

Mycelium Acoustic Panel

Growing, testing and designing with a novel bio-composite material

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Track of Building Technology

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PREFACE

Before starting this endeavour, mycelium was only briefly mentioned, which was in a presentation on possible graduation topics, hidden away between the numerous slides. The unknown material sparked my curiosity. At first, I was sceptical, mainly after finding designs and installations online with extreme claims. But after finding out more about the novel material, I slowly became more convinced of its qualities and the possibilities. It was very interesting to find out everything about this strange bio-composite, to grow my own panels and to learn a lot more about building acoustics than what I have learned in my Bachelor.

I would like to acknowledge everyone who has helped with this project. First of all, my first mentor, Regina Bokel — my second mentor, Marcel Bilow, also for helping out moving and building the panel mounting — Martin Tenpierik for providing feedback regarding the acoustics and for helping out with the different measurements — Marc Postel and Joost Vette from Fungalogic for helping me grow all the different samples and panels — all the companies that were so kind to send me product samples — Henry den Bok at TNW for letting me use the reverberation chamber — all the different biologists, mycologists and fungi-enthusiasts for providing me with literature and inspiration —and last but not least, my family and friends for their support.



ABSTRACT

Mycelium composites are a novel material type. Mycelium is the 'root'-network of a fungus and can be used to grow shapes on substrates of agricultural waste fibres. A few designs exist that use the material and information on material properties is limited. The goal of this thesis is to find out how mycelium composites can be produced, designed with and perform in an acoustic building product. A literature study on material properties shows acoustic absorption and thermal insulation are suitable functions for this material. The thesis describes impedance tube tests done on samples of mycelium and existing acoustic building products, reverberation room tests done on larger panels and shows microscopic images of the surface and sections. By growing the panels myself, a lot of hands on experience is gained, which was used to gather input for designing acoustic building products. Balancing acoustic absorption with mechanical properties and connecting the panels to the wall are important issues that have to be addressed, while there are opportunities in creating shapes and in sustainability. The designed panel was compared with existing mycelium, other bio-based and more conventional products in terms of acoustics, safety, health, durability, sustainability and price.

Keywords: Mycelium, Building acoustics, Impedance tube, Reverberation chamber, Product development, Biodegradable, Biocomposites.



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1. INTRODUCTION

1.1. PROBLEM STATEMENT

Mycelium is a novel building material with unknown performance and application. Some research has been done on the material properties, but more tests are needed. Furthermore, it is not clear what is the most suitable function for this material to fulfil. Aside from how the different materials perform, it is unknown why they behave this way and how future mycelium materials can be predicted. Different from conventional materials is the production, or the growth process. This probably also needs a new approach for the design process. And when it finally is marketed, the mycelium products will have to compete with existing products. This is not a simple comparison, since an underperformance in one criterium does not mean it is not a feasible alternative if it has other upsides that are large enough.

1.2. RESEARCH QUESTIONS

Main research question:

“How can the new material, mycelium grown on biological (waste) substrates, be produced, designed with and perform in an acoustic building product?”

Sub-questions:

Material performance:

- On a qualitative level, what is a suitable function or what are the specific qualities of mycelium?
- On a quantitative level, how well does mycelium perform?
- How to predict this performance?

Design and production:

- How are mycelium composites produced?
- How is mycelium applied in the design phase?
- What are the issues and potentials when designing a mycelium acoustic panel?
- How does a mycelium acoustic panel perform compared to existing products?

1.3. METHODOLOGY

Literature study:

- On the existing research done on material properties of mycelium to see what suitable functions are. (Mechanical, acoustic insulation, thermal insulation, fire proofing, etc.)
- On the availability of waste biological fibres for the selection of the substrate.
- On acoustical theory to be able to predict material performance.
- On how acoustical theory applied in the building environment.
- Or an interview with a biologist to gain insight in relevant biological aspects.

Research by design:

- Designing and making building products to find possible issues.
- Compare theoretical or measured values to demands from use.
- Compare the performance of the final design with specifications of other building products.
- List and weigh these pros and cons.

Tests:

- Impedance tube tests to see how the mycelium material performs.
- Impedance tube tests of conventional and other innovative building products for comparison.
- Reverberation chamber tests for realistic measurements and compared to impedance tube
- Look at the surface of the mycelium material with a microscope to be able to explain acoustic behaviour.

1.4. STRUCTURE

The chapters follow the research structure as shown in Figure 11 and are broadly in chronological order. Before starting with the literature research on material properties in chapter 3, some background is given on this novel material in the next chapter. Chapter 4 provides the relevant information on acoustics for the acoustic tests and the design chapters. Chapter 5 then goes into the impedance tube tests, with the addition of microscopic imaging of some samples in chapter 6. Chapter 7 describes the relevant topics for designing with mycelium. A mycelium acoustic panel is then described in chapter 8, which is tested in the reverberation chamber in chapter 9 and compared with existing products in chapter 10.

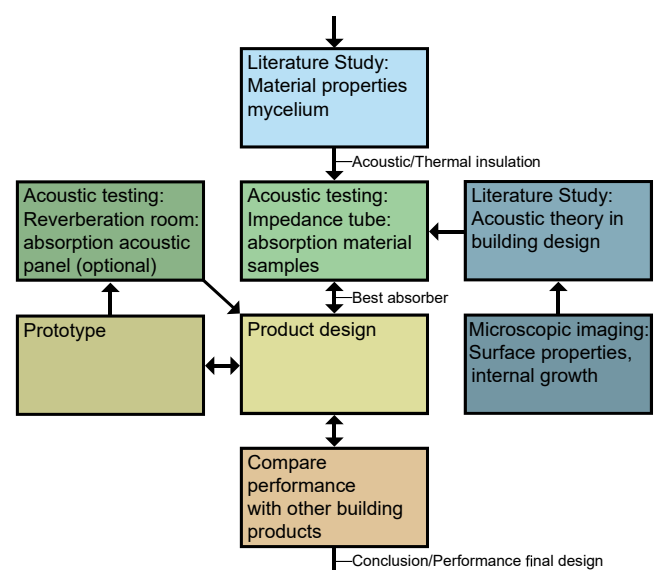


FIGURE 11 RESEARCH STRUCTURE

2. MYCELIUM AS A NOVEL MATERIAL IN DESIGN

Mycelium is the part of a fungus that is usually described as the “root”-network. First, this chapter will give some biological background information where relevant for the use as a building material. Second, the practice of making a mycelium composite is described. And third, the existing developments in research and design are described.

2.1. USING A LIVING MATERIAL: BIOLOGICAL BACKGROUND

All living organisms can be divided into groups to form a taxonomic hierarchy. On top of this are the domains Archaea, Eucarya and Bacteria. Fungi are part of the Eucarya, which also include animals and plants and share having a nucleus in their cells. (Petersen, 2013) The main difference from plants is that fungi use chitin in their cell walls. Fungi are more similar to animals, although animals ingest their food, where fungi absorb nutrients externally. Mycelium is the often-underground network of a fungus. The full organism also contains the fruiting body, often in the form of a mushroom. The fungi relevant for the use in mycelium composites are the white rot fungi, or more specifically, the fungi that are best equipped to decompose the lignin in wood. (Moore, Robson, & Trinci, 2011) These are mainly from the class Agaricomycetes and are part of the larger division Basidiomycota, see Figure 22. The Basidiomycota all have a weak spore release. These spores usually fall down, instead of being shot in the air in a cloud as with most Ascomycota, the other division of fungi with compact tissues and fruiting bodies. Therefore, elevated locations, such as on the trunk of a tree, help with the release of spores. As spores can cause allergic reactions and respiratory problems, for the use in mycelium composites, his slow release is preferred over the release in spore clouds. Although, stopping growth before the formation of fruiting bodies is best for both types.

Typical for fungi is the way the cells grow, aside from the aforementioned external absorption of nutrients and the chitin in their cell walls. Fungi have long cells called hyphae. By rapid growth of these cells a fungus is able to explore its surroundings and search for nutrient-rich resources. (Moore et al., 2011) The hyphae consist of long interlinked cells with a shared outer cell wall. The internal cell walls are called septa, through which some parts of the cell can pass. The tip of the hypha is called the Spitzenkörper. Here the hyphae can extend itself or branch out. To understand how the mycelium creates a specific



FIGURE 21 MUSHROOMS OF THE *GANODERMA LUCIDUM*, *PLEUROTUS OSTREATUS* AND *TRAMETES VERSICOLOR*

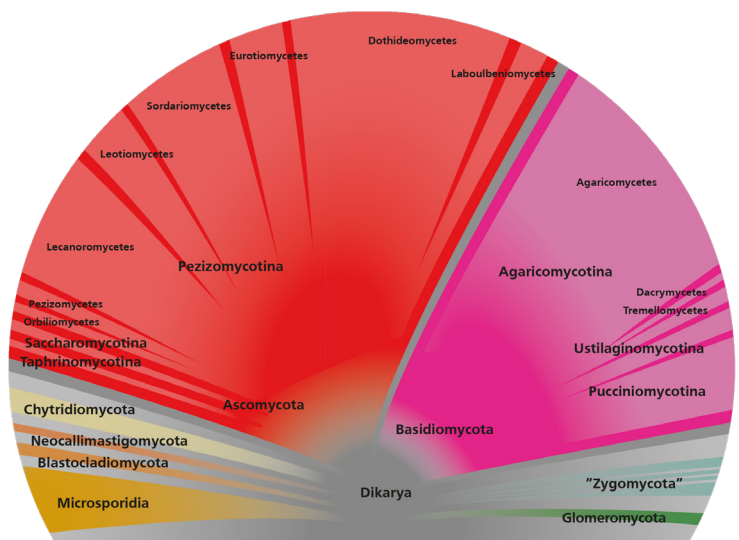


FIGURE 22 DIAGRAM OF THE MAJOR GROUPS IN THE FUNGI KINGDOM FROM PETERSEN (2013)

structure, three different growth processes can be defined: hyphal growth in the same single direction, branching frequency and autotropism. (Moore et al., 2011) Where autotropism is the self-avoidance reaction of hyphae, which is clearly visible in the outer edges of the mycelium, see Figure 23. The reverse reaction is also possible, which causes the tips to be directed toward the mycelium and may result in fusion of hyphae. This type of growth takes place at the oldest part of the mycelium and in the formation of fruiting bodies.

