

AN EXPLORATION OF NATURE-BASED MATERIALS TO GROW ARCHITECTURE

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ABSTRACT

To prevent the earth from heating up further and being exploited, the current way of building has to change drastically. For centuries, nature has been leading the way by growing 'architecture'. Through implementing nature-based materials in the build environment this example can be followed. Out of eight high potential disruptors, mycelium-based composites come out best with the predetermined requirements of being renewable, biobased and biodegradable. This natural decomposer of organic matter supports all life on earth and can be used for building purposes. Current and future applications already envision mycelium-based building elements and the qualitative and quantitative experiments show material properties that most closely match foams, but also results in material properties leaning towards natural materials and elastomers.

Keywords: *Climate Change, Nature-based Materials, Mycelium-Based Composites, Ganoderma Lucidum*

I. INTRODUCTION

Earth's climate has changed throughout history. Most of the temperature differences were the result of a change in earth's orbit that influenced the amount of solar energy planet earth received (NASA, 2018). Yet, in modern times, a different influence entered the arena: humanity. From the industrial revolution onward earth's temperature has risen 0,9 Celsius. The Intergovernmental Panel on Climate Change warns the world for further temperature rise towards 1,5 Celsius, which would have irreversible consequences for our planet such as the loss of valuable ecosystems (IPCC, 2018). Together with the increasing world population and the depletion of fossil fuels and raw materials, climate change is one of the large scale challenges of our time (Luscuere et. al., 2018).

1.1 Climate change & the build environment

Within the build environment the challenges are related to the physical consumption of natural resources: energy, water, materials and topsoil (Luscuere et al., 2016). In 1995, the build environment was accountable for 40% of the total global raw materials usage (Roodman & Lenssen, 1995). In 2016, the Netherlands exceeded that number with the use of 50% of the total raw materials (MIE & MEA, 2016). Already, non-renewable resources are becoming scarce goods. Looking at Figure 1, it can be stated that with the current reserves of fossil fuels and minerals - that are economically able to be extracted - oil will last another 30 years and Antimony (Sb) will run out in 3 years (Quick, 2012). According to the study 'The Limits to Growth' executed in 1971 by, among others, Dennis and Donna Meadows, an abundance of natural resources will lead to an increase in deaths and births. While the population, pollution, food and services per capita decrease (Figure 2). Furthermore, the build environment is responsible for 36% of the global final energy use and nearly 40% of energy related carbon dioxide emission in 2017 (UN Environment, 2018). Concrete - world's most used resource after water - is responsible for 8% of the total carbon dioxide emission (Preston & Lehne, 2018). On top of the high carbon dioxide emissions and raw material depletion, the build environment is often a linear process (take-make-dispose). According to the Circularity Gap Report, in 2019 only 9% of our world is circular, which means that products and services are traded in closed loops. Therefore, the construction industry has a large share of the global challenges that the earth is facing.

1.2 Nature leads the way

In contrast to mankind's 200.000 years of depletion, *Mother Nature* has been innovating for 3.8 billions years true trial and error, forming closed loops with beneficial consequences to planet earth. Therefore, an opportunity arises for mankind to break through its fixed-minded ideas and search for fundamental new beliefs in nature. Nature's architecture has evolved highly efficient systems and processes that can inform solutions to many of the waste, resource efficiency and management problems that we now struggle with today (Benyus, 1997). What if we could use the force of nature to grow architecture? This paper intends to inform architects, (industrial) designers, engineers, builders and all engaging in the 'beyond sustainability' movement.

1.3 Method

This research is divided into two phases, the first phase consists out of an analysis of eight promising nature-based materials that offer opportunities in the transition towards a circular building process. According a literature study an overview is created and tested on predetermined requirements. The second phase includes an in depth research towards the most eligible nature-based material via interviews and experiments. The following entities will be the target for the interviews: (international) universities, startups, corporates, industry, market leaders, scientists and designers. Each party will be asked the same questions to gain objective insights into the market. Both qualitative and quantitative experiments are executed in a self build lab in Eindhoven and in The Material Lab at the faculty of Industrial Design at the Delft University of Technology.

To summarize, the posed research question is formulated in two-fold:

- 1) *Which nature-based materials have the potential to grow architecture?*
- 2) *Can we use mycelium-based composites for building purposes?*

II. OVERVIEW OF NATURE-BASED MATERIALS

Survival is the only criterion of success in biology. It is largely concerns adaptation to the surroundings conditions and change in local and global context. In order to create beneficial structures to the environment, nature suggests ways of achieving this goal (Gruber, Imhof, Speck, & Hoheneder, 2016). An overview of eight promising nature-based materials that have the potential grow architecture is represented below and in Figure 3. After a short introduction, these materials - that are part of a carefully selected shortlist of nature-based materials - will be compared with each other on the requirements of being renewable, scalable and biobased.

2.1 Algae

One of the oldest forms of life on earth is the single celled organism called algae. In nature they grow in freshwater, seawater and may also grow in damp soil and rocks (Algae Biomass Organization, 2018). Individually, algae are tiny, but together they produce three quarters of the oxygen in our atmosphere (Fothergill, 2006). Recently, algae found its way into the sectors of biofuel, food and pharmacy. In the construction area, one innovation is taking place in the form of an algae 3D filament. However, this process is still heavily dependent on the slow biodegradable and genetically modified bioplastic PLA (Polylactic acid) (Atelier luma, 2018).

2.2 Mycelium

Mycelium is the vegetative part of a fungus. Mycelium is highly important to the ecosystem as they help to decompose organic material. Via massive underground networks as widespread as forests, the released nutrients are given to the connected plants that enable life on earth (Stamets, 2008). Material made from mycelium has already entered the packing industry and is slowly embedded in the construction industry by means of small pavilions and insulation material.

2.3 Coral

In 2010 Ginger Krieg Dosier researched the growth of corals and utilized this process to grow bricks. The BioBrick combines sand particles with bacteria that glue the grains of the sand together to form stone (TU Delft, 2013). Resulting in construction bricks with strength and durability comparable to those of conventional bricks (Biomason, 2019).

2.4 Microorganisms

In 2015 the BiotAlab at the Bartlett School of Architecture, University College London created a bio-receptive concrete that enables the hosting of microorganisms and nurtures bio colonization. The organisms growing in the concrete produce oxygen and absorb CO₂ and pollution. Bio-receptive-concrete that is carbonated to lower the pH value and geometrically designed to promote the growth of common mosses in certain areas, will allow plant life to thrive on buildings in a way that is both more sustainable and more efficient than existing walls (The Building Centre, 2017).

2.5 Beeswax

Honey bees play an important role in our ecosystem by pollinating plants and flowers that either provide food for humanity or animals we consume (BBC & The British Beekeepers Association, 2014). The bees build their nests in a hexagon structure, which is - viewed from a mathematical perspective - the most efficient way (Morgan, 1999). In order to create such structures a wax is secreted from a special gland in their body and mixed with honey and pollen (Graham, 1992). A bee could be viewed as a living and flying 3D printer. A Chinese artist called Ren Ri utilized this process to his benefit by placing designed elements in hives. The bees will naturally start 'filling' the created object and can therefore be 'programmed' to create an object of choice (Jobson, 2014).

2.6 Silk

Silk is a natural protein fiber that can be produced by a number of insect species. Silk is mainly produced by the larvae of insects undergoing complete metamorphosis, however some insects such as webspinners and raspy crickets produce silk throughout their lives. The most known and economically important producer of silk is the silkworm (Zhang, 2013). Recently, silkworms made their debut in architectural context in *The Silk Pavilion* by Neri Oxman. In which 6000 silkworms squirm over a man-made structure combining biological and digital fabrication (MIT Media Lab, 2013).

2.7 Crystals

A crystal is a solid material caused by a natural process called crystallization. When liquids cool or harden, atoms and molecules bound together in an uniform and repeating pattern in their search for stability. This pattern causes the material to grow in various unique shapes. In nature the process of crystallization occurs when for example, magma cools or salt water evaporates (Beckmann, 2013). Crystals are mostly known for their purpose in the sectors of jewelry or decoration. But it also has a great industrial purposes due to the hardness of the material. Diamonds for example, are the hardest natural occurring material in the world (Angus, 1997). There are no executed examples of crystals used in constructive context. Yet futuristic visions have been created, envisioning cities built by the crystallization process (Geboers, 2018).

2.8 Wood

Wood is a porous and fibrous structural tissue found in the stems and roots of trees. The organic material is a composite of cellulose fibers with strong tension capacity, lignin that is resistant to compression and hemicellulose (Hickey & King, 2000). Since human appearance on earth, wood has been utilized as the main raw material. Due to the development of new materials such as steel, plastic and concrete, wood was relatively less used during the industrial period (Wrigley, 1962). But since light shined upon the environmental impacts of that time, wood has gained popularity. Examples of

this movement are the development of the tallest wooden residential building in the Netherlands by Arup (Arup, 2018) and the innovativeness of using trees for living structures by Baubotanik in Germany (Baubotanik, 2018).

2.9 Material choice

In order to compare the different nature-based materials to each other, a number of criteria has been drawn up to determine the most high potential disruptor of the build environment. These criteria are, renewability, biodegradability and scalability. A material is renewable if it is not depleted by use (Cambridge Dictionary, 2019). Biodegradability means the capability of a material to be decomposed by bacteria or other living organisms and thereby avoiding pollution (Wösten, 2019). The scalability represents the capacity to be changed in size or scale (Oxford University Press, 2019). If looked upon the criterion renewability, Table 1 shows that microorganisms, crystals and biobrick make use of non-renewable resources and are therefore not selected. Due to complex manufacturing processes, the involvement of animals and the slow growth rate, beeswax and silk score much lower on the criteria of scalability than algae, mycelium and wood. Since mycelium, algae and wood are all biodegradable a new criterion is added; feasibility. How likely will we be building with these materials in the future? In contradiction to wood and mycelium, algae has no examples of implementation in the build environment and the mentioned 3D printing filaments are still heavily depending on polluting plastics. This in combination with a hard regulatable incubation process makes algae less feasible than its competitors (Klarenbeek, 2019). In comparison to mycelium, wood in the Netherlands is not harvested locally. In 2013, 8,6% of Dutch consumption of wood and wood products came from Dutch forests (CBS, 2016). Furthermore, indigenous species have a relative slow growth rate compared to tropical species (Clerkx & Schelhaas, 2015) and are often processed with chemicals to better structural properties (Jonkers, 2019). Considering the symbiosis in nature, material characterization and mutual benefit, a combination of mycelium and wood has been chosen. Where wood functions as the substrate and mycelium is the natural binder that ‘glues’ the wooden particles together creating mycelium-based composites.

Nature-based material	Renewable	Scalable	Biodegradable	Weight (kg/m3)	O2 production	Growth rate
Algae	Yes	Medium	Yes	920	Yes	200% in 1 day*
Mycelium	Yes	Easy	Yes	305	No	1 brick takes 5 days*
Coral	No	Easy	No	1450	No	1 brick takes 1-2 week*s
Microorganisms	No	Easy	No	2300	Yes	1 year*
Beeswax	Yes	Difficult	Yes	961	No	1-1,5 kg in 7 days*
Silk	Yes	Difficult	Yes	250-450	No	433m per day per worm*
Crystals	No	Medium	No	2170	No	Differs per type
Wood	Yes	Easy	Yes	160 - 1355	Yes	1cm takes 15 min-15 jr*

*Sources: (Raven, J., & Geider, R. 1988), (Ecovative, 2019), (Biomason, 2019), (BiotA Lab, 2017), (Graham, 1992), (MIT Media Lab, 2013), (Wilson, 1984).

