces may be influencing the overall performance. Compared to the tiny sawdust pieces, the cardboard ones and newspaper pieces had a length of approximately 15 mm.

The last two pieces containing sawdust and sand in different ratios, MM-S-FS-PO-03 and MM-S-FS-PO-04, have not shown unexpected results. Same as in the compression tests, sand appears to be a bad additive.



Graph 4: Three-point fl

n (mm)

nt flexural test - various samples

name	maximum_force	maximum_stress	maximum_distance
parameter	total calculated area	total calculated area	total calculated area
unit	N	N/mm^2	mm
MM-CS1-PO-06	147,95	0,34675	3,83
MM-CS1-PO-07	151,95	0,35614	3,92
average	149,95	0,35145	3,88
standard deviation	2,82843	0,00664	0,06364
area	4,00000	0,00939	0,09000
MM-CS1-FS-PO-01	44,87	0,10516	2,09
MM-CS1-FS-PO-02	75,17	0,17617	3,92
average	60,02	0,14067	3,01
standard deviation	21,4253	0,05021	1,29401
area	30,3000	0,07101	1,83000

Table 11: Three-point flexural test - cellulose, beech sawdust + cellulose

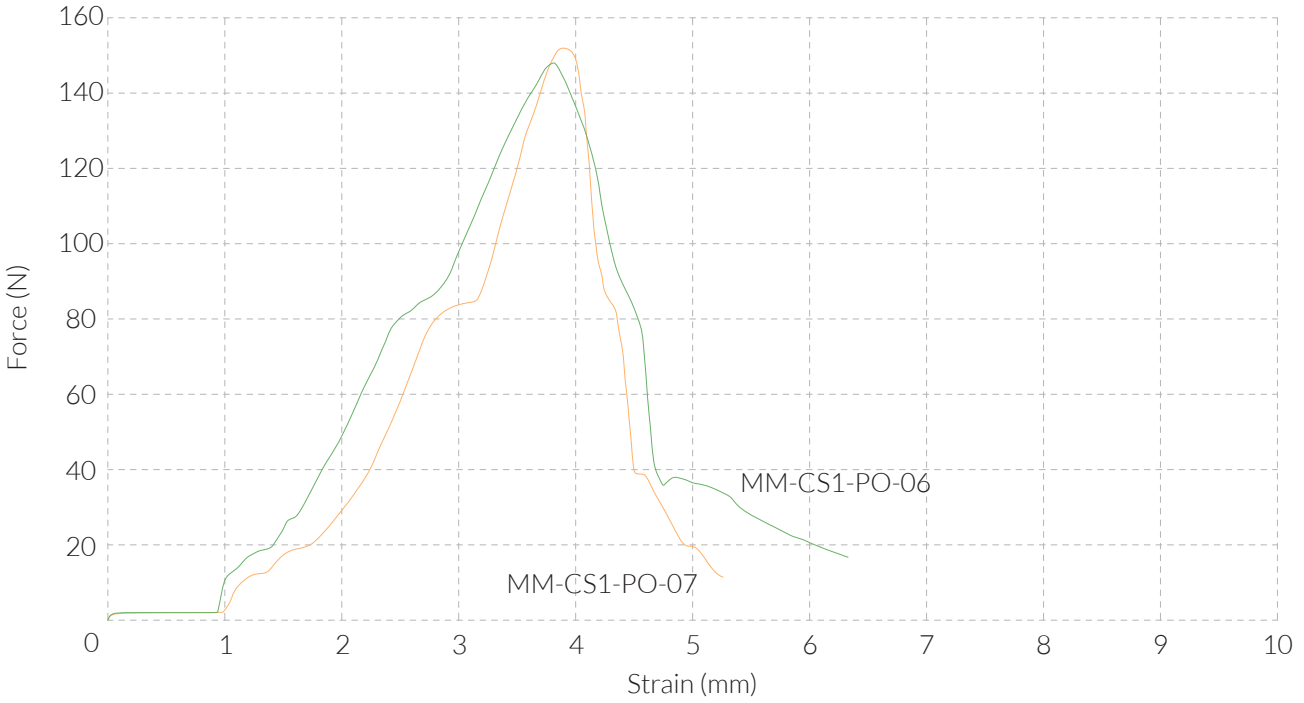
Fig. 136: MM-CS1-FS-PO-01