The tip of the hypha also produces hydrophobins, which is used for multiple functions of the mycelium, but can also self-assemble into hydrophobic layers. This is visible in mycelium composites, where water droplets form on top of the surface. Hydrophobins play an important role in the growth process, which can be seen when deleting the gene for hydrophobins. As a result, the density of mycelium greatly increases, which improves the mechanical properties. However, the material is no longer hydrophobic and directly absorbs the water. (Appels et al., 2018)

Aside from the mycelium part of the mycelium composites, the substrate also plays an important role in the material properties. In vascular plants, lignin is present in the cell walls. It improves the structural properties and is hydrophobic. Because it is difficult to decompose compared to the other parts of the cell wall it also protects the plant. Lignin is in general difficult to degrade but can be decomposed by white-rot fungi. In a composite these substrate particles can play an important role in the mechanical properties of the material. These particles can contain different amounts of lignin, depending on from which plant and which plant-part they are from. Wood has a high amount of lignin, but smaller branches from the same plant or grass leaves contain less.

2.2. DESCRIPTION FABRICATION PROCESS

Probably the most used method for making shapes with mycelium is the one described by Ecovative for their Grow-It-Yourself kit (Ecovative, 2018). They provide a bag containing a patented mixture with pre-treated hemp fibres and mycelium. This method was used for growing the first samples, see Figure 26. The rest was grown at Fungalogue and its growth method is described below in more detail.



FIGURE 25: SCHEMATIC OVERVIEW OF THE GROWTH PROCESS BY ECOVATIVE

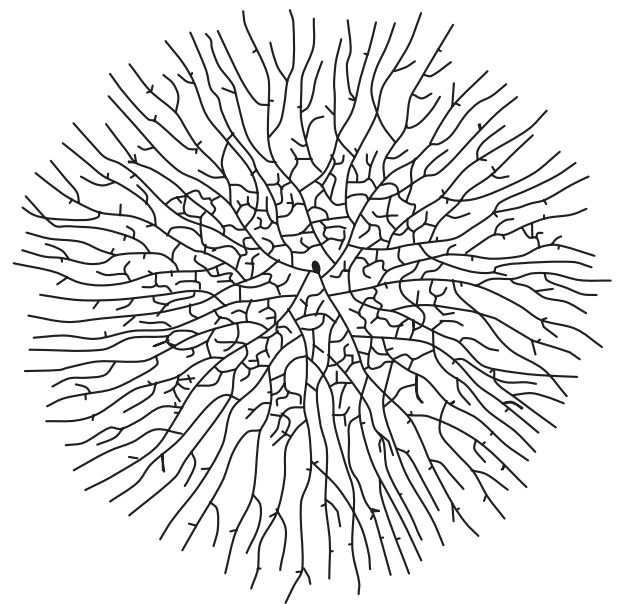


FIGURE 23 SKETCH OF A FUNGAL COLONY (MOORE ET AL., 2011)

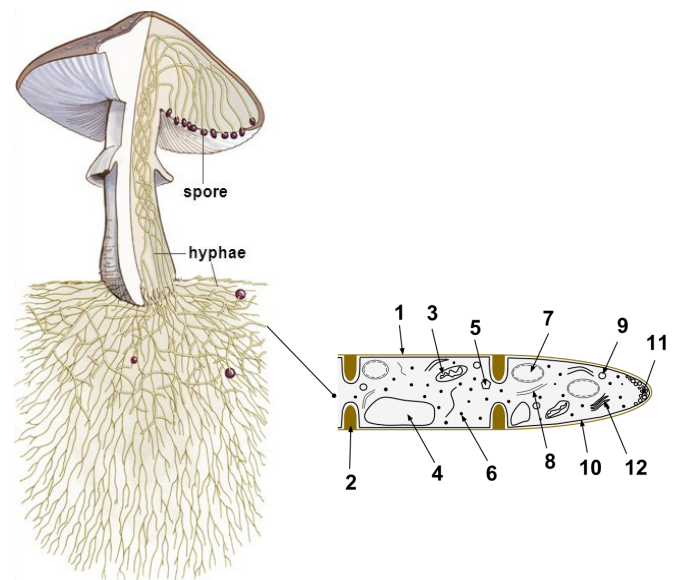


FIGURE 24 FUNGUS WITH MYCELIUM AND HYPHA CELLS (1: HYPHAL WALL; 2: SEPTA; 11: SPITZENKÖRPER)



FIGURE 26 USE OF THE GROW-IT-YOURSELF KIT: SET-UP; BAG; GROWTH IN BAG; GROWTH IN SHAPE; DRYING; FINAL PRODUCT

2.2.1. SUBSTRATE TREATMENT

With the Grow-It-Yourself kit, the substrate is already pre-treated and inoculated. When starting with untreated natural particles, they contain bacteria, fungi and enzymes. To make sure only your own fungus will grow, the substrate is pasteurised. This deactivates or kills the existing pathogens. Not boiling the material also keeps the substrate particles rigid. The particles are mixed, if necessary, and put into bags. The standard mix consists of straw and hemp in a 2:1 volume ratio. Before pasteurisation water is added in a 3:2 weight ratio of water to substrate. Air is pressed out of the bags to prevent insulation. The sealed bags are then put into a container and steamed for 2 hours between 72°C and 89°C.



FIGURE 27 MIXING THE SUBSTRATE; DIFFERENT SUBSTRATES IN BAGS; CONTAINER FOR STEAMING; AFTER PASTEURISATION

2.2.2. INITIAL GROWTH

When the bags have cooled down, 10 wt% of spawn is mixed through the substrate. The mix is then left to grow for 1 week in a dark environment with a temperature of 25°C.

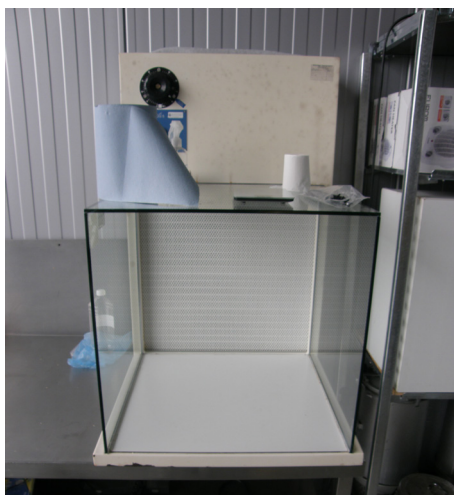


FIGURE 28 CABINET WITH HEPA FILTER

The workplace and tools are sterilised with 70% alcohol. The mixing with the spawn is done in a cabinet with a HEPA filter, see Figure 28. This is extra important because the risk of contamination is the highest in this part of the growth process. The spawn used here are grains inoculated with a fungus. This method is used for practical reasons. It is also possible to directly inoculate the substrate, which could improve the growth.



FIGURE 29 SUBSTRATES AFTER 1 WEEK OF GROWTH

2.2.3. GROWTH IN SHAPE

The mycelium has spread through the substrate but has not completely grown together as a solid block. First the growth shapes, workplace and tools are sterilised. Then, in the cabinet with the HEPA filter, the substrate is taken out of the bag, broken up and put into the growth shapes. In slightly less than 2 weeks in a dark environment, most of the mycelium growth has taken place and the shapes are fully grown.



FIGURE 210 BEFORE AND AFTER THE SECOND GROWTH PHASE

2.2.4. DRYING

The fully-grown shapes of mycelium composite still contain a lot of moisture. The shapes are released from the growth shapes and left to dry. These can be air dried or dried in a ventilated and heated environment, see Figure 211. The main difference is the duration. With high drying speeds the shapes may deform more. Drying at high temperatures also kills the fungus, which prevents the formation of spore bearing fruiting bodies but stops the self-healing ability of the material. It is also possible to keep the mycelium growing when the shape is taken out of the growth shape. This was done with some samples by keeping them in a room with a relative humidity of 95%.