Table 1. Overview of nature-based materials set off against the predetermined requirements.

III. BIOLOGICAL BACKGROUND OF MYCELIUM

The fruiting body of a fungus is often viewed as the main organism, while in fact the underground fungal threads called mycelium, form the larger part of the organism. Compare it with an apple tree, in which a mushroom represents an apple and the tree is the hidden network of mycelium. In order to fully understand the fundamentals of these species called fungi, the biological aspects are looked upon.

3.1 The fifth kingdom

In 1751 Carl Linnaeus created the separation of the three kingdoms in nature. 'If it simply existed it was a mineral. If it lived it was a vegetable. If it also had senses it was an animal' (Harding, 2008, p. 15). In 1960 radically new schemes for the classification of five kingdoms (Protista, Fungi, Plantae, Animalia and Monera) were proposed. But it was not until 1980 that the concept became widely accepted and fungi were perceived as own kingdom. In Figure 4, a representation of the tree of life shows that fungi are closer related to animals than to plants (Stamets, 2008). In contradiction to plants, fungi are heterotrophic, which mean they can not produce their own food Fungi consist out of a very diverse assemblage of organisms and microorganism that obtain their nutrients from decaying organic materials, living plants, animals or even other fungi. Their habitat include soil, water and organisms. (Harding, 2008). At the moment 144,000 species are known but scientist reveal that it is only a fraction of the 93 percent that is yet undiscovered (Royal Botanic Gardens, Kew, 2018). It is estimated that the total number of fungal species on earth is somewhere between 2.2 and 3.8 million, a number that exceeds the number of plants by more than six times (Hawksworth & Lücking, 2017).

3.2 Function in nature

Due to its predominantly life below the surface, animals and plants received more scientific attention than mycelium. But the more research is done, the more researchers realize how this intriguing kingdom of organism underpins all life on earth. The main function of mycelium is to recycle dead organic matter into key plant nutrients that are released back into the soil. Thereby allowing the next generation of seedlings to grow (Royal Botanic Gardens, Kew, 2018). Without this nutrient cycling, life on Earth as we know would not exist. By connecting the roots of various plants, mycelium - that can be seen as nature's internet - enables a nutrition flow throughout forests (Stamets, 2005). This principle forms the basis of the science fiction movie that premiered in 2008 called Avatar. Reality reveals that more than 92 percent of all plant species are linked into this network that does not only shares nutrients (BBC, 2014). Recent studies have shown that this system also enables communication between the participants and warn for danger (Zeng, 2010). Nonetheless, its 'cyber security' will not withstand the depleting force of humanity. Because already one third of all arable land in the world is degraded either due to pollution or to erosion (Guardian, 2018). Therefor mycelium is being used in innovative projects to realize soil recovery and to restore ecosystems (Stamets, 2005).

3.3 Growth process

By gaining knowledge from mycelium experts such as Gavin McIntyre (Ecovative), Maurizio Montalti (Officina Corpuscoli), Davine Blauwhoff (Centre of Expertise Biobased Economy), Han Wösten (Utrecht University), Elise van den Elsacker (Vrije Universiteit Brussel), Rob Banken (Banken Champignons), Bert Rademakers (CNC Exotics), Marc Postel (Fungalagic) and Elvin Karana (Delft University of Technology) insights into the growing process are acquired (Figure 5 + 6). In nature mycelium can grow undisturbed if exposed to the right growing conditions and nutrition. In general mycelium absorb cellulose, hemicellulose and lignin, some species even 'eat' plastics or oils. While digesting, the mycelium acts as a natural binder that glues organic material together. This technology could be used to add value to the world of construction (Critical Concrete, 2018). In order to create a building material with mycelium, an organic substrate of choice is sterilized, inoculated with a mycelium specie of choice and placed in a mold of choice. The substrate gets gradually digested by the mycelium, hereby forming a solid mass. Depending on the size of the mold the substrate is fully grown after approximately 1 week. The length of the incubation period depends mostly on the type of mycelium, temperature and humidity (Wösten, 2019). After full growth, the mycelium can be terminated by heating the substrate on 90 degrees until it weighs one third of its original weight (Karana, 2019). Drying the substrate by sun is also a possibility that requires less energy. Not only can mycelium be grown in molds, innovative projects are occurring that explore 3D printing and growing in open air environments (Ecovative, 2019).

IV. APPLICATIONS FOR MYCELIUM-BASED COMPOSITES

Through interviews with the above mentioned market leaders and experts, an overview of the current and future applications for mycelium-based composites is created (Figure 7).

4.1 Current applications

Growing materials, once viewed as science fiction, yet turning into reality. In the world of mycelium-based composites there is one absolute market leader: Ecovative. In 2007 the company was founded by two graduate students from the Rensselaer Polytechnic Institute in Green Island. By patenting their recipes and growth process they gained a head start on the competition. After building a factory and performing long term research and development, they now offer two types of materials: a mycelium-based composite and a pure mycelium foam. The composite is the main product that is able to replace styrofoams and is mainly marketed as a compostable packaging product. With customers, such as IKEA and Dell this is their main proposition. Furthermore, this product can be used in a range of applications including construction, theater sets, wetland rafts and acoustic barriers. The mycelium foam is viewed as a suitable replacer for synthetic foams. Therefore, their focus lies in the area of apparel, compostable cosmetic applicators, cell-based meat and tissue engineering. Even though this product is ready to market, Ecovative is developing the ideal product-market fit before entering new terrain (Ecovative, 2019). In contradiction to the large scale - industry focused - manufacturer, some small groups such as Krown-design and Mogu are entering the field with more every day products like wall and floor tiles, lampshades and flowerpots (Krown-design, 2019) (Mogu, 2019).

4.2 Future applications

Due to the current environmental challenges, the demand for nature-based materials rises (Marketresearch, 2018). This movement inspires and encourages artists and designers all over the world to work with the white thread organism. Since 2008, visionaries created concepts such as mycelium dresses (Morby, 2016), a growing chair (Klarenbeek, 2018) and a temporary outdoor pavilion build from 'mycobricks' (Arup, 2017). Although these - rather pioneering - examples gained new insights and inspired the world, the question remained: *'How will mycelium-based composites be used in the future?'*. By talking to the experts, this question was answered. One of the future developments is to turn mycelium and agricultural by products into a material that has similar properties as leather. Hereby creating a renewable source of leather like material that is not tied to the livestock industry (Mycoworks, 2019). In the field of construction the question remains: *'Will we actually build with this material?'*. If it is up to microbiologist Han Wösten the whole Ashby Chart will be filled with mycelium. At the moment the material is categorized as a foam or soft wood when pressed (Karana, 2019). But he is open to the fact that higher qualities can be achieved through more research and genetic modification. Designer and researcher Maurizio Montalti is developing a 3D printable mycelium filament that is able to grow in an open environment. He states 'There are many opportunities such as; interior architecture, developing facades and structural elements'. Expert Dr. Drew Endy (Professor of Bioengineering at Stanford University) states: 'Wood fungus are going to be one of the major engines for manufacturing in the 21st century'. This all sounds very promising, yet the discovery of Ecovatives special project gives more credible confidence for a future of mycelium structures. In conversation with Ecovative's co-founder Gavin McIntyre, a discreet project with the US Defense Advanced Research Projects Agency was revealed. In 2017 Ecovative was awarded with \$9.1 million to develop & scale a new generation of living building materials together with researchers from Columbia University, New York University and the Massachusetts Institute of Technology (Ecovative, 2017).

V. EXPERIMENTAL RESEARCH

In order to learn more about mycelium and its material properties several experiments have been carried out. With these results and previously acquired knowledge a clear view on mycelium's purpose in construction can be made. Both qualitative and quantitative experiments have been executed.

5.1 Ganoderma Lucidum

On the advice of the spoken experts, the fungi species *ganoderma lucidum* is chosen for the experiments due to its relative high mechanical properties in comparison with other species. The fruiting body of the *ganoderma lucidum* is one of the most popular medicinal mushrooms in Asia and is referred to as 'the mushroom of immortality' (Chang & Miles, 2004). The mushroom typically grows on dead hardwoods, but sometimes is also found on softwood species.

5.2 Method

For this experiment hempflax is used as substrate with flour and water as nutritional additives. The raw material is obtained through Bert Rademakers of CNC exotics who is currently European's only license holder of Ecovative's patented material. Plastic thermoformed moulds (16 × 16 × 4 cm, PET-G) were filled with pre grown substrates in a sterilized environment. The materials were hand-pressed in the mold to obtain uniform shapes and covered with perforated cellophane foil (0.35 µm, standard commercial PPI). Throughout three months more than 50 mycelium based composites with different qualities were made (Figure 8). An overview of the different samples is shown below in Table 2. Depending on the experiment, samples vary in growth temperature, light conditions, particle size, density, treatment (and use of mold. The standard sample (GH) was grown in a mold at 27°C, had no daylight, particle size of 5-20mm and underwent average pressure resulting in a density of 106,91 kg/m³. All other samples differ only in one of the above mentioned aspects, the differentiations are highlighted with a grey gradient in the Table below.

Code	Fungus	Substrate	Growth Temp.	Daylight	Particle size	Density	Treatment	Mold
GH	Ganoderma Luci.	Hempflax	27°C	0%	5-20mm	106,91 kg/m ³	Terminated	Yes
GHL	Ganoderma Luci.	Hempflax	27°C	0%	5-20mm	222,04 kg/m ³	No	Yes
GHSP	Ganoderma Luci.	Hempflax	27°C	0%	0-5mm	106,91 kg/m ³	Terminated	Yes
GHMP	Ganoderma Luci.	Hempflax	27°C	0%	0-5 + 5-20mm**	115,13 kg/m ³	Terminated	Yes
GHL D	Ganoderma Luci.	Hempflax	27°C	0%	5-20mm	82,24 kg/m ³	Terminated	Yes
GHHD	Ganoderma Luci.	Hempflax	27°C	0%	5-20mm	131,58 kg/m ³	Terminated	Yes
GH2127	Ganoderma Luci.	Hempflax	21 + 27°C*	0%	5-20mm	82,24 kg/m ³	Terminated	Yes
GH2721	Ganoderma Luci.	Hempflax	27 + 21°C*	0%	5-20mm	82,24 kg/m ³	Terminated	Yes
GH21	Ganoderma Luci.	Hempflax	21°C	0%	5-20mm	65,79 kg/m ³	Terminated	Yes
GHDL	Ganoderma Luci.	Hempflax	21°C	100%	5-20mm	106,91 kg/m ³	Terminated	Yes
GHML	Ganoderma Luci.	Hempflax	21°C	50%	5-20mm	106,91 kg/m ³	Terminated	Yes
GHNM	Ganoderma Luci.	Hempflax	21°C	0%	5-20mm	57,57 kg/m ³	Terminated	No

*Halfway the growth cycle, the temperature is adjusted up or down

**50% of small particles mixed with 50% of regular particles

Table 2: Overview of mycelium based composites that are used for the qualitative and quantitative experiments.

5.3 Qualitative experiments

The qualitative experiments were performed in order to get grip on the technical and experimental material properties of the mycelium-based composites. The experiments yield the influence of light and temperature on the growth conditions and the influence of water, fire and outdoor climate on living mycelium-based composites and terminated mycelium-based composites.