Fig. 137: MM-CS1-FS-PO-01 - at breaking point

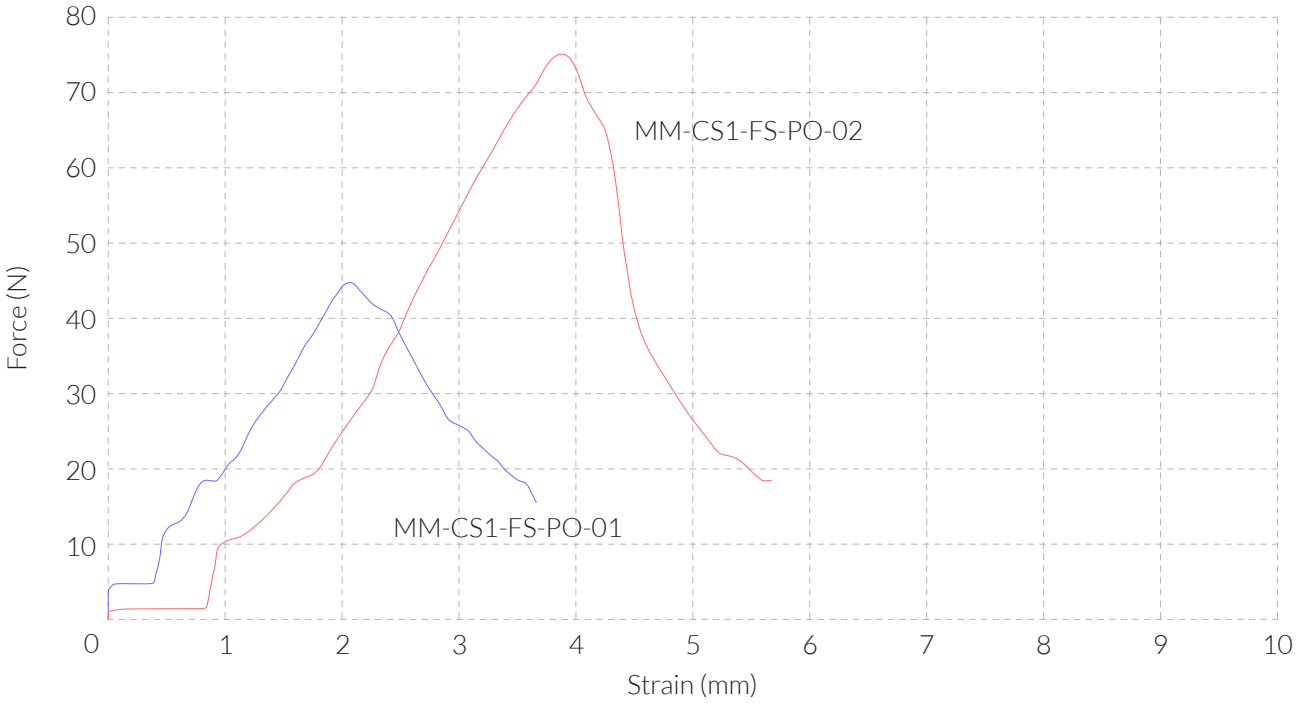
Even though only two samples were tested, both of them show very similar results, which indicates that other ones would probably show comparable outcomes. The cellulose samples showed by far the best mechanical properties.

The following two samples were a combination of beech sawdust and cellulose, homogeneously integrated into one piece. The first one, MM-CS1-FS-01 contained 30% cellulose and 70% sawdust, whereas the second one, MM-CS1-FS-02, had 70% cellulose and 30% sawdust. The goal of these experiments was to determine if adding another organic component enhances or decreases the tested qualities. Even though the sample that contains more cellulose performed better, the 30% of sawdust in the sample decreased its overall performance when compared to the samples containing only cellulose. On the other hand, adding 30% cellulose to the sample containing mainly sawdust has not drastically changed the result if compared to the average of the sawdust samples from the Table 11.