2.3. USE OF MYCELIUM IN PRACTICE

2.3.1. DEVELOPMENTS IN RESEARCH AND DESIGN

Mycelium as a building material is new, but fungi have been used in a lot of different ways throughout history. As this was mainly as food and for medical purposes, particular attention will be paid to the current research and new applications in design and technology. Although, at the moment most design with mycelium is either temporary or conceptual. Only a few applications of mycelium in commercially available products exist.

The first mycelium materials were developed by Eben Bayer and Gavin McIntyre in 2007. With the company Ecovative they patented the method of making mycelium grown on biological waste-fibres. Ecovative started with making insulation, followed by packaging and do-it-yourself kits. Since then different projects in art and design were made, mainly in architecture, furniture and fashion. Research on mycelium materials then mostly consisted of finding out

its material properties. These experiments were mainly on mechanical, but also on acoustic, thermally insulative and fire proofing properties. The next chapter will go into this further.

What direction future research and development on mycelium materials will take is not completely clear. At the moment there are 47 granted or pending patents, most of them from Ecovative, Mycoworks and Ford. (Cerimi, Akkaya, Pohl, Schmidt, & Neubauer, 2019). However, only a few mycelium products exist. Still, more and more research is being done, with the amount of papers increasing every year. These contain improved results on material properties, but also new approaches to altering the material, such as hydrophobin gene deletion (Appels et al., 2018) and fruiting body inhibition (Chang et al., 2019).

2.3.2. NOTABLE EXAMPLES OF MYCELIUM DESIGN

The examples can be divided into four categories. The first category is that of pure mycelium, without using substrate materials. The other categories are about mycelium in a bio-composite, where the second category is grown in a mould and the third uses it as a feed for a 3D-printer. The fourth category consists of examples of acoustic panels.

Pure mycelium is grown by supplying it with sugar. Fashion designer Aniel Hoitink used patches of mycelium grown together to make a dress, a bag and a shirt, see Figure 212. By using mycelium, designs could be made into a seamless and custom sized fabric. Although mycelium is usually brittle when dried, Hoitink succeeded in making it flexible. MycoLeather is developed by Philip Ross of Mycoworks. Mycoworks initially focussed on making building blocks, but switched to growing mycelium leather. The leather is made with pure mycelium and afterwards treated with a biodegradable plasticiser agent and/or worked mechanically to make it flexible. (Ross, Wenner, & Moorleghe, 2017) In addition to the fabric by Hoitink it is also compressed and heat treated to give it a certain thickness and surface qualities.



FIGURE 212 SHIRT MADE OF MYCELIUM TEXTILE BY ANIELA HOITINK AND KARIN VLUG 2016



FIGURE 213 MYCOLEATHER BY MYCOWORKS

Composite blocks are made of mycelium grown on biological waste fibres. Most of them are used in architectural applications. The MycoTree is a project designed by the Karlsruhe Institute of Technology and ETH Zürich for the Seoul Biennale for Architecture and Urbanism in 2017. It uses mycelium composite blocks in a structure with only compression loads. This way the relatively weak material can be used optimally.



FIGURE 214 MycoTree BY KARLSRUHE INSTITUTE OF TECHNOLOGY AND ETH ZÜRICH, 2017

A similar project is the Hy-Fi tower, designed by The Living. As a showcase for what can be done with mycelium a 13m high temporary tower was built at the courtyard of MoMA PS1. Similar to the MycoTree, the shape of the tower was optimised to withstand wind loads. It was made almost entirely from mycelium bricks stacked on each other, except for some wooden support structures.



FIGURE 215 Hy-Fi tower BY THE LIVING, 2014



FIGURE 216 Grow-It-Yourself KIT OF ECOVATIVE

FIGURE 217 PACKAGING MATERIAL BY ECOVATIVE

So far most realised projects with mycelium are conceptual designs. More commercial applications are less common and usually these are products and designs on a smaller scale. Good examples of are the Grow-It-Yourself kit and the mycelium packaging, both by EcoVative. The kits are used by hobbyists, researchers and designers all around the world. The material is sometimes also supplied in larger quantities, as for example for the Hy-Fi tower and for their own tiny house, see Figure 218.



FIGURE 218 FILLING THE WALL CAVITY OF THE TINY HOUSE WITH MYCELIUM COMPOSITE, 2013 (WWW.MUSHROOMTINYHOUSE.COM)



FIGURE 219 PRINTED STOOL AND CHAIR BY ERIC KLARENBECK, 2014

Mycelium composites can also be used as a feed material for 3D-printers. This was done by Eric Klarenbeek in his design for a chair and a stool. Most mycelium designs use a reusable growth-shape, which makes them suitable for mass production. With 3D-printing the product can be customised and more intricate structures can be made to make it lighter and stronger.

For acoustic applications specifically, there are some examples of products which already use mycelium composites. The first is Sinewave by Ken Lush of Ecovative. Using their mycelium composite material, they created a panel that diffuses sound. It was part of a series in 2016 for which they invited 5 different designers to design an acoustic panel. More recently, in 2019, Mogu launched a product line with soundabsorbing panels that use textile residues as a substrate. The panels are made in different shapes and sizes and have a top layer of pure mycelium that gives it a velvety touch. Fungalogic, a start-up company in the Hague, developed a phone booth together with Stichting Glastuinbouw Innovation. The panels are grown on tomato stalks that are leftovers from horticulture. Fungalogic also helped growing the products for this thesis.



FIGURE 220 SINEWAVE PANELS BY KEN LUSH, 2016

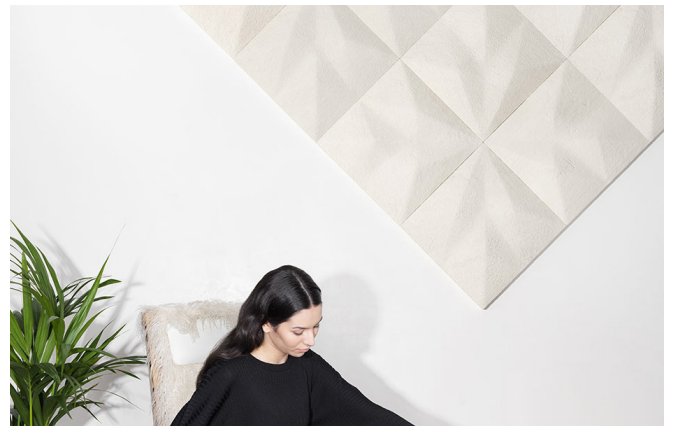


FIGURE 221 KITE PANELS BY MOGU, 2019



FIGURE 222 PHONE BOOTH BY FUNGALOGIC, 2019

3. LITERATURE RESEARCH ON MATERIAL PROPERTIES

This chapter will describe the relevant research for building products already done on mycelium. The sections are divided into acoustic, thermal insulation, fire proofing and mechanical properties. For most of these topics the material research done only consists of a few papers, but for all of the papers found, more than half of them were about the mechanical properties. Of the other properties, water resistance and surface finish were the ones still generally relevant, where most of them were about the handling or post treatment of the specific product used in that paper.

When comparing the research results, material differences have to be considered. Most of the time a composite of mycelium and bio-based fibres is used. Sometimes the material is made of pure mycelium. With these composites, the substrate and fungal strain used are often the biggest difference. Combinations with other materials in a layered composite were also found, as for example a sandwich panel.

3.1. ACOUSTIC

For the acoustic properties of mycelium two papers were found, both from the same main author, and one product test by Mogu. The first paper is about mycelium composites on different substrates and mixes, which were tested with a road-noise spectrum (Pelletier, Holt, Wanjura, Bayer, & McIntyre, 2013). The second paper focusses on the influence of density on the acoustic performance, looking at both absorption and through-transmission. (Pelletier et al., 2017) The tests by Mogu were done in a reverberation chamber on different designs with mycelium grown on textile waste. (Mogu, 2019) Since these were the only sources of information available on the acoustic properties, this paragraph will go into more detail compared to the other paragraphs on material properties.

The study from 2013 is a more exploratory one. This makes it possible to oversee what mycelium composite will be the best for further research and, in the end, application in practice. The samples use the following biological substrates: cotton-bur, switch-grass, rice straw, sorghum stalks, flax shive, kenaf and hemp. In addition, combinations of these are used in a 50/50% ratio. Conventional ceiling tiles, foam board and plywood were also included in the tests. The sound of road noise, between 300 and 4000 Hz, was chosen mainly with the automotive industry in mind, but is also relevant for building construction.

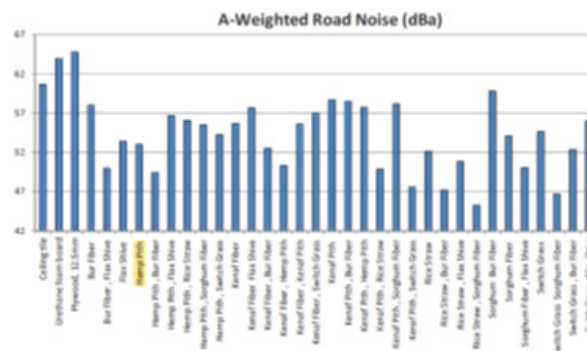


FIGURE 31: OVERVIEW OF TEST MATERIALS IN PELLETIER (2013): INTEGRATED A-WEIGHTED RESPONSE TO ROAD NOISE. HEMP IS HIGHLIGHTED BECAUSE OF ITS USE IN THIS GRADUATION PROJECT.