5.3.1 Experiential characterization

By tinkering and observing the experiential qualities (Figure 9) of the developed mycelium-based composites an experimental characterization is created. This concerns how the samples feel and what meaning, emotion and action they evoke. At first sight, the material has a slightly yellow-like color. By first touch the samples were experienced lightweight, solid and spongy (living sample) or brittle (terminated sample). When interacting with the material, a soft skin is revealed that is made out of pure mycelium. The softness of the material ‘invites you’ to touch, stroke, press and break it. By examining up close, a mushroom smell is recognized that reminds the mind that the material is organic.

5.3.2 Growing conditions

By varying the growing temperature, exposure to daylight and growth in or outside a mold, the influence of the growing conditions on the mycelium-based composites is researched in this experiment. The results of the temperature variation are shown below in Table 3. The materials that were exposed to temperature of 27°C showed a higher growth rate than the materials exposed to 21°C. After 4 days the materials grown at 27°C were fully colonized, while the materials grown at 21°C needed 2 more days.

Material growth temperature	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
21°C	0%	3%	6,25%	12,5%	25%	50%	100%
27°C	0%	12,5%	25%	50%	100%		

Table 3: The growth rate (%) of mycelium composites grown at different temperatures (21°C and 27°C)

Figure 10 shows the influence of temperature and daylight. The materials that were exposed to daylight and high temperatures tend to grow outside and form a pure mycelium skin, while the materials that were exposed to less or no daylight and low temperatures tend to grow inward and form less skin. The material that grew outside the mold initially had no signs of growth. But when a cross section was made the mycelium had only grown inwards.

5.3.3 Water repellency

The experiments with water involve research towards the influence of water on the mycelium-based composites. In the first experiment a terminated (GH) and living (GHL) mycelium-based composite are exposed to a few drops of water. As seen on Figure 11, both samples do not absorb the water and show hydrophobic properties. Another setup (Figure 12) examines the floatability and water absorption of the materials. Both samples were weighed and placed in a glass bowl with 500 ml of water. While placing the samples in water the floatability property immediately appeared. The terminated mycelium-based composite (GH) weighed 30 grams at start and 36 grams after 8 weeks, while the living mycelium-based composite (GHL) weighed 54 grams at start and 40 grams after 8 weeks. After 8 weeks both samples floated and did not show signs of sinking deeper in the water, when the start position and the end position in the water is compared. After 6 weeks the terminated sample (GH) hosted a new mold at the interface of water and air, hereby starting the decomposing phase.

5.3.4 Fire resistance

How fireproof are mycelium-based composites? In the building regulations, requirements are set to material applications in relation to fire safety. To determine the focal point of the mycelium-based composites, five samples are exposed to different oven temperatures (Figure 13). Each sample is baked for 30 minutes at 100°C, 150°C, 200°C, 250°C or 300°C. The experiment showed that sample exposed to 300°C started burning at 260°C. In order to get a better insight of how the mycelium-based composites behave when exposed to fire, a terminated (GH) and living (GHL) mycelium-based composite are exposed to a gas flame (600°C) for 15 seconds. To compare the results, samples of hempflax without mycelium growth, pinewood and styrofoam are also tested. The results (Figure 14) show that all samples were only burned at surface level, except for the styrofoam sample that had been melted for approximately 70 percent. After removing the flame, the living mycelium-based composite (GHL) and the styrofoam sample extinguished directly, however the styrofoam continued to melt for 2 more seconds. The terminated mycelium-based composite (GH) and the pinewood both extinguished after 1,5 seconds, while the hempflax sample - that was not grown through with mycelium - kept on burning for 10 seconds.

5.3.5 Degradability

Most buildings are made of materials that can withstand extreme weather conditions. How will the mycelium-based composites respond to the Dutch climate? In this experiment (Figure 15) a living and a terminated sample are placed outdoors for 6 weeks starting from January 9th 2019, to be exposed to the sun, wind, rain, snow and temperature differences in order to research its degradability. After 6 weeks the living mycelium-based composite (GHL) showed little to no change. The only noticeable difference is that the color was slightly darkened. While the color of the terminated mycelium-based composite (GH) has even darkened more, another remarkable event occurred. After 6 weeks the sample hosted various new colorful fungi and small insects, hereby starting its decomposing phase.

5.3.6 3D printing

The technology of 3D printing offers the build environment a chance to integrate modern production techniques into the construction process. This experiment (Figure 16) explores 3D printing with a mycelium paste. The mycelium substrate was mixed with agar, a gelling agent. Which provides stiffness and viscosity to the paste and also provides nutrition for the mycelium (Ecovative, 2019). Different particles sizes (0-5mm or 5-20mm) of the mycelium substrate were mixed with different amounts of agar (50%, 66% or 90%). The smaller the particles (0-5mm) of the mycelium substrate, the easier it was to extrude the mixture. The larger the percentage of agar in the total mixture, the greater the shrinkage of the substrate.

5.4 Quantitative experiments

The quantitative experiments contain various mycelium-based composites that will be tested on bending and compressive strength. The results will be used to determine the position of the material in the Ashby Chart. These experiments have been selected in discussion with Henk Jonkers, who is a leading researcher and expert on self-healing bio-concrete and the sustainability Chair Leader of the Materials and Environment section in the Faculty of Civil Engineering and Geosciences at the University of Technology in Delft. The tests were performed with a Zwick/Roell Z010 (Ulm, Germany) universal testing machine.

5.4.1 Three-point bending test

A bending test of a material allows for the determination of that material's ductility, flexural strength, fracture strength and resistance to fracture. These characteristics can be used to determine whether a material will fail under a certain bending moment and are especially important in any construction process involving ductile materials loaded with bending moments (TestResources, 2019). The three-point bending test is set up with a cross head speed of 200 mm/min, force shutdown threshold of 40% F_{max} and clamp support distance of 120 mm. Looking at the results (Figure 17, 18 and Table 4), it

is striking that the living mycelium-based composite (GHL) shows - on average - 3 times more deformation (dL: 34mm) with increasing force, while the terminated samples show less deformation (dL: 8,0-13,7mm). By decreasing force, the living mycelium-based composite (GHL) continues to displace, while the majority terminated samples rapidly stop their displacement. Therefore, it can be stated that the living mycelium sample (GHL) shows elastic properties, while terminated samples act as a brittle material. The influence of lower (21°C) growth conditions results in higher resistance (F_{max} and F_{Break}), while the deformation remains almost the same. Sample GH grown at 27°C had a F_{max} of 45,2N and F_{Break} of 27,0N, while GH21 grown at 21°C had a F_{max} of 54,0N and F_{Break} of 32,4N. When looking at the samples GH2127 and GH2721 that were exposed to both temperatures, the sample that was grown for 3 days at 21°C followed by 3 days at 27°C (GH2127) gained higher values compared to the sample first grown at 27°C (GH2721). GH2721 not only resulted in lower values than GH2127 but also as GH, which grew at 27°C. Looked upon the particle sizes, the results show that the smaller the particle size, the smaller the force resistance, but the more deformation took place. GHMP (0-5 + 5-20mm) showed a F_{max} of 33,6N with a deformation of 11,5mm, while GHSP (0-5mm) showed a F_{max} of 23,0N with a deformation of 13,7mm. It is noteworthy that sample GHSP shows the fastest break after peak load among all samples, hereby being the most brittle. The aspect of pressure results in samples with low (GHL) and high (GHHD) density. The sample GHL results in lower force resistance than GHHD by almost the same deformation, but the GH results in higher force resistance than GHHD. The sample that grew outside the mold (GHN) was the weakest sample among all with F_{max} of 17,9N, F_{Break} of 12,4N and deformation of 8,0 mm.

Code	F_{max} (N)	dL at F_{max} (N)	F_{Break} (N)	dL at break (mm)	W to F_{max} (Nmm)	S_0 (mm ²)
GH	45,2	8,7	27,0	9,8	199,1	1425,0
GHL	43,1	27,7	25,9	34,0	703,9	1615,4
GHSP	23,0	13,6	21,9	13,7	172,3	1342,3
GHMP	33,6	11,0	20,1	11,5	170,9	1413,6
GHL	25,9	7,7	15,5	10,4	104,0	1225,0
GHHD	41,0	7,2	24,6	8,3	144,5	1580,0
GH2127	48,7	8,2	29,2	9,7	201,7	1343,1
GH2721	30,6	9,3	18,3	10,8	142,6	1440,2
GH21	54,0	8,5	32,4	9,6	227,7	1427,8
GHN	17,9	7,5	12,4	8,0	68,3	1332,2

Table 4: Overview of the results of the three-point bending test.

5.4.2 Compression test

The goal of a compression test is to determine the behavior or response of a material while it experiences a compressive load by measuring fundamental variables, such as strain, stress, and deformation (TestResources, 2019). The samples are placed between two plates that distribute load at 200 mm/min across the entire surface and stop after a maximum displacement of 50mm or by the force shutdown threshold of 30% F_{max} . The results are shown in Figure 19, 20 and Table 5. After the peak load, when the force decreases and the displacement increases, the material has failed. Therefore the results after the first peak can be neglected (Jonkers, 2019). In contrast to all terminated mycelium-based composites, the living sample (GHL) results in an almost linear line. While most samples broke or showed irreversible deformation, GHL behaved like an elastic material that partially distorted to its original shape after compression. The influence of growth temperature results in a

higher resistance for samples grown at lower temperatures (21°C). GH21 showed a F_{max} of 330N, while GH2127, GH and GH2721 showed a F_{max} of 295N, 268,3N and 190,4N. Looked upon the particle sizes, the results show that the smaller the particle size, the smaller the compression strength, with a comparable deformation rate. GHMP (0-5 + 5-20mm) showed a F_{max} of 189,1N, while GHSP (0-5mm) showed a F_{max} of 101,7N. The high density mycelium-based composite (GHHD) resulted in the least deformed sample by a force of 277,1N. The sample that grew outside the mold (GHNM) was again the weakest among all with maximum force of 97,9N.

Code	F_{max} (N)	dL at F_{max} (N)	F_{Break} (N)	dL at break (mm)	W to F_{max} (Nmm)	S_0 (mm ²)
GH	268,3	17,3	187,8	24,2	2451,5	1520,5
GHL	491,0	49,9			11055,9	1472,0
GHSP	101,7	15,1	71,2	21,2	658,6	1417,4
GHMP	189,1*	49,9			7202,3	1401,6
GHLD	128,3*	49,9			4812,7	1179,7
GHHD	277,8	10,9	194,5	33,4	1702,6	1680,8
GH2127	295,5*	49,9			11305,9	1353,6
GH2721	190,4	20,4	133,3	29,1	2087,1	1386,7
GH21	332,4*	49,9			12459,7	1365,3
GHNM	97,9	25,8	68,5	30,3	1591,3	1067,6

*Determined by first peak load

Table 5: Overview of the results of the compression test.