All in all, substituting a certain amount of organic part in a sample does not change the overall result, regarding beech sawdust and cellulose. Another aspect, which could be further researched, would be adding an organic compound with drastically different characteristics, e.g. shredded newspaper or cardboard, which both performed surprisingly well, as seen in the Table 10 .



Graph 5: Three-point flexural test -cellulose samples



Graph 6: Three-point flexural test - beech sawdust + cellulose samples

6.4 CAPILLARY WATER ABSORPTION

The method of determining the water absorption coefficient due to capillary action in hardened mortar, defined by the European Committee for Standardization, was borrowed to measure the coefficient in mycelium composites.[49]

The testing follows several steps. Firstly, the sample needs to be completely dried out, possibly in a drying chamber. Further on, the shell surface has to be sealed (the ones tested here were sealed with a gluing gun, as it was the simplest method on hand). The dry weight of this sample is determined (M0). The sample is then usually placed on a triangular bar, but since dried mycelium bricks float in water, this step was unnecessary. The container is then filled with demineralized, or in this case, distilled water until the samples are submerged 5 cm. In order to make sure there is no air trapped beneath the sample, as it has an uneven surface, it should be placed in the tray in a sloping way. The following steps include weighing the samples in a specific time frame - after 10, 30, 60, 90 minutes, 2, 4, 8 and 24 hours (Table 14). As defined in the test for determining the capillary activity of mortar, two phases are the most important ones, phases after 10 (M1) and 90 (M4) minutes. A formula for determining capillary water absorption in fungi does not officially exist and after consulting an expert in the field of material testing, I was recommended the formula for determining the same properties in mortar instead.

There were five tested samples. Three of them were identical, consisting of beech sawdust inoculated with *Pleurotus ostreatus*, another one with the same substrate but inoculated with *Ganoderma lucidum*, and finally a sample with oak sawdust inoculated with *Ganoderma lucidum* as well .

For calculating the results, the following formula applies:

49 see European Committee for Standardization (CEN) 2002.

Fig. 138: Sealing the sample surface

Fig. 139: Samples during testing

$$C = 0{,}1\ (M4\text{-}M1)\ kg/(m^2 \times min^{0.5})$$

The results displayed in Table 13, show an obvious dissociation of values; the samples inoculated with *Pleurotus ostreatus* and *Ganoderma lucidum*, whereby the latter show significantly lower water absorption than the first sample group. These results lead to a conclusion that *Ganoderma lucidum* increases water repellency in the given samples inoculated with sawdust. To categorize the results, Table 14 was taken as a reference. *Pleurotus ostreatus* samples show water repellent, and *Ganoderma lucidum* waterproof qualities.

Time	-	10 min	30 min	60 min	90 min
Sample/Phase	M0	M1	M2	M3	M4
MM-FS-PO-17	285 g	291 g	299 g	313 g	325 g
MM-FS-PO-18	280 g	286 g	292 g	302 g	308 g
MM-FS-PO-19	273 g	281 g	289 g	304 g	311 g
MM-Q-GL-02	240 g	241 g	244 g	247 g	248 g
MM-FS-GL-20	233 g	233 g	234 g	237 g	239 g

Table 12: Capillary water al

Fig. 140: Samples after testing - noting the weight

sample	C [kg/(m² x min$^{0.5}$)]
MM-FS-PO-17	0,0034
MM-FS-PO-18	0,0022
MM-FS-PO-19	0,0030
MM-Q-GL-02	0,0007
MM-FS-GL-20	0,0006

Table 13: Capillary water absorption - results

water absorption coefficient [kg/(m² x min$^{0.5}$)]	behaviour towards water
> 2,000	strongly absorbent
≤ 2,000	water resistant
≤ 0,500	water repellent
≤ 0,001	waterproof