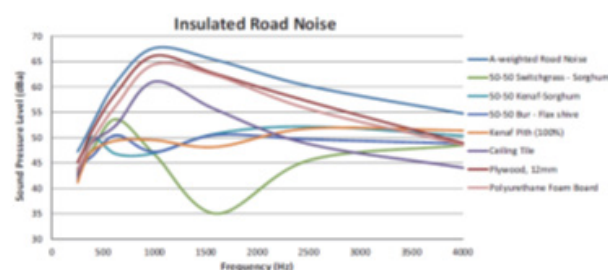


FIGURE 32: SELECTION OF “BEST PERFORMERS” IN PELLETIER (2013) TO COMPARE THE ACOUSTIC SPECTRUM PERFORMANCE

Looking at the results, all of the different mycelium composites perform well compared to the conventional products, both in general (see Figure 31) and when looking at the absorption spectrum curves (see Figure 32). When selecting a mycelium material for a building product, the non-acoustic properties will also have to be taken into account, since the difference in acoustic properties are not significant.

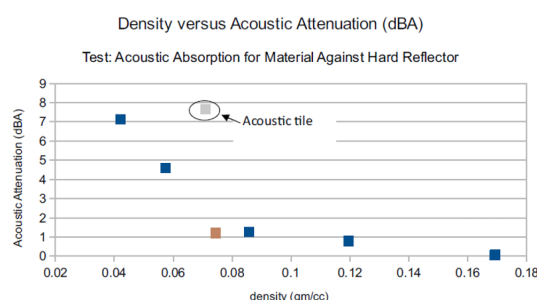


FIGURE 33: ACOUSTIC ABSORPTION DECREASES WITH INCREASING DENSITY (PELLETIER, 2017). ACOUSTIC TILE IN GREY, CORK UNDERLAYMENT IN BROWN, MYCELIUM SAMPLES IN DARK BLUE

The study from 2017 continues on this by using the same mycelium composite with different densities. The previous study looked at the absorption and mainly used low density samples. For this research the density is increased: 0.042 (uncompressed), 0.057, 0.086, 0.120 and 0.169 g/cc. The experiments also measure the through transmission.

3.2. THERMAL INSULATION

For the thermal insulation only a single paper was found, written by Holt et al. (2012). The authors did research on multiple material properties of mycelium composites grown on cotton agricultural waste. Twelve different composites were tested, with two different inoculation methods and six different particle size blends. The blends consisted of cotton carpel, cotton seed hull, starch and gypsum.

For the thermal conductivity, the best performer gave a value of 0.10 W/m*K and the worst performer a value of 0.18 W/m*K.

3.3. FIRE PROOFING

Material properties for fire safety are not directly used to determine if a new material is safe, because the product or construction in which the material is used, has to be subjected to a fire test. The properties do give a good indication and make it possible to compare different materials. Two papers were found that looked into the fire proofing abilities of mycelium. The first is a broad research on different characteristics (Haneef et al., 2017). The second is specifically about the fire proofing properties (M. P. Jones et al., 2018).

The research done by Haneef et al. (2017) looks at multiple properties, of which thermal decomposition is one of them. The mycelium material is different from the mycelium composites based on biological waste fibres in that it is grown on pure amorphous cellulose. Two different fungal strains are used, *G. lucidum* and *P. ostreatus*, and potato dextrose broth is added to half of the samples as a source of sugar. This makes that there are four different samples.

The method data for determining a thermal decomposition temperature is gotten from thermogravimetric analysis, where the loss of mass is measured while the temperature is increased. Here all mycelium materials started degrading around the same temperature, from 293 to 295 °C. In the paper the authors state that these are high degradation temperatures, which indicates they are thermally stable, and that for this material property it is similar to petrol-derived plastics.

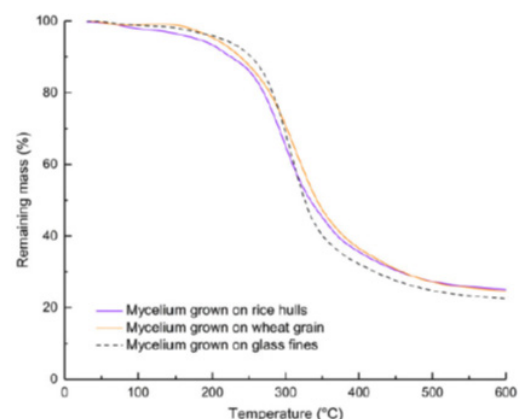


FIGURE 37 THERMOGRAVIMETRIC ANALYSIS RESULTS SHOWING A DROP FROM 250 °C (JONES ET AL., 2018)

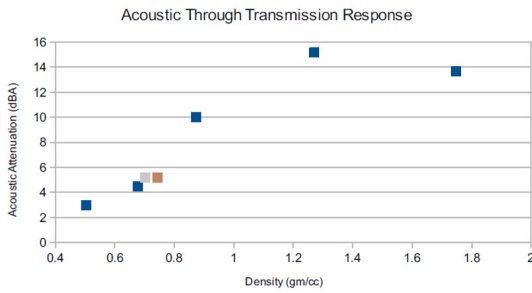


FIGURE 34: ACOUSTIC THROUGH TRANSMISSION SHIELDING IMPROVES WITH INCREASING DENSITY (PELLETIER, 2017). ACOUSTIC TILE IN GREY, CORK UNDERLAYMENT IN BROWN, MYCELIUM SAMPLES IN DARK BLUE.

The acoustic absorption tests show that a lower density gives a higher absorption (see Figure 33). But for the through transmission shielding this is the opposite (see Figure 34). The two samples with the highest density do not show any significant improvement from the rest. This is why they are left out in Figure 35, where the through transmission spectrum is shown for the first three mycelium samples, together with plywood, cotton insulation and cork underlayment. Here the mycelium composite with the highest density almost has a perfect shielding and the lighter two have a curve below it.

An optimal balance will be determined by the demands from application. Selecting a denser material will give better through transmission shielding, but lower absorption.

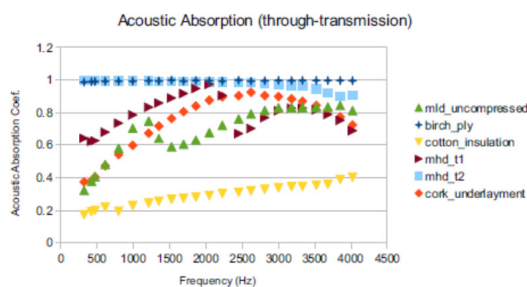


FIGURE 35: ACOUSTIC SPECTRUM FOR THROUGH TRANSMISSION SHIELDING (PELLETIER, 2017). COMPRESSING THE MYCELIUM COMPOSITES ANY FURTHER DOES NOT HAVE ANY SIGNIFICANT EFFECT. (MLD_UNC.: 0.5 GM/CC; MHD_T1: 0.68 GM/CC; MHD_T2 0.87 GM/CC)

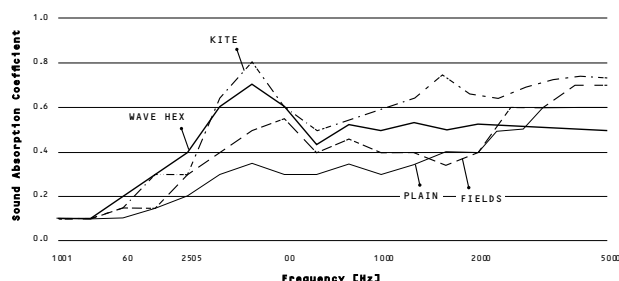


FIGURE 36 REVERBERATION CHAMBER TEST RESULTS OF FOUR ACOUSTIC PANELS DESIGNED BY MOGU, 2019

The results from the tests done by Mogu show a good absorption in the mid-frequencies, see Figure 36. Compared to the previously mentioned papers, the frequencies measured also extend to ones below 500 Hz, which is relevant for the absorption of speech.

The research by Jones et al. (2018) is focussed on the fire safety properties of three different mycelium composites. They used rice hulls, wheat grains and a mixture of glass fines and rice hulls/wheat grains as substrates for the mycelium to grow on.

Similar to the paper discussed in the previous paragraph, they did a thermogravimetric analysis, but here the results were displayed in a graph instead of just stating a temperature. The results show a similar behaviour, where the materials start degrading around 250 °C (See Figure 37).

The fire performance is tested with a 3-cell cone calorimeter. The different fire safety parameters are shown in Table 1. Comparing it with polystyrene foam, the mycelium materials generally perform better, where the composites with glass fines show great improvements, with even similar or better results compared to the structural grade wooden particle board.