5.4.3 Material comparison

In order to compare the mycelium-based composites with other materials, the Ashby Chart is used. This scatter plot displays two or more properties of many materials or classes of materials. For this experiment the Young's modulus (E_{mod}) and density (ρ) are chosen as properties. The E_{mod} is determined with the help of Hooke's Law ($E_{mod} = \sigma / \epsilon$), for this the strength (σ) and strain (ϵ) of the material are needed. The strength (σ) is determined by dividing the maximum force (F_{max}) by the surface of the sample (S_0). Resulting in the formula, $\sigma = F_{max} / S_0$. To determine the strain (ϵ) the deformation (dL) is divided by the total length of the sample (h); $\epsilon = dL / h$. In Table 6 the density (ρ) and calculated Young's Modulus (E_{mod}) are shown. In Figure 21 these data are placed in the Ashby Chart. It becomes clear that most samples for these experiments can be compared with (flexible polymer) foams. However, two samples differ from the rest; the high density sample (GHHD) makes a throw towards the category of natural materials, while the living sample (GHL) results in a material in between foams and elastomers.

Code	GH	GHL	GHSP	GHMP	GHLD	GHHD	GH2127	GH2721	GH21	GHNM
ρ (kg/m ³)	106,91	222,04	106,91	115,13	82,24	131,58	82,24	82,24	65,79	57,57
E_{mod} (GPa)	9,3E-04	6,7E-04	8,8E-04	9,7E-04	9,2E-04	1,3E-03	9,8E-04	8,2E-04	9,9E-04	8,7E-04

Table 6: Young's modulus and density of various mycelium-based composites.

VI. CONCLUSION

Humanity has entered a stage in which further temperature rise towards 1,5 Celsius would have irreversible consequences for our planet if not act upon. One of the main contributors to this cause is

the current way of building, that results in high carbon dioxide emissions, raw material depletion and is often a linear process. When looking at nature's architecture and innovation, this provides enormous opportunities to contribute to the climate problem by developing new renewable, scalable and biodegradable building materials to grow architecture. The reviewed nature-based materials (algae, mycelium, coral, microorganism, beeswax, silk, crystals and wood) provide an overview of the potential disruptors that have shown that mycelium in combination with wood meets all predetermined requirements. For which wood functions as the substrate and mycelium is the natural binder that 'glues' the wooden particles together creating mycelium-based composites. Mycelium plays a key role in our existence by decomposing organic matter into key plant nutrients that are released back into the soil. Thereby allowing the next generation of seedlings to grow. The big question is whether it can play a major role of significance through an application in the build environment? The answer is yes. This can be concluded when looked upon the results of the interviews, applications, qualitative and quantitative experiments. Designers, artist, market leaders and scientist from all over the world have captured the mycelium virus by creating mycelium-based chairs, dresses, pavilions, up to 3D printing living mycelium structures. They are convinced that mycelium will have a purpose in construction. But what kind of purpose? From the results of the qualitative experiments, the following material properties of mycelium-based composites were obtained: lightweight, solid, elastic or brittle (depending on the termination process), fast growing, biobased, biodegradable, renewable, water repellent, floatable, (more) fire resistant and 3D printable. The quantitative results classify most mycelium-based composites in the category foams, while some make a throw towards the category of natural materials or elastomers. Direct applications in the construction industry are therefore possible whereby mycelium could directly replace foams such as polystyrene foam or insulation material. However, mycelium-based composites show unique material properties that not yet have been optimal utilized by the market. Therefore, more research and development is required so that new concepts can be discovered, that will show the world of construction what nature has been showing us for ages.

DISCUSSION

Although intended at first, due to a lack of time this research did not include experiments with combinations of various fungi species and (in) organic substrates. Therefor the conclusion of this paper only applies to mycelium-based composites made from the *Ganoderma Lucidem* and hempflax. With the same argument the acoustical and insulation properties of the mycelium-based composites were not tested, although prior researches indicated these abilities. When looked at the calculations of the Young's Modulus, the E_{mod} was determined by a compression test. Although the mycelium-based composites are isotropic (identical physical properties when measured in different directions), the most accurate results would be gained by a tensile test. Therefor the results as shown in Figure 20, might differ per test (Henk Jonkers, 2019). In order to gain higher mechanical values, the density of the mycelium-based composites could be increased by compressing the material with a hot or cold pressing machine. Throughout the research a new quality of the mycelium-based composites arose. After finishing the compression test, two pieces of the living mycelium sample (GHL) were - without intention - placed in a closed ziplock plastic bag (20 x 30mm). After 4 days the materials had grown together. This characteristic may be worth investigating further. For now, three major challenges emerge in fundamental research, growing conditions and product-market fit. The first one is to further explore the material properties of mycelium-based composites by varying substrates and fungal species, potentially resulting in new material categories. Secondly an opportunity arises when a specific substrates combination is taken to a higher level by investigation towards new growth techniques such as 3D printing and growing outdoors with substrates from local resources. Thirdly, research (e.g. the Material Driven Design approach) has to be done on new products and services to implement mycelium-based composites in the (construction) market, where it can fulfill its full potential.

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VIII. APPENDIX

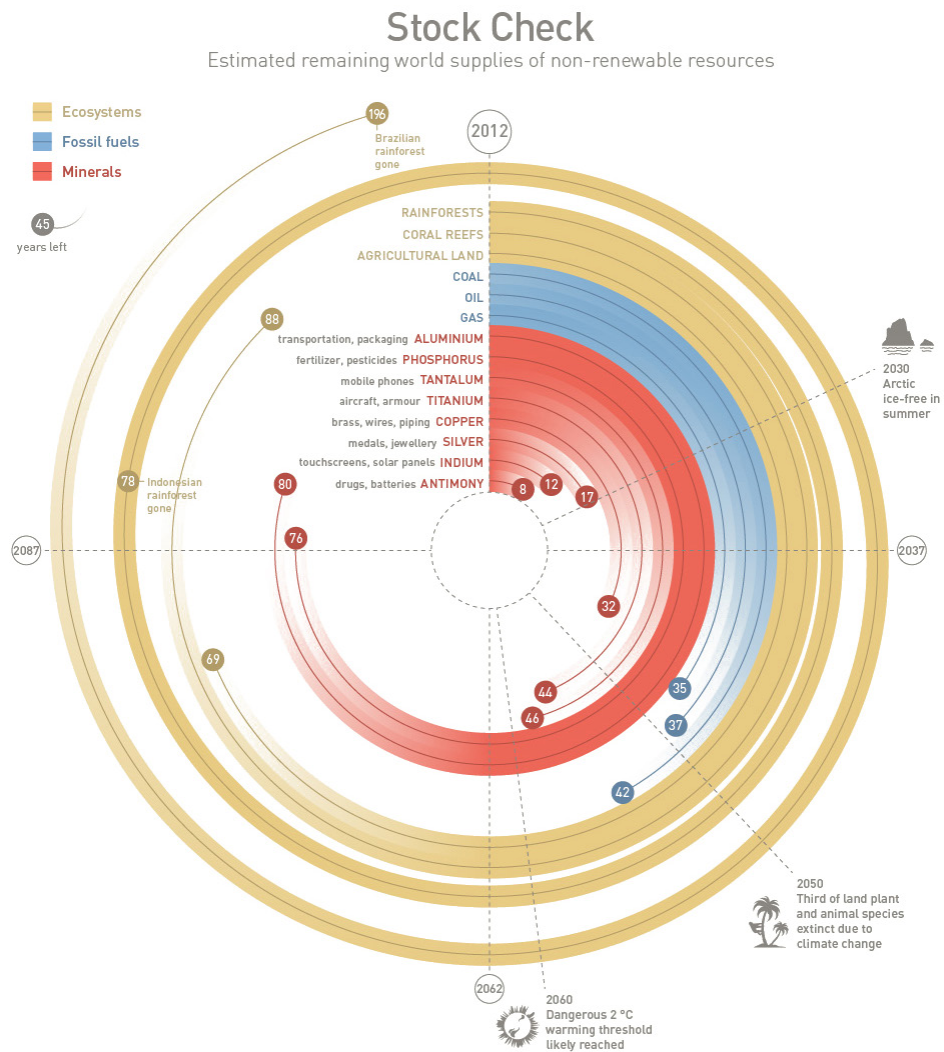


Figure 1: Overview of estimated remaining world supplies of non-renewable resources (Quick, 2012).

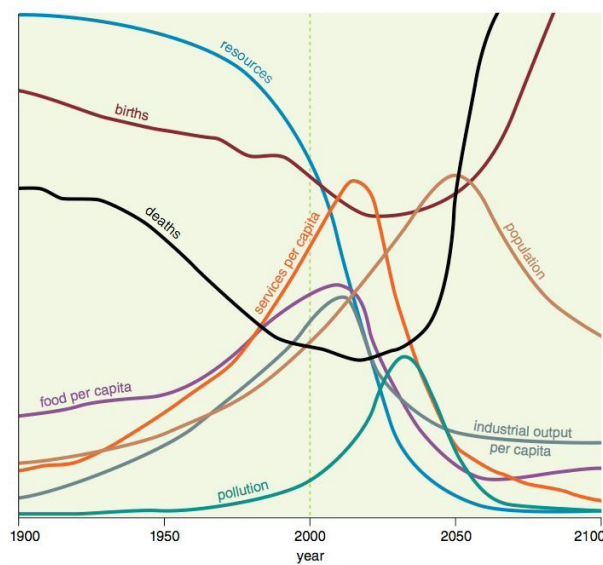


Figure 2: Computer simulation of exponential economic and population growth with a finite supply of resources (Meadows, 1972).

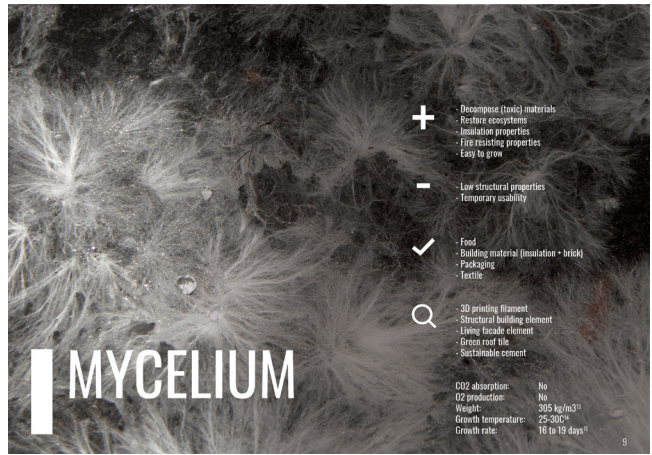


ALGAE

- +**
 - Fast growing
 - Easy to grow
 - CO₂ absorption
 - Form freedom
 - Lightweight
- - Never been used in construction
 - Soft material
 - Grass harm marine life
- ✓**
 - Biofuel
 - Food
 - Pharmacy
 - Cosmetics
- Q**
 - 3D printing filament
 - Bioplastics
 - Facade sheeting
 - Green roof/facade
 - Algae brick
 - Sustainable cement

CO₂ absorption: Yes
 O₂ production: Yes
 Weight: 320 kg/m³
 Growth temperature: 5-40°C
 Growth rate: 200% in 1 day¹

4



MYCELIUM

- +**
 - Decomposes (toxic) materials
 - Restores ecosystems
 - Insulation properties
 - Fire resisting properties
 - Easy to grow
- - Low structural properties
 - Temporary usability
- ✓**
 - Food
 - Building material (insulation + brick)
 - Packaging
 - Textile
- Q**
 - 3D printing filament
 - Structural building element
 - Living facade element
 - Green roof tile
 - Sustainable cement

CO₂ absorption: No
 O₂ production: No
 Weight: 305 kg/m³¹
 Growth temperature: 25-30°C⁴
 Growth rate: 16 to 19 days¹¹