Table 14: Capillary water absorption - classification

	2 h	4 h	8 h	24 h	-	-
	M5	M6	M7	M8	M8 - M1	M4 - M1
	338 g	393 g	472 g	565 g	274 g	34 g
	311 g	327 g	254 g	423 g	137 g	22 g
	318 g	346 g	399 g	505 g	224 g	30 g
	249 g	258 g	290 g	577 g	336 g	7 g
	244 g	272 g	355 g	546 g	313 g	6 g

er absorption - measuring

7 OUTLOOK

Fig. 141: MM-CS1-PO-09 - truss

Fig. 142: Curved cellulose sample

7.1 POTENTIALS AND LIMITATIONS

Trough research and conducted experiments I have obtained comprehensive knowledge in the field of mycelium composites. Their potential as well as limitations became very clear – these conclusions will be addressed in this chapter.

The first advantage of the circular production of mycelium composites is their ability to digest almost any substrate used, from waste products in wood and paper industry, to plant-based agricultural leftovers. It is important to note that mycelium digests lignocellulosic substrate; different mushrooms require a higher lignin or cellulose amount as their nourishment. This is usually closely related to their natural habitat, i.e. mushrooms growing on tree trunks require a higher lignin percentage than the ones sprouting from the soil.

In that manner, the resources needed for mycelial growth are limitless, as long as the waste presented originates from plant-based matter. After the material fulfils its purpose, it can be introduced back to the environment where it initially came from. Not only does it not cause harm to the ecosystem, it increases its nutrition rate, and finally degrades completely.

As for the substrate itself, the primary choice of my experiments was wood, i.e. sawdust since it is effortlessly obtained locally, thereby reducing transportation costs. The second most used substrate was cellulose, which actually ranked a lot higher in all of the material testing results than any other organic component. However, obtaining cellulose in high quantities is not as simple as sawdust. That is why cellulose, as a substrate for mycelium, should be used when aiming at specific results. For instance, when building a structure that requires elements with a higher load bearing capacity, they should be based on cellulose as a substrate and the rest could be grown out of sawdust, to act as "lighter" pieces.

Another big potential that is yet to be explored is the possibility of targeted material distribution within a certain element. The principle is similarly to the one explained in the last paragraph, but planned as a heterogeneous composite with a more complex geometry. The sample could have parts with different organic or inorganic compounds, depending on the function it needs to attain. This idea was already tested when making a series of trusses out of bleached (Fig. 141) and unbleached cellulose and one with both of the mentioned cellulose types, but differently distributed (the two material types differ in their lignocellulosic ratio). The experiment would provide insight which material carries the force flow better, depending on its position, but due to contamination and breakage of the truss when unmoulding was abandoned.

The scaling of the elements is another important aspect. In the setting I worked in, the proportions remained approximately close to the standard brick dimensions. Since contamination still poses a risk to the well-being of growing mycelium, bigger samples mean higher difficulty when handling the single pieces, and therefore a higher contamination rate. For that reason, a modular system remained a limitation for a structural piece. Scaling the material would not cause a problem if a proper working environment was available. As already seen in the projects presented in the chapter *References* (4), growing bigger elements is possible (4.4.1 - The Circular Garden and 4.4.3 - The Growing Pavilion). To ensure such a production, industrial equipment is needed.

The shrinkage factor can be limiting, but also potentially beneficial. A decrease in volume highly depends on the chosen substrate and its preparation and it should be taken in consideration when planning shapes of a certain geometry. For instance, cellulose has a high shrinkage rate and subsequently high density but also a substantial deformation of the surfaces (Fig. 142), as the materials lumps on certain areas. Deformation of the surface could be considerably favourable, because if it could be controlled, it would become a method of designing curved surfaces, without prestressing the material in a shape or using elaborate scaffolding systems.

Mycelium has an ability of "healing itself", i.e. it can grow back after a piece was broken. This is possible as long as the organism is alive; once the sample is thermally treated, the growth stops and the composite becomes stagnant. This is an interesting aspect which can be used for assembly methods; growing pieces separately and stacking them while they are still alive, then letting them fuse into one component. This method was already researched in the project *Modular Mycelia*[50], conducted at the ICD, University of Stuttgart. A previously mentioned truss broke during unmoulding, so the broken pieces were put together and regrew back to one piece (Fig. 141).