TABLE 1 RESULTS FROM THE FIRE TEST INCLUDING RESULTS FOR COMPARABLE BUILDING PRODUCTS (JONES ET AL., 2018)

Type	Sample	ρ (kg/m ³)	t_{ig} (second)	RHR ₁₈₀ (kW/m ²)	PHRR (kW/m ²)	t_{60} (second)	TSR (m ² /m ²)	COP ₁₈₀ (g)	CO ₂ P ₁₈₀ (g)
Synthetic	ClimaFoam® extruded	33	9	114	503	61	1184	0.48	15.2
	polystyrene (XPS) foam								
	STRUC-TAUF® particleboard	689	26	134	200	173	64	0.47	30.0
Mycelium composite*	75 wt% wheat grains	359	12	107	185	94	70	0.33	23.8
	75 wt% rice hulls	193	7	85	133	75	40	0.02	14.6
	25 wt% wheat grains +50 wt% glass fines	589	12	42	79	370	5	0.39	10.2
	25 wt% rice hulls +50 wt% glass fines	450	7	33	85	311	0.9	0.91	6.3

ρ , density calculated from the volume and mass; t_{ig} , time to ignition; RHR₁₈₀, average heat release rate from ignition to 180 seconds after ignition; PHRR, peak heat release rate; t_{60} , estimated time to flashover in room fire test²¹; TSR, total smoke release; COP₁₈₀, carbon monoxide produced from ignition to 180 seconds after ignition; CO₂P₁₈₀, carbon dioxide produced from ignition to 180 seconds after ignition.

*Inoculated using 25 wt% wheat grain inoculum.

For the mechanical properties of mycelium materials, 7 papers were found. They include slightly different material tests, but most of them mention the density and have results for the elastic modulus and either tensile, compressive or flexural strength. Although, even with different properties, an indication can be given on how the material will perform compared to another. Aside from the different mechanical properties, the tests have been done on different material types: composites grown on a biological substrate, pure mycelium and sandwich composites. The discussion below is structured into three parts by these material types.

To be able to compare the different results, they have been put in an overview, shown in Table 2. Remarks about spread, significance, test conditions and how the samples are produced are left out to improve the readability. The source of the results is also put into the table and should be looked up before using this data for decisions in the product design. Although for the comparison, the following paragraphs, discussing the specific papers, will mention the most important remarks.

3.4.1. MYCELIUM COMPOSITES

Probably the most commonly used mycelium materials are the ones that grow mycelium on a biological waste material, such as hemp pith. Three papers were found that describe the mechanical behaviour of these composites.

The results from Appels et al. (2019) present a wide range of properties, but also show the effects of different types of compression. The samples are made from

three different substrates: rapeseed straw, beech sawdust and cotton. Combined with two different fungal strains and an optional cold or hot pressing, the results show a wide range of mechanical properties. The big outliers however are the ones that were heat pressed, where the use of a specific fungal strain or substrate did not have a big effect on the results. The tensile test for the non-pressed cotton was not possible because of problems with clamping the sample and therefore is missing in the table. Comparing this research with the other papers show that the found values are as good or even better when looking at the non-pressed variants. The heat-pressed materials outperform even the sandwich composites, although this is just for the mechanical properties.

The two test results from Felix Heisel (2018) show the elastic modulus from a compressive test for the MycoTree project, a design for the 2017 Seoul Biennale of Architecture and Urbanism. The project is designed for compression and only includes results for this type of loading. The substrates used are woodchip with sawdust and sugarcane with cassava roots. The results can be compared with those from other papers to see if they are in the same range. It is difficult to draw any conclusions because the material is quite dense, but the elastic modulus does not seem to deviate from the rest. Not mentioned in the table is the average compressive stress at 5 % deformation: 0.17 MPa for the one with woodchip and sawdust and 0.61 MPa for the one with sugarcane and cassava roots.

TABLE 2 OVERVIEW MECHANICAL PROPERTIES OF MYCELUM MATERIALS.
(PRESENTATION OF DATA IS SIMPLIFIED, FOR FURTHER REMARKS ABOUT
SPREAD, SIGNIFICANCE, TEST CONDITIONS AND THE PRODUCTION OF
SAMPLES, SEE THE CORRESPONDING PAPER.)

Data from:	Material type	Components/treatment	Substrate	Fungal strain	Density (kg/m ³)	Elastic modulus (Yield strength (M UTS (Mpa)	Tensile modulus	Elongation at bre	Compressive stre	Flexural strength	Flexural modulus
Appels et al., 2019	Composite	Non-pressed	Rapeseed straw	T. multicolor	100	4	0.04	4.7	0.0054	0.22	3
Appels et al., 2019	Composite	Non-pressed	Beech sawdust	T. multicolor	170	13	0.05	1.5	0.009	0.29	9
Appels et al., 2019	Composite	Non-pressed	Cotton	P. ostreatus	130	-	-	-	0.0023	0.05	1
Appels et al., 2019	Composite	Non-pressed	Rapeseed straw	P. ostreatus	130	2	0.01	2.8	0.0062	0.06	1
Appels et al., 2019	Composite	Cold-pressed	Rapeseed straw	P. ostreatus	240	6	0.03	1.4	0.0033	0.24	12
Appels et al., 2019	Composite	Cold-pressed	Cotton	P. ostreatus	240	9	0.03	0.8	0.0033	0.21	15
Appels et al., 2019	Composite	Heat-pressed	Rapeseed straw	T. multicolor	350	59	0.15	0.9	0.0085	0.86	80
Appels et al., 2019	Composite	Heat-pressed	Cotton	P. ostreatus	350	35	0.13	1.6	0.011	0.62	34
Appels et al., 2019	Composite	Heat-pressed	Rapeseed straw	P. ostreatus	390	97	0.24	0.7	0.0014	0.87	72
Heisel et al., 2018	Composite		Woodchip + sawdust		420	3.97					
Heisel et al., 2018	Composite		Sugarcane + cassava roots		440	22.7					
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 1	Ganoderma	32.04	0.3681			0.0054	0.0261	
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 2	Ganoderma	32.04	0.3956			0.009	0.0235	
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 3	Ganoderma	32.04	0.3174			0.0023	0.0123	
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 4	Ganoderma	32.04	0.1991			0.0062	0.0104	
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 5	Ganoderma	32.04	0.2834			0.0085	0.0219	
Holt et al., 2012	Composite	Grain inoculum	Cotton blend 6	Ganoderma	32.04	0.2884			0.011	0.0259	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 1	Ganoderma	32.04	0.2538			0.0335	0.0208	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 2	Ganoderma	32.04	0.1228			0.0033	0.007	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 3	Ganoderma	32.04	0.3442			0.0722	0.0164	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 4	Ganoderma	32.04	0.3318			0.0011	0.0097	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 5	Ganoderma	32.04	0.6745			0.0014	0.0196	
Holt et al., 2012	Composite	Liquid inoculum	Cotton blend 6	Ganoderma	32.04	0.3088			0.003	0.0101	
Haneef et al., 2017	Pure mycelium	With cellulose	-	G. lucidum		12	1.1	14			
Haneef et al., 2017	Pure mycelium	With cellulose + PDB	-	G. lucidum		4	0.8	33			
Haneef et al., 2017	Pure mycelium	With cellulose	-	P. ostreatus		28	0.7	4			
Haneef et al., 2017	Pure mycelium	With cellulose + PDB	-	P. ostreatus		17	1.1	9			
Islam et al., 2017	Pure mycelium		-		30	0.6	0.04				
Islam et al., 2017	Pure mycelium		-		50	2	0.08				
Jiang et al., 2019	Sandwich textile reinforced	Jute									4.654
Jiang et al., 2019	Sandwich textile reinforced	Jute + bioresin									22.24
Jiang et al., 2019	Sandwich textile reinforced	Flax									4.650
Jiang et al., 2019	Sandwich textile reinforced	Flax + bioresin									30.440
Jiang et al., 2019	Sandwich textile reinforced	BioMid									6.567
Jiang et al., 2019	Sandwich textile reinforced	BioMid + bioresin									25.68
Ziegler et al., 2016	Sandwich textile reinforced	Down woven mat	Fiber cotton			70.57	0.2		1.18		
Ziegler et al., 2016	Sandwich textile reinforced	Woven mat	Hemp pith			66.14	0.1		1.06		
Ziegler et al., 2016	Sandwich textile reinforced	Non-woven mat	Hemp pith			71.77	0.13		0.67		

The research from Holt et al. (2012) was conducted with the aim of replacing Styrofoam packaging material with a mycelium composite. Different material properties were researched to be able to compare the two and see if it is possible. The mechanical properties were only a part of this and the research is tailored to this specific question. The substrates contain a specific blend of processed cotton carpel, cotton seed hull, starch, and gypsum. Six different blends were provided by Ecovative using different cotton particle size fractions, unspecified, but with sizes ranging from 0.1 to 51 mm, resulting in composites with densities from 66.5 kg/m³ to 224 kg/m³. The substrates are inoculated with a fungus by either adding a grain or a liquid as the carrier. Before comparing the results, it is important to notice that the values are normalised to match the density of polystyrene packaging, which is 32,04 kg/m³. This means that the values given in the paper for the elastic modulus, the compressive strength and flexural strength are probably a lot lower than the actual test results, but it was not clear how this conversion was done. The results show that the values are in the same range, with a few outliers for every property. It is difficult to compare the mechanical properties with the other values in substrates: rapeseed straw, beech sawdust and cotton. Combined with two different fungal strains and an optional cold or hot pressing, the results show a wide range of mechanical properties. The big outliers however are the ones that were heat pressed, where the use of a specific fungal strain or substrate did not have a big effect on the results. The tensile test for the non-pressed cotton was not possible because of problems with clamping the sample and therefore is missing in the table. Comparing this research with the other papers show that the found values are as good or even better when looking at the non-pressed variants. The heat-pressed materials outperform even the sandwich composites, although this is just for the mechanical properties.