9



BIOBRICK

- +**
 - No need for energy
 - Made in ambient temperatures
 - No CO₂ emissions
 - Can be made on site
 - No waste in manufacturing
- - Highly stable production environment
 - Toxic by products
 - Slow growth
- ✓**
 - Biobrick
 - Furniture
- Q**
 - Sustainable cement
 - 3D printing filament
 - Facade elements

CO₂ absorption: No
 O₂ production: No
 Weight: 1400 kg/m³¹
 Growth temperature: Ambient temperature¹⁴
 Growth rate: 1 brick takes 1-2 weeks¹²

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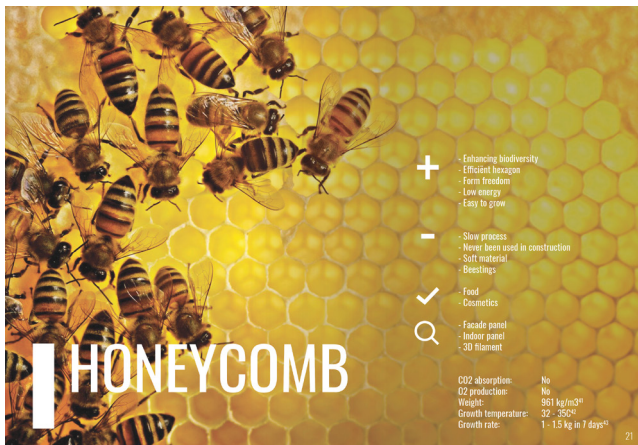


BIORECEPTIVE CONCRETE

- +**
 - Enhancing biodiversity
 - Clean air
 - Water management
 - No soil
 - No irrigation
- - Slow growth
 - Early stage technology
 - Exterior usage
- ✓**
 - Facade panel
- Q**
 - Roof tile
 - Exterior walls
 - Infrastructure
 - Slump for wet concrete

CO₂ absorption: Yes
 O₂ production: Yes
 Weight: 2400 kg/m³¹
 Growth temperature: Ambient temperature
 Growth rate: 1 year¹⁶

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HONEYCOMB

- +**
 - Enhancing biodiversity
 - Efficient hexagon
 - Form freedom
 - Low energy
 - Easy to grow
- - Slow process
 - Never been used in construction
 - Soft material
 - Beestings
- ✓**
 - Food
 - Cosmetics
- Q**
 - Facade panel
 - Indoor panel
 - 3D filament

CO₂ absorption: No
 O₂ production: No
 Weight: 861 kg/m³¹
 Growth temperature: 32 - 35°C⁴
 Growth rate: 1 - 1.5 kg in 7 days²¹

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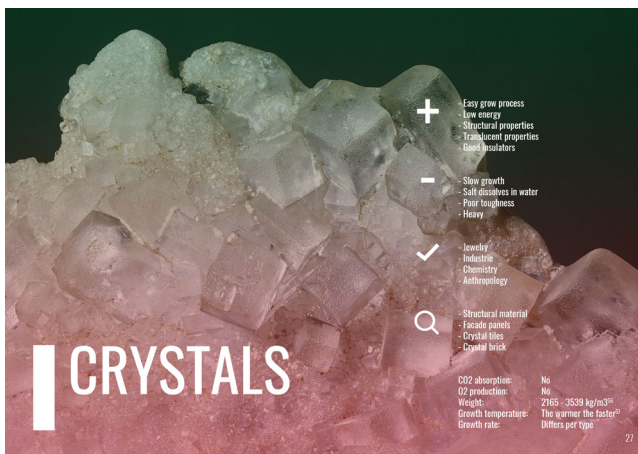


SILKWORM

- +**
 - Enhancing biodiversity
 - Efficient hexagon
 - Form freedom
 - Low energy
 - Easy to grow
- - Slow process
 - Never been used in construction
 - Soft material
 - Beestings
- ✓**
 - Food
 - Cosmetics
- Q**
 - Facade panel
 - Indoor panel
 - 3D filament

CO₂ absorption: No
 O₂ production: No
 Weight: 250-450 kg/m³¹
 Growth temperature: 25°C¹
 Growth rate: 433m per day per worm²²

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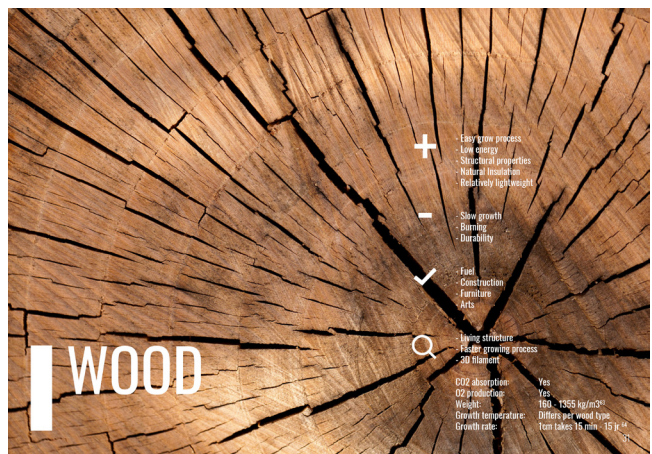


CRYSTALS

- +**
 - Easy grow process
 - Low energy
 - Structural properties
 - Translucent properties
 - Good insulators
- - Slow growth
 - Salt dissolves in water
 - Poor toughness
 - Heavy
- ✓**
 - Jewelry
 - Industry
 - Chemistry
 - Anthropology
- Q**
 - Structural material
 - Facade panels
 - Crystal tiles
 - Crystal brick

CO₂ absorption: No
 O₂ production: No
 Weight: 2165 - 3539 kg/m³¹
 Growth temperature: The warmer the faster²³
 Growth rate: Differs per type

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WOOD

- +**
 - Easy grow process
 - Low energy
 - Structural properties
 - Natural insulation
 - Relatively lightweight
- - Slow growth
 - Burning
 - Durability
- ✓**
 - Food
 - Construction
 - Furniture
 - Arts
- Q**
 - Living structure
 - Filter for grow process
 - 3D filament

CO₂ absorption: Yes
 O₂ production: Yes
 Weight: 160 - 1855 kg/m³¹
 Growth temperature: Differs per wood type
 Growth rate: Tree takes 16 min - 15 h²⁴

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Figure 3: Overview of eight promising nature-based materials to grow architecture.

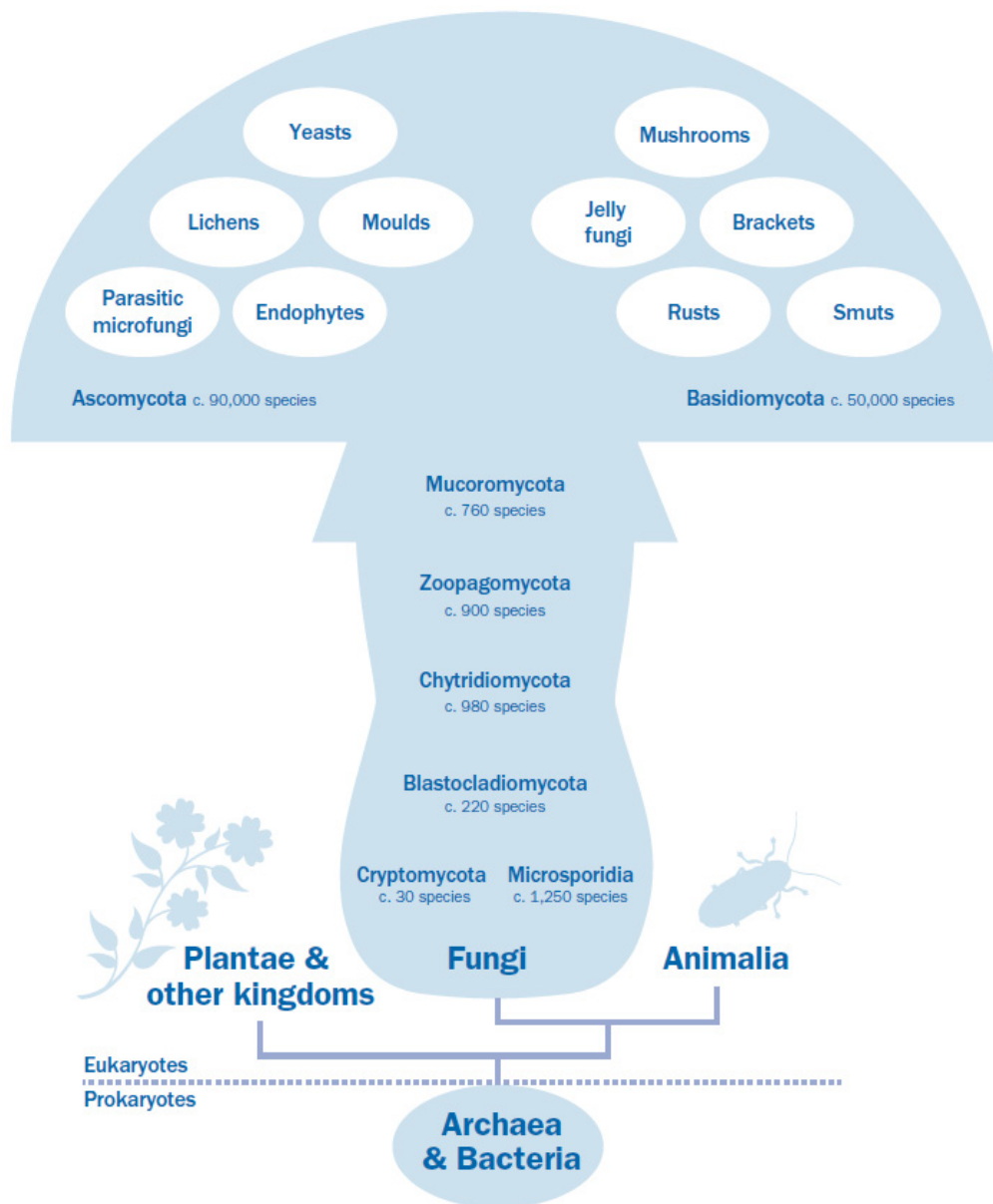


Figure 4: Schematic representation of the fungi kingdom within the tree of life (Stamets, 2002).

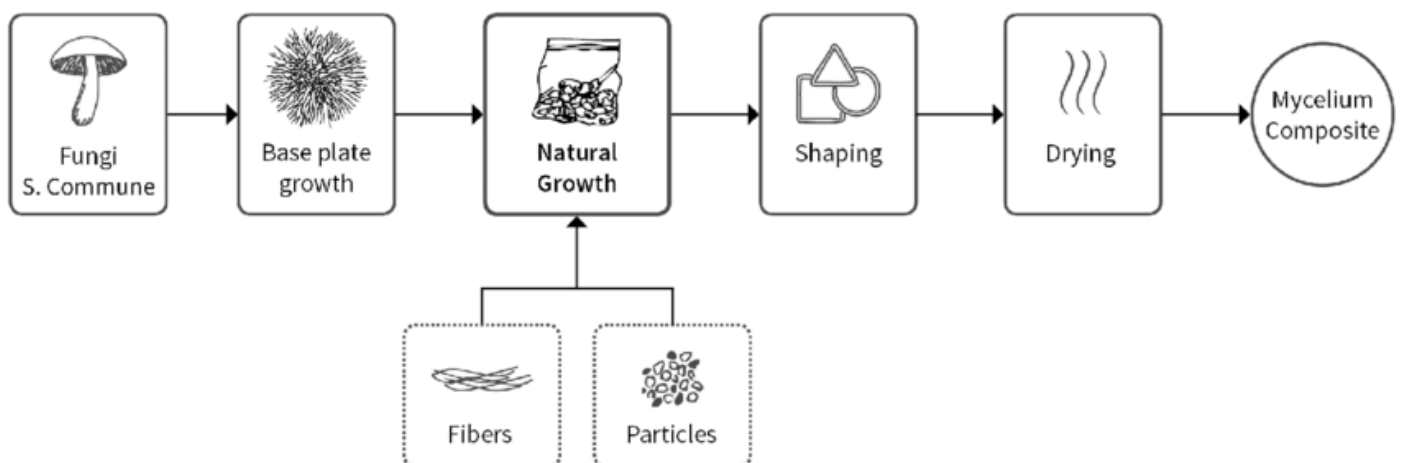


Figure 5: Growth process of mycelium-based composites (Karana, 2018).