Milling as a surface modification of the mycelium composite is possible as well. There are two implementation methods, milling the sample after terminating the growth (Fig. 143) and while the mycelium is alive (Fig. 144). The first method is disadvantageous due to the crumbling of the milled surface. The second approach is better because the mycelium has the "time to heal" and the milled surface regenerates its protective surface.

Considering the current research on mycelium´s other material properties, its use in thermal and sound insulation shows a great potential, and are already present on the market. It is possible to use mycelium composites as an infill in a certain building components, in order to enhance its thermal insulation e.g. a classic hollow brick filled out with mycelium based insulation product. This kind of an approach is an alternative to conventional insulating materials.

50 Campbell et al. - 2017.

Fig. 143: MM-FS-PO-20

Fig. 144: MM-FS-PO-21

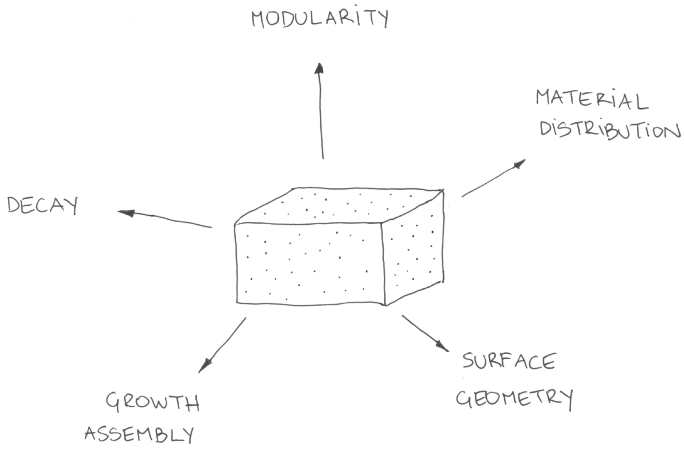


Fig. 145: Single element - accounted parameters

7.2 FROM GROWTH TO DECAY - FUTURE PROSPECTS

Some of the specifications mentioned in the previous chapter will be further researched and adapted to achieve certain features necessary for developing a new structural design strategy.

One of those parameters is modularity. Production of a continuously uniform piece simplifies the overall manufacturing process and makes reuse of one mould type several times possible. The assembly method using mycelium growth as a binding agent is very advantageous because no additional material or physical binder is needed to connect the single elements.

Material distribution is the following factor that is taken into account. It is determined by the position of the single element in the system - cellulose used as a substrate at the position with a greater load-bearing capacity, gradually turning to a homogeneous substrate mixture until the solely light elements are positioned.

Decomposing as the last stage of nature's circular process is another factor. There are no exact data regarding mycelium composite's life-span, there is only data related to the mycelium and substrate type, humidity levels, storage conditions, etc. Philip Ross states in one of his lectures, if mycelium bricks would be dug up in the ground, they would decompose in a few years by the moisture of the ground, as well by insects eating into them.[51]

With the aspects listed, the application of mycelium-based structures is clearly the future of impermanent architecture, finding its use in temporary and short-term public events. Exhibitions, festivals, conferences and similar venues generate a large amount of waste, making therefore the substitution of conventional elements with biodegradable architecture highly pragmatic and necessary. One of those substitutes could for example be objects made only out mycelium composites. Experimenting with different material combinations and joining mycelium composites with inorganic compounds makes the material more durable and resilient.

51 Ross, Mycotecture 2014.

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8.5 LIST OF FIGURES

Photos on following pages were taken by Hannah Pansinger:

76, 77, 102, 103, 108, 109, 110, 111, 118, 119, 138 and 139.

Image on page 50 was scanned from: Hebel, Dirk E.: Cultivated Building Materials: Industrialized Natural Resources for Architecture and Construction, 136.

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