The two test results from Felix Heisel (2018) show the elastic modulus from a compressive test for the MycoTree project, a design for the 2017 Seoul Biennale of Architecture and Urbanism. The project is designed for compression and only includes results for this type of loading. The substrates used are woodchip with sawdust and sugarcane with cassava roots. The results can be compared with those from other papers to see if they are in the same range. It is difficult to draw any conclusions because the material is quite dense, but the elastic modulus does not seem to deviate from the rest. Not mentioned in the table is the average compressive stress at 5 % deformation: 0.17 MPa for the one with woodchip and sawdust and 0.61 MPa for the one with sugarcane and cassava roots.

Table 2, because of the relatively low density, but when selecting a lightweight building material this data could become relevant again.

3.4.2. PURE MYCELIUM

Growing mycelium on a substrate of biological waste material has a big impact on the material properties, showing great differences depending on what substrate is used. The pure mycelium is expected to be more consistent and is in general less brittle. With differences in the used fungal strain and additives, there is still some variance possible.

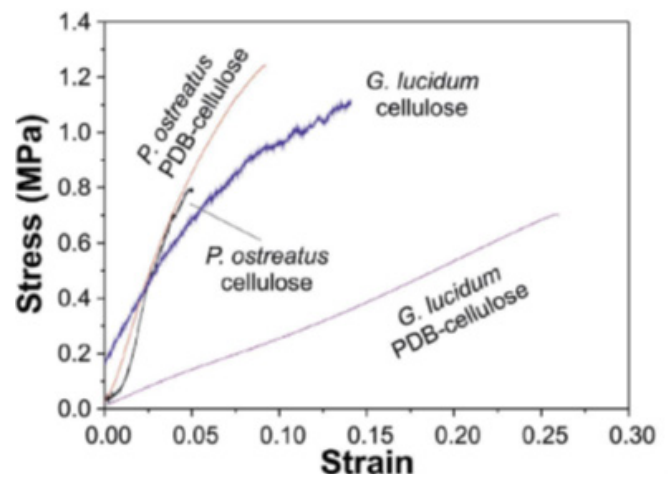


FIGURE 38 REPRESENTATIVE STRESS-STRAIN CURVES FOR THE 4 SAMPLE TYPES (HANEEF ET AL., 2017)

The first of the two papers on the non-composite mycelium materials is from Haneef et al. (2017). As mentioned before in the fire proofing properties, they use two fungal strains, *G. lucidum* and *P. ostreatus*, which are grown on cellulose with the possible addition of sugar, in the form of potato dextrose broth. The cellulose is consumed completely, unlike the substrates of the mycelium composites that only get consumed partially and then become part of the final material. The results from the tensile test indicate that the material is indeed more ductile compared to the composites, having very high elongation values. Comparing the four sample types among themselves show an even bigger increase in ductility when the potato dextrose broth is added. Lacking other types of mechanical testing makes it difficult to make an exact comparison with the other mycelium materials, but it will probably not resist much when subjected to a bending test.

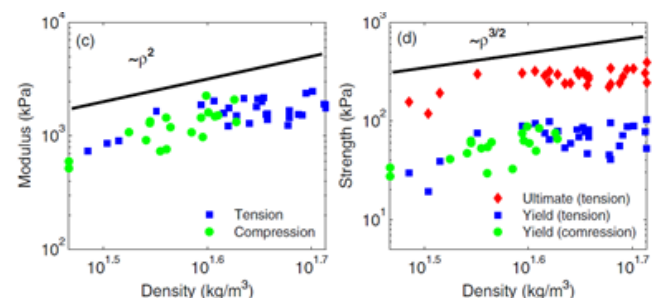


FIGURE 39 PLOT OF THE MODULI AND STRENGTHS FROM TENSION AND COMPRESSION TESTS ON DIFFERENT DENSITIES OF PURE MYCELIUM. (ISLAM ET AL., 2017)

The second paper on pure mycelium is from Islam et al. (2017). The material is not specified, but it is provided by Ecovative and has densities ranging from 30 to 50 kg/m³.

The exact values from the tension and compression tests are not provided, but are shown in a plot, see Figure 39. The authors state that for tension and compression the

moduli range from 0.6 to 2.0 MPa and the yield strengths from 0.04 to 0.08 MPa. In tension the ultimate tensile strength is stated to be in between 0.1 and 0.3 MPa. For the overview in substrates: rapeseed straw, beech sawdust and cotton. Combined with two different fungal strains and an optional cold or hot pressing, the results show a wide range of mechanical properties. The big outliers however are the ones that were heat pressed, where the use of a specific fungal strain or substrate did not have a big effect on the results. The tensile test for the non-pressed cotton was not possible because of problems with clamping the sample and therefore is missing in the table. Comparing this research with the other papers show that the found values are as good or even better when looking at the non-pressed variants. The heat-pressed materials outperform even the sandwich composites, although this is just for the mechanical properties.

The two test results from Felix Heisel (2018) show the elastic modulus from a compressive test for the MycoTree project, a design for the 2017 Seoul Biennale of Architecture and Urbanism. The project is designed for compression and only includes results for this type of loading. The substrates used are woodchip with sawdust and sugarcane with cassava roots. The results can be compared with those from other papers to see if they are in the same range. It is difficult to draw any conclusions because the material is quite dense, but the elastic modulus does not seem to deviate from the rest. Not mentioned in the table is the average compressive stress at 5 % deformation: 0.17 MPa for the one with woodchip and sawdust and 0.61 MPa for the one with sugarcane and cassava roots.

Table 2 the top and bottom values for this range are treated as if they are two materials. Comparing these results with the previously mentioned paper show that the tensile properties are much lower, although in the same order of magnitude. The material used here is not specified, but it shows that differences in pure mycelium can still exist. The exact cause for this might be found by looking at the used fungal strain, nutrients or growth conditions.

3.4.3. SANDWICH COMPOSITES

Adding a textile layer at two sides of a mycelium composite creates a sandwich structure that makes use of the mycelium to not only form the core material, but also connect the layers. Two papers were found describing the mechanical properties of these sandwich structures, both using a natural textile as a skin. Jiang, Walczyk, McIntyre, Bucinell, and Li (2019) use jute, flax and BioMid textile skins with an optional bio-resin treatment. All six sandwich samples are subjected to a flexural test, which results in a value for the flexural modulus. R. Ziegler, Bajwa, Holt, McIntyre, and Bajwa (2016) use fibre cotton with a down woven mat and hemp pith with both a woven and a non-woven mat. Here the samples are tested for tension and compression. The results for the sandwich materials compared to the regular mycelium composites and pure mycelium show

great improvements in all modes. The use of a resin greatly improves the results from the flexural test.

Looking at the data from all three material types shows a wide range of mechanical properties. Improving a property usually means the density will also increase. Additional steps in the manufacturing process can greatly improve the material, as shown in the sandwich materials and the pressed materials, but these benefits have to be weighed against the cost of extra labour costs.

3.5. CONCLUSION

The mycelium materials show promise for numerous building construction applications, although a trade-off has to be made when selecting or growing the mycelium material. When only looking at the results for acoustic transmission and absorption, mycelium seems suitable for an acoustic product. As thermal insulation, the material will function, but this is usually applied in areas with a lot of moisture. Fire proofing is also possible with mycelium, but it is not clear if this is mainly because of the addition of glass particles. It also requires the material to have a consistent application and function in a fire test. And finally, the mechanical properties should be considered in general, although not as the main function in a structural application.

Over the course of 2019 and 2020, after the literature research was done, multiple additional research papers have been written on the material properties of mycelium. It is very likely that a lot of the properties have been improved.

4. ACOUSTICS IN THEORY AND IN PRACTICE

4.1. ACOUSTICS PRINCIPLES

Sound is the vibration of, for instance, air and can be captured by the human ear. It can be described as a continuous wave with peaks and valleys of different particle densities, as shown in Figure 41. When a single soundwave passes from one transmission medium to another, its trajectory changes depending on the two material or fluid types and on the angle of incidence. In building acoustics, sound usually travels from the air in one room, through the material of a building element and into the air of the same or a different room. In Figure 42, a soundwave enters an acoustic panel: a part of the wave is reflected at the boundary, inside the panel a part is absorbed and converted into thermal energy and the rest is transmitted. Depending on the shape of the panel, the reflections can either be converging, diverging, specular or diffuse. Acoustic absorbers can have different mechanisms. The main product types are: porous absorbers, Helmholtz absorbers, membrane absorbers, micro-perforated panels and Schroeder diffusers.