Figure 6: Visiting mushroom farmers in the Netherlands.



Figure 7: Overview of current and future application for mycelium-based products.



Figure 8: Impression of the creation of the mycelium-based composites.



Figure 9: Tinkering and observing mycelium-based composites to determine the experiential characterizations.

OVERVIEW - 27C + NO DAYLIGHT (GH)



SECTION - 27C + NO DAYLIGHT (GH)



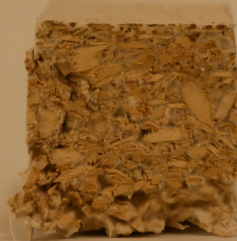
MICROSCOPE - 27C + NO DAYLIGHT (GH)



OVERVIEW - 21C + 100% DAYLIGHT (GHDL)



SECTION - 21C + 100% DAYLIGHT (GHDL)



MICROSCOPE - 21C + 100% DAYLIGHT (GHDL)



OVERVIEW - 21C + 50% DAYLIGHT (GHML)



SECTION - 21C + 50% DAYLIGHT (GHML)



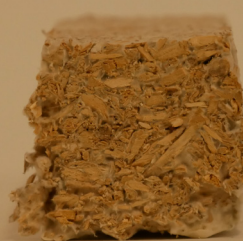
MICROSCOPE - 21C + 50% DAYLIGHT (GHML)



OVERVIEW - 21C + NO DAYLIGHT (GH21)



SECTION - 21C + NO DAYLIGHT (GH21)



MICROSCOPE - 21C + NO DAYLIGHT (GH21)



OVERVIEW - 21C + NO MOLD (GHNM)



SECTION - 21C + NO MOLD (GHNM)



MICROSCOPE - 21C + NO MOLD (GHNM)



Figure 10: Experiments with mycelium-based composites that have grown under different growth conditions (temperature, daylight and mold).

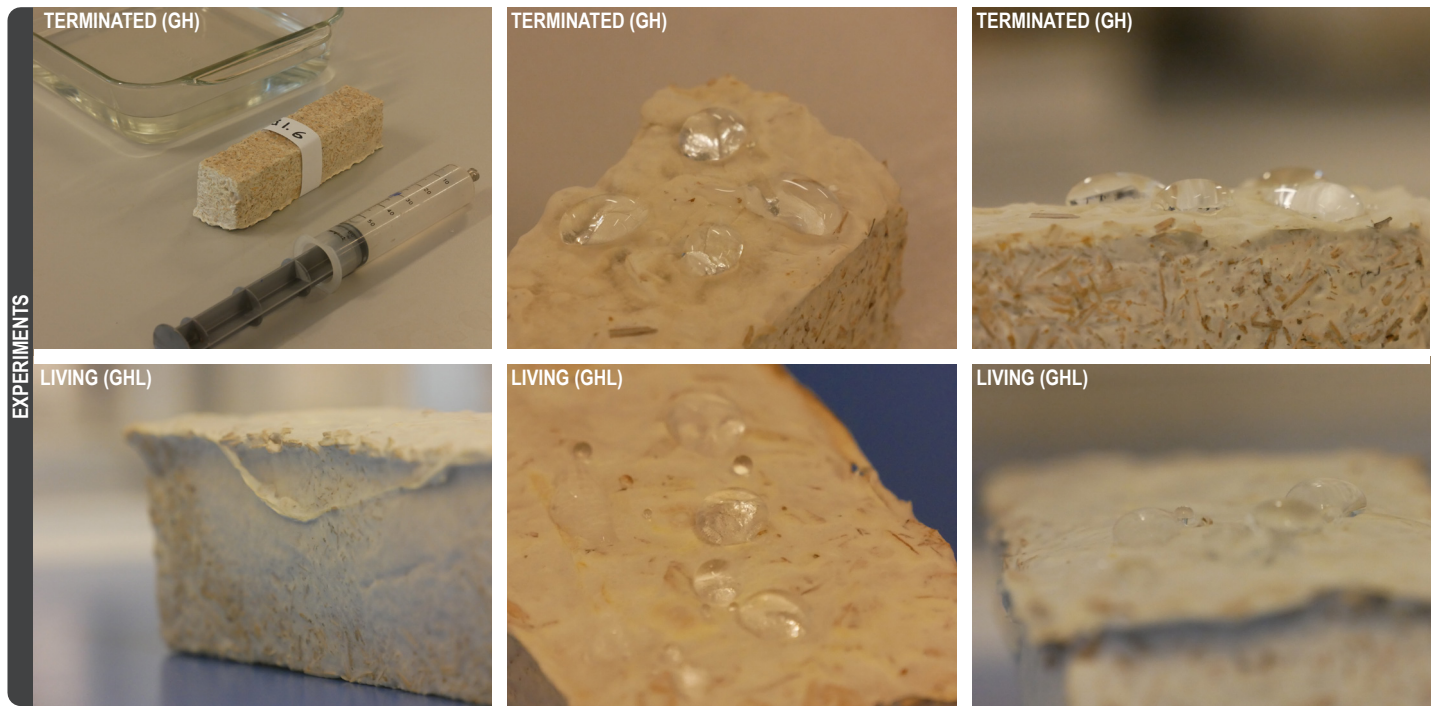


Figure 11: Experiments with water exposure to terminated (above) and living (below) mycelium-based composites.



Figure 12: Experiments with long term water exposure (8 weeks) to terminated (above) and living (below) mycelium-based composites.



Figure 13: Experiments with 5 identical mycelium-based composites baked at 100°C, 150°C, 200°C, 250°C and 300°C (top to bottom).

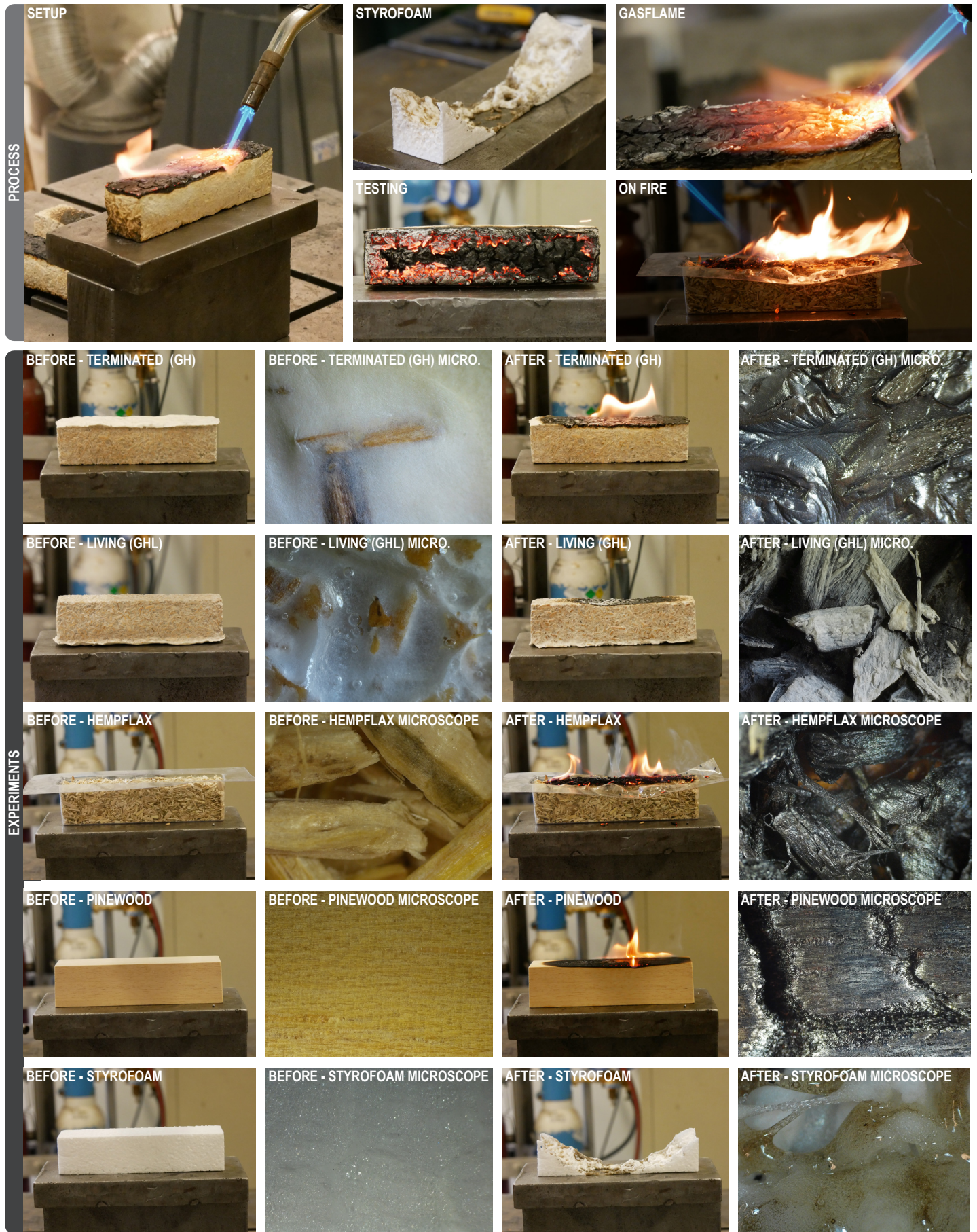


Figure 14: Experiments with gas flame exposure to (from top to bottom) terminated and living mycelium-based composites, hempflax, pinewood and styrofoam.

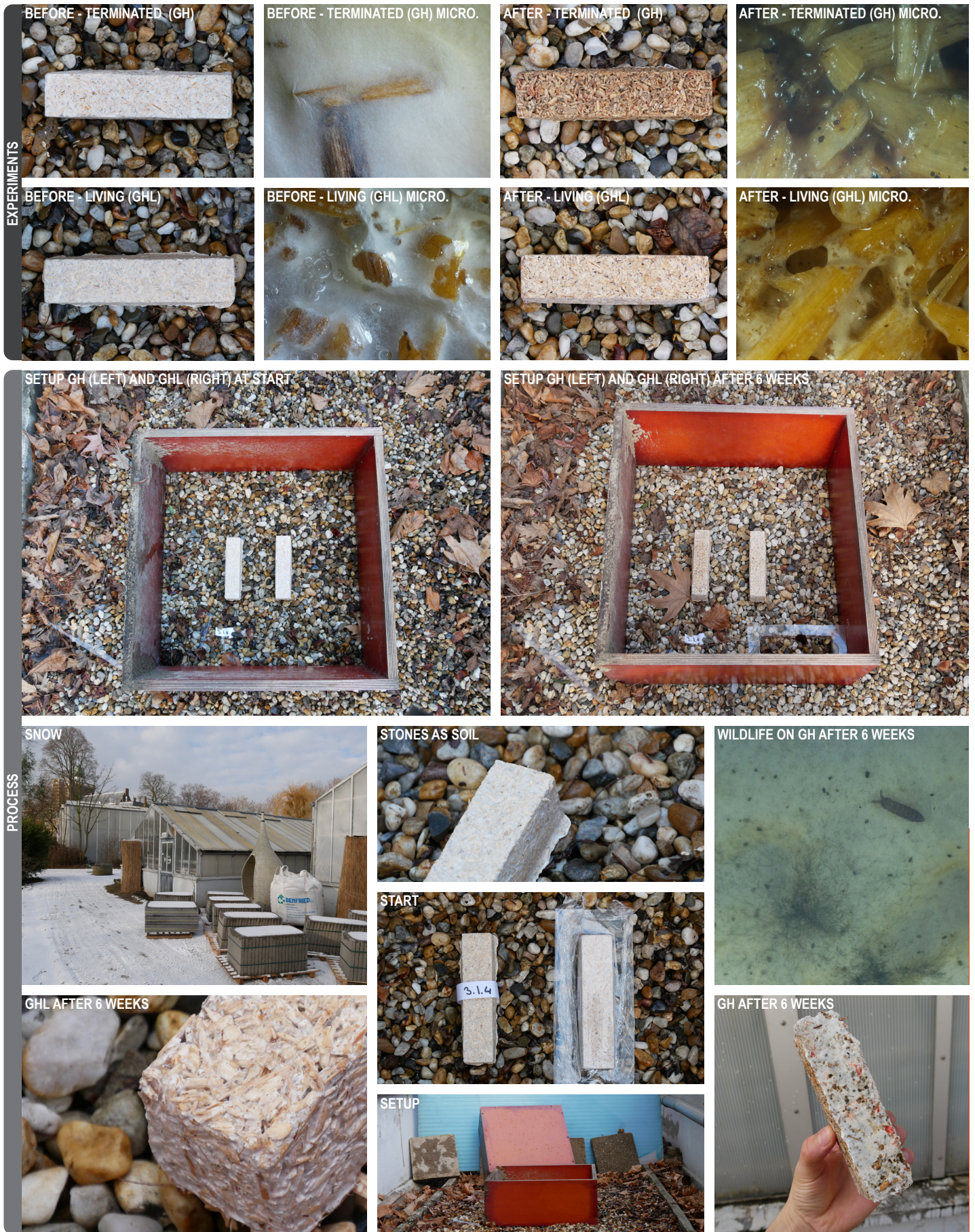
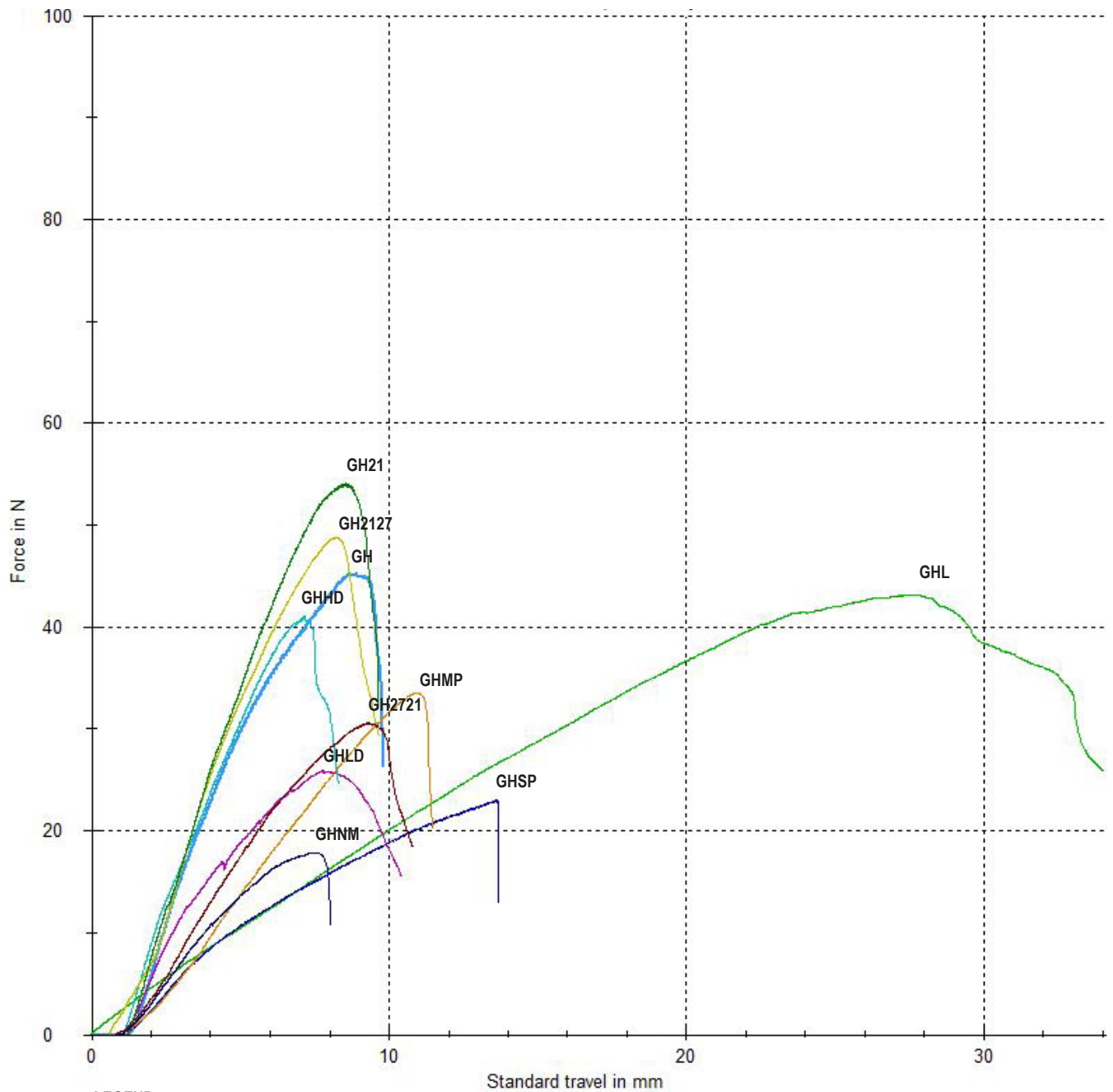


Figure 15: Experiments with the influence of the Dutch climate on terminated and living mycelium-based composites.



Figure 16: Experimenting with 3D printing mycelium-based composites.



LEGEND

Code	Fungus	Substrate	Growth Temp.	Particle size	Density	Treatment	Mold
GH	Ganoderma Luci.	Hempflax	27°C	5-20mm	106,91 kg/m ³	Terminated	Yes
GHL	Ganoderma Luci.	Hempflax	27°C	5-20mm	222,04 kg/m ³	No	Yes
GHSP	Ganoderma Luci.	Hempflax	27°C	0-5mm	106,91 kg/m ³	Terminated	Yes
GHMP	Ganoderma Luci.	Hempflax	27°C	0-5 + 5-20mm**	115,13 kg/m ³	Terminated	Yes
GHLD	Ganoderma Luci.	Hempflax	27°C	5-20mm	82,24 kg/m ³	Terminated	Yes
GHHD	Ganoderma Luci.	Hempflax	27°C	5-20mm	131,58 kg/m ³	Terminated	Yes
GH2127	Ganoderma Luci.	Hempflax	21 + 27°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH2721	Ganoderma Luci.	Hempflax	27 + 21°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH21	Ganoderma Luci.	Hempflax	21°C	5-20mm	65,79 kg/m ³	Terminated	Yes
GHNM	Ganoderma Luci.	Hempflax	21°C	5-20mm	57,57 kg/m ³	Terminated	No

*Halfway the growth cycle, the temperature is adjusted up or down

**50% of regular particles mixed with 50% of small particles

Figure 17: Results of the three-point bending test of various mycelium-based composites.