The terms to describe sound are the relative sound pressure level (dB) and frequency (Hz). Humans perceive frequencies that are doubled as similar or as an 'octave' higher. Therefore, frequencies are conventionally plotted in a logarithmic scale. Measurements are often simplified by measuring once every 1/3 octave and then averaged for every octave, see Figure 44, or converted into a single absorption number, α_m . (Adams, 2016) Common centre frequencies in Hertz for octave bands are: 31, 63, 125, 500, 1000, 2000, 4000 and so forth.

The relevant frequencies for acoustic building products are mostly related to the human voice. In Figure 45, the common frequencies and sound levels for human speech are plotted. Vowels are essential for intelligibility. They have the highest sound levels and are in between 250 to 4000 Hz. Hopkins (2007) also states: "In building acoustics, the main frequency range used to assess sound insulation lays between the 100 and 3150 Hz one-third-octave-bands; an optimal extended frequency range is defined between the 50 and 5000 Hz one-third-octave-bands."

4.2. ACOUSTIC THEORY AND THE BUILT ENVIRONMENT

4.2.1. SPATIAL EFFECTS AND DEMANDS FROM USE

Sound in an open space travels directly to the receiver and does not produce any indirect sounds. In a confined space, sound also produces reflections that arrive shortly

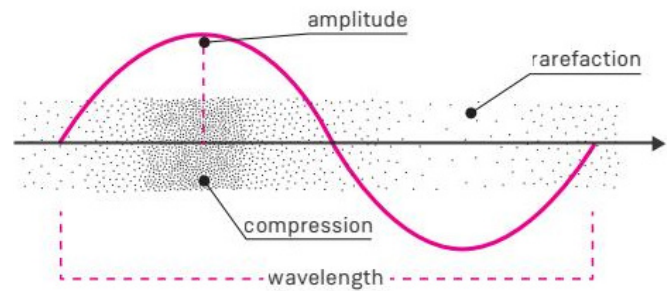


FIGURE 41 SOUND AS A WAVE: SOUND LEVEL RELATES TO AMPLITUDE, WAVELENGTH TO FREQUENCY (ADAMS, 2016)

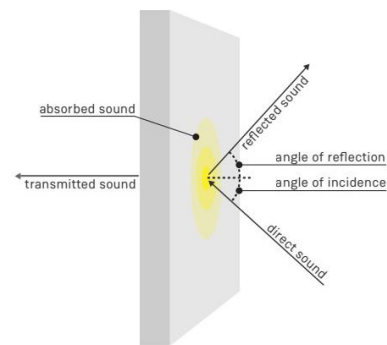


FIGURE 42 REFLECTION, ABSORPTION AND TRANSMISSION IN AN ACOUSTIC PANEL (ADAMS, 2016)

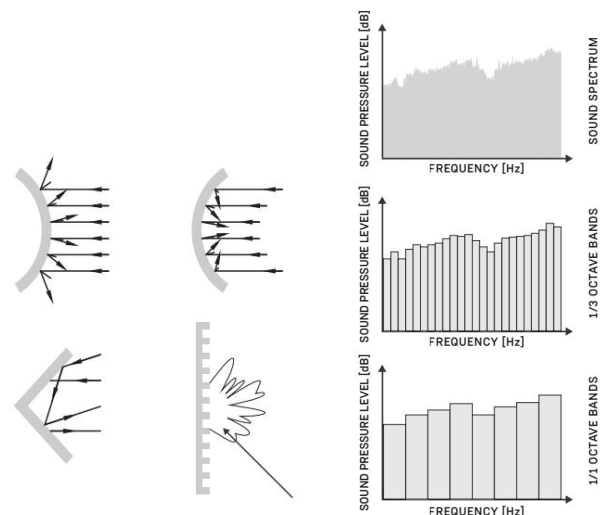


FIGURE 43 CONCAVE, CONVEX, FLAT AND DIFFUSING SURFACES (ADAMS, 2016)

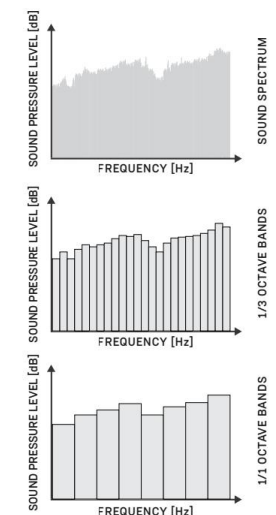


FIGURE 44 FREQUENCY SPECTRUM DISPLAYED AS ONE-THIRD AND SINGLE OCTAVE BANDS (ADAMS, 2016)

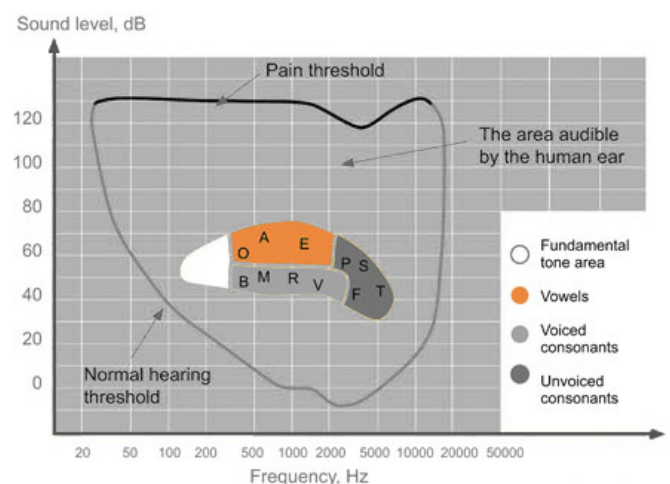


FIGURE 45 HUMAN HEARING AND SPEECH RANGE, MOST IMPORTANT ARE THE VOWELS (ADAPTED FROM WWW.ECOPHON.COM)

after the direct sound. When these reflections arrive too soon or are too loud, speech becomes unintelligible.

Intelligibility is affected in different ways. The main effect is of space and materialisation on the reflections. Reflections can for example arrive too early when there is a hard surface nearby and when the whole room keeps reflecting sound, the receiver might hear multiple echoes. The shape of a room can also cause interference between soundwaves. Direct sound can be distorted by the early reflections when their peaks and valleys partially cancel each other. At low frequencies standing waves can form. These are waves that match the distance between two walls in a multiple of half or full wavelengths. At frequencies where this is the case, the sound level has a fixed distribution of peaks and valleys. Depending on where the sound is received, this can give unwanted distortions. However, these effects are mainly relevant in extreme cases and in recording studios, where there are high demands on sound quality. Finally, there is also a subjective factor in intelligibility. Expectations are related to the type of use. The required concentration and noise sources are different in for example an open-plan office and a factory hall.

To improve the intelligibility absorption and diffuse reflection can be improved. Here a balance has to be found between too much absorption, sounding muffled, or too much reverberation, sounding too noisy. Intelligibility also needs to be good through the whole room, for every user, so the spread and direction of sound are also important. Next to improving intelligibility by absorption, sometimes sound is completely unwanted and transmission shielding between parts of a room might be necessary.

4.2.2. DESIGN STRATEGIES AND ACOUSTIC PRODUCTS

One can prevent acoustic problems by paying attention during the design phase to the shape, size and materialisation of a room in relation to its use and related sound sources and receivers. It is also possible to apply products afterwards when problems arise. The goal can be to reduce the sound level, reduce echo, improve intelligibility, isolate sound or spread sound. The location and amount of acoustic materials matter when finding a balance in the amount of absorption and diffusion.

Acoustic materials are mostly used in the ceiling, the walls and the floor. A suspended ceiling is most common. Furthermore, furniture and people themselves also contribute to the acoustics of a room. An acoustic material can have a single function, but it can be combined with other function such as thermal insulation. The placement of a material also matters. For example, distancing an absorber to a wall improves its performance in the lower frequencies. Because the particle velocity close to a wall is low, material at that location is less efficient. On a product scale, absorbing materials can be layered in different densities to have the outer layer more open to sound. When having to cover an absorbing material, different coatings and fabrics exist that have a minimal

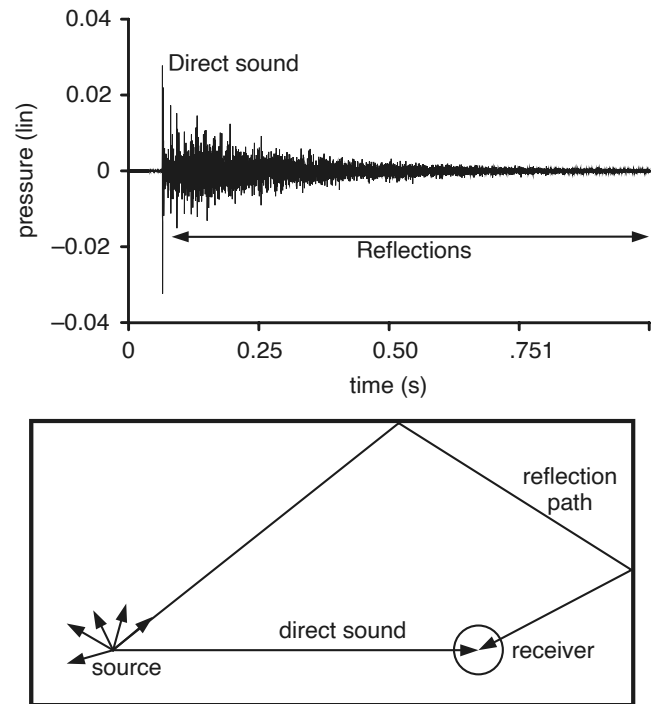


FIGURE 46 RESPONSE OF A ROOM TO A SINGLE IMPULSE (COX, D'ANTONIO, & SCHROEDER, 2005)

effect on the openness of the surface.