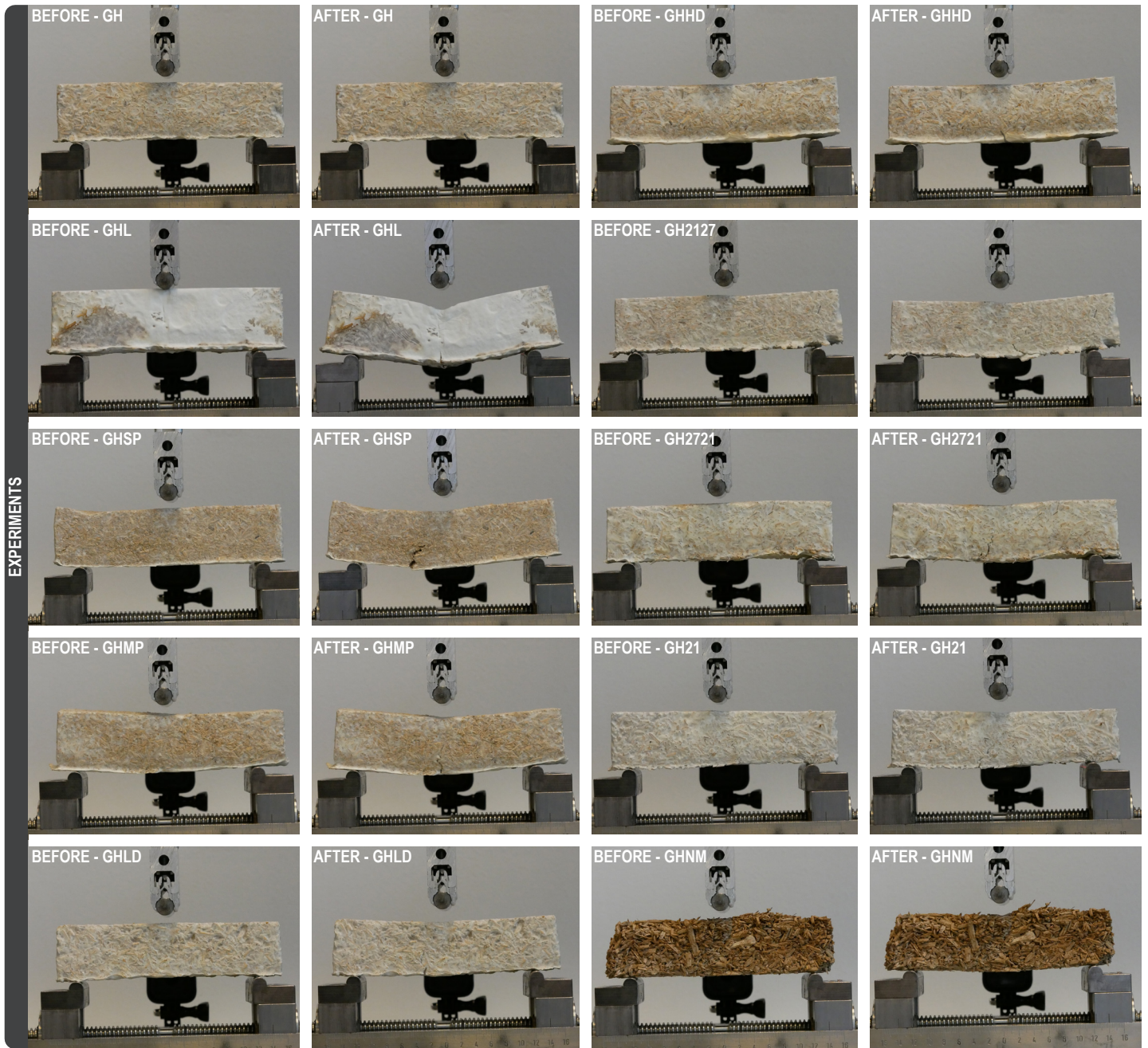
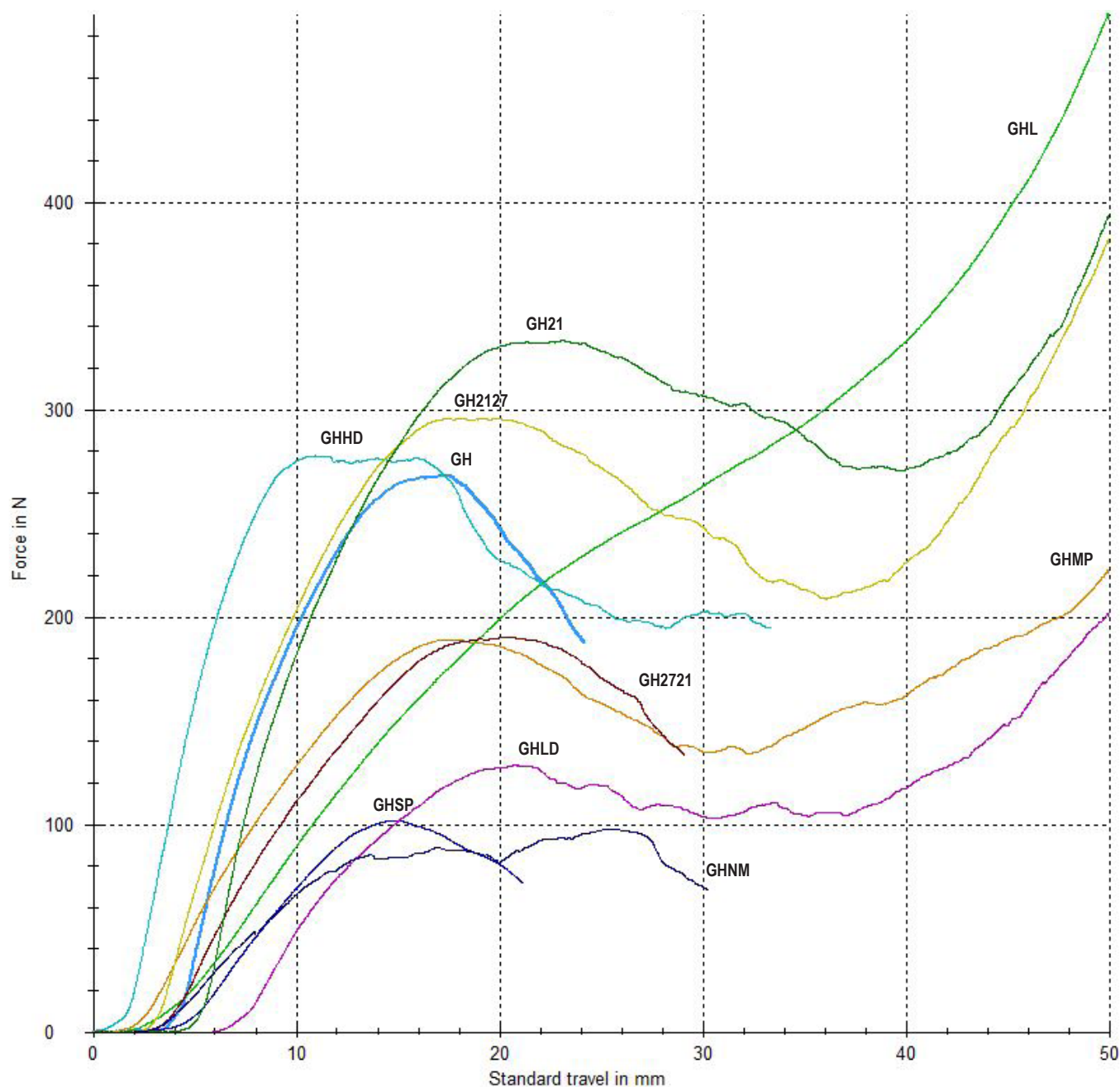


Figure 18: Before and after results of the three-point bending test of various mycelium-based composites.



LEGEND

Code	Fungus	Substrate	Growth Temp.	Particle size	Density	Treatment	Mold
GH	Ganoderma Luci.	Hempflax	27°C	5-20mm	106,91 kg/m ³	Terminated	Yes
GHL	Ganoderma Luci.	Hempflax	27°C	5-20mm	222,04 kg/m ³	No	Yes
GHSP	Ganoderma Luci.	Hempflax	27°C	0-5mm	106,91 kg/m ³	Terminated	Yes
GHMP	Ganoderma Luci.	Hempflax	27°C	0-5 + 5-20mm**	115,13 kg/m ³	Terminated	Yes
GHLD	Ganoderma Luci.	Hempflax	27°C	5-20mm	82,24 kg/m ³	Terminated	Yes
GHHD	Ganoderma Luci.	Hempflax	27°C	5-20mm	131,58 kg/m ³	Terminated	Yes
GH2127	Ganoderma Luci.	Hempflax	21 + 27°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH2721	Ganoderma Luci.	Hempflax	27 + 21°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH21	Ganoderma Luci.	Hempflax	21°C	5-20mm	65,79 kg/m ³	Terminated	Yes
GHNM	Ganoderma Luci.	Hempflax	21°C	5-20mm	57,57 kg/m ³	Terminated	No

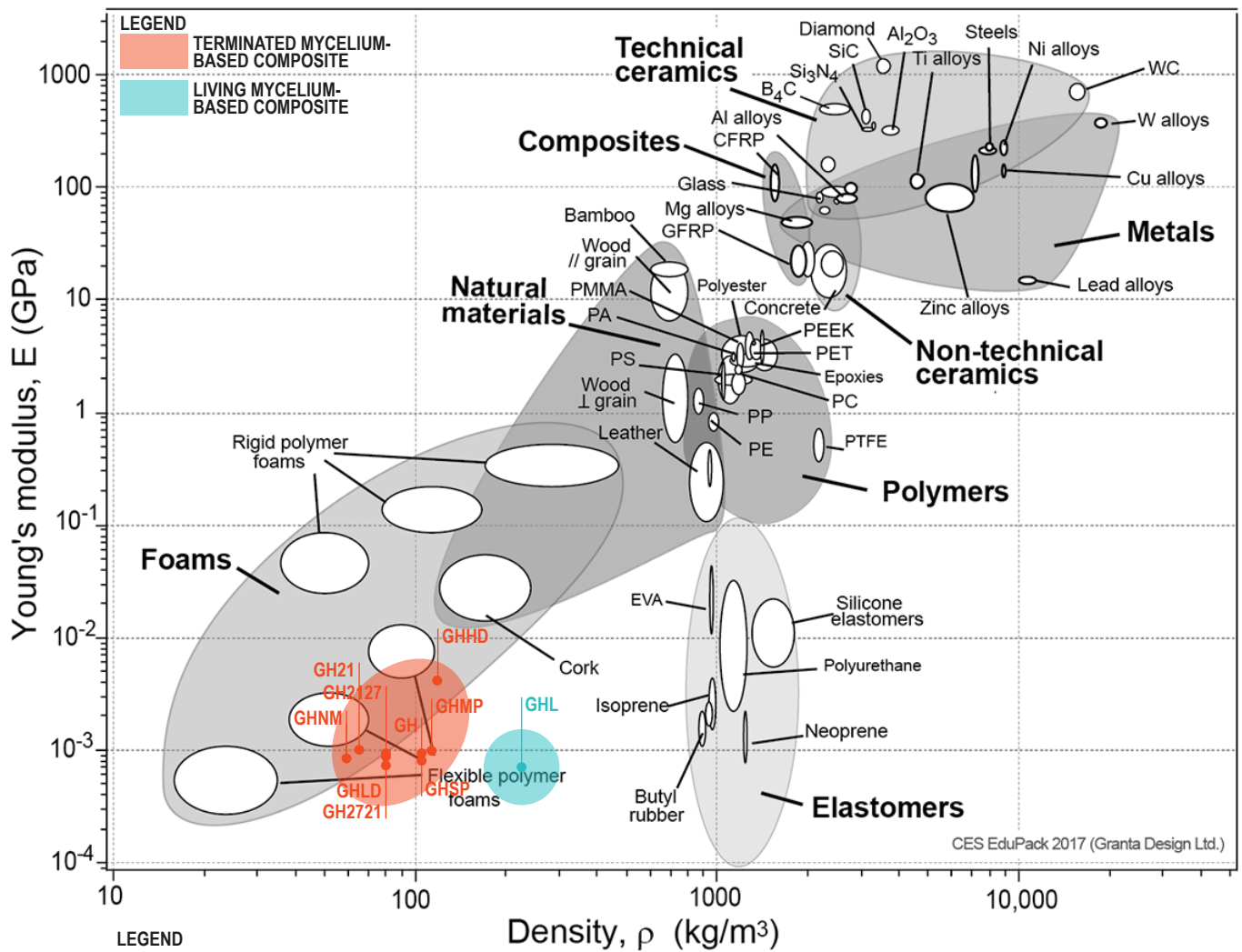
*Halfway the growth cycle, the temperature is adjusted up or down

**50% of regular particles mixed with 50% of small particles

Figure 19: Results of the compression test of various mycelium-based composites.



Figure 20: Before and after results of the compression test of various mycelium-based composites.



LEGEND

Code	Fungus	Substrate	Growth Temp.	Particle size	Density	Treatment	Mold
GH	Ganoderma Luci.	Hempflax	27°C	5-20mm	106,91 kg/m ³	Terminated	Yes
GHL	Ganoderma Luci.	Hempflax	27°C	5-20mm	222,04 kg/m ³	No	Yes
GHSP	Ganoderma Luci.	Hempflax	27°C	0-5mm	106,91 kg/m ³	Terminated	Yes
GHMP	Ganoderma Luci.	Hempflax	27°C	0-5 + 5-20mm**	115,13 kg/m ³	Terminated	Yes
GHLD	Ganoderma Luci.	Hempflax	27°C	5-20mm	82,24 kg/m ³	Terminated	Yes
GHHD	Ganoderma Luci.	Hempflax	27°C	5-20mm	131,58 kg/m ³	Terminated	Yes
GH2127	Ganoderma Luci.	Hempflax	21 + 27°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH2721	Ganoderma Luci.	Hempflax	27 + 21°C*	5-20mm	82,24 kg/m ³	Terminated	Yes
GH21	Ganoderma Luci.	Hempflax	21°C	5-20mm	65,79 kg/m ³	Terminated	Yes
GHNM	Ganoderma Luci.	Hempflax	21°C	5-20mm	57,57 kg/m ³	Terminated	No

*Halfway the growth cycle, the temperature is adjusted up or down

**50% of regular particles mixed with 50% of small particles

Figure 21: Mycelium-based composites placed in the Ashby Chart.