At the moment there are different types of absorbers available on the market: porous absorbers, resonant absorbers and other types, such as microperforated panels and Schroeder diffusers. Porous absorbers are good in absorbing high frequencies. They consist of an accessible surface and behind it an interconnected porous structure. The sound is absorbed through energy losses in viscous boundary layer effects. A more detailed description will be given in chapter 4.3.

Resonant absorbers can be divided into two types: Helmholtz absorbers and membrane or plate absorbers. They both rely on a system where a mass vibrates against a spring, in this case the incoming soundwaves against an enclosed or semi-enclosed volume of air. In the case of the Helmholtz absorbers, the air passes through a perforated plate to a cavity. This greatly increases its velocity locally, especially at the resonant frequencies. By placing porous absorption material directly behind the panel, the absorption takes place with a peak in the spectrum at its resonant frequency. Helmholtz absorbers function in the low and mid frequencies.

Plate or membrane absorbers function in a similar way although the air cavity is closed off from the outside. A plate, or a part of a membrane, vibrates and forces the air inside through an absorber. Plate absorbers function in the lower frequencies and are often used in recording studios.

Microperforated panels function in a similar way as the Helmholtz absorbers, although here there is a larger amount of perforations and with a diameter smaller than a millimetre. The holes are small enough to have enough viscous energy losses for absorption without the need for an additional porous absorber. Microperforated panels function in a wide range of frequencies, although higher frequencies are only possible when the size of the holes can be made small enough.

Schroeder diffusers sometimes showed to have some absorption, especially when poorly constructed. In general these diffusers can be built to have a wideband absorption, in the mid frequencies, but it is also possible to extend this to low frequencies to even outperform Helmholtz absorbers by adding plates in the wells. (Wu, Cox, & Lam, 2001) The principle behind this type of is absorption is the resonance of wells with different lengths. Wells closed at the back resonate when the depth is equal to a quarter wave plus a multiple of half waves. When two wells with different depths are next to each other, at ones resonating frequency there is an energy flow from the resonating well to its neighbour that has a different depth. Absorption then takes place as the air moves around the edge. In Figure 411 shows a Schroeder diffuser with some resonating waves drawn in each well as examples. In reality the complete sound spectrum causes multiple resonances and the wells have to be arranged into a specific grid layout for optimal absorption.

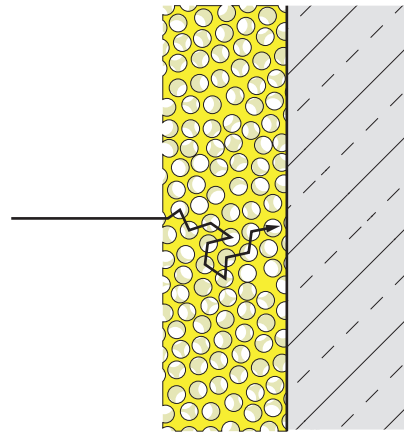


FIGURE 47 POROUS ABSORPTION IN A FOAM PANEL

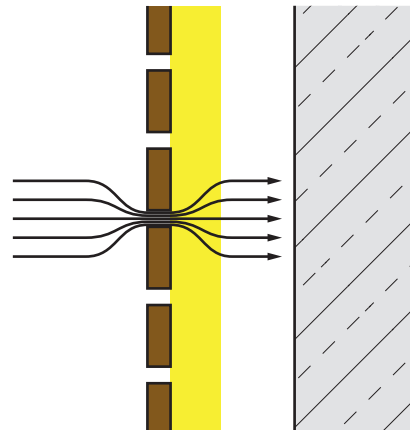


FIGURE 48 RESONANT ABSORPTION IN A HELMHOLTZ PANEL

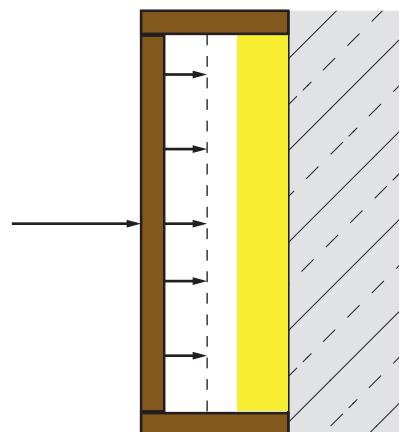


FIGURE 49 RESONANT ABSORPTION IN A PANEL ABSORBER

4.3. ACOUSTIC ABSORPTION AS A MATERIAL PROPERTY

4.3.1. RELATED MATERIAL PROPERTIES

Common material properties to predict or describe the acoustic behaviour of porous absorbers are porosity, tortuosity, surface openness, and flow resistivity. (Cox, D'Antonio, & Schroeder, 2005)

Porosity is the volume fraction of accessible air in a material. Most commercial porous absorbers have a porosity close to 1. This does not say anything about the shape of the pores or their distribution, but in general it is good to get as much air as possible into the material for porous absorption.

Tortuosity is about the complexity of the possible paths through the material. Materials with the same porosity can already have different absorption values when the pores in one material are slightly less aligned and have different viscous energy losses. Viscosity can be seen as the resistance of the fluid to deformation. When the air is pushed through the cavities, it will lose more energy when it needs to go around a corner for example. The air on the inside will go faster than that on the outside, causing internal friction in the air.

The openness of the surface is the part of the surface area that consists of open pores, connected to the pore structure inside the material. This usually becomes relevant when a material is different at the surface than inside, which can happen when a coating or fabric is applied to protect the material.

Flow resistivity is the resistance per thickness of a material to air moving through it. This property can be measured directly, therefore also including the effect of porosity, tortuosity and surface openness. In addition, it also includes thermal losses, which depend on the material, pore shape and temperature. Although this is much less of influence as viscous effects and mainly has an effect on lower frequencies. Even though flow resistivity is an important property for predicting acoustic absorption, it usually needs to be measured and is therefore less interesting for this paper, since we are directly measuring the acoustic absorption.

Material elasticity is often not very relevant for predicting porous absorbers, because in practice motion in a panel is constrained, either by the panel being placed against a wall or by its connections to it. When a material is very elastic however, sound waves can travel through the material structure itself, which can slightly reduce the absorption.

4.3.2. EXISTING MATERIAL TYPES

Frequently used materials for acoustic panels are often made of fibres or foams. (Cox et al., 2005, pp. 132-

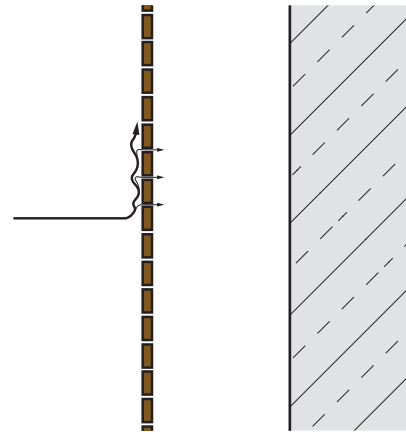


FIGURE 410 ABSORPTION BY VISCOUS LOSSES IN A MICROPERFORATED PANEL

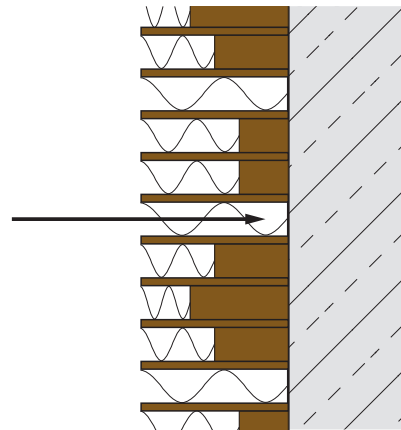


FIGURE 411 ABSORPTION BY ENERGY FLOW FROM RESONANT WELLS OF A SCHROEDER DIFFUSER

133) Mineral wool is made of fibres from rock, basalt or glass, and a small amount of binder. Foams are often open cell structures made of polymers but can even be made of metals. Both materials are often covered with a porous coating for aesthetic and hygienic reasons. A big advantage of these materials is that the fibre length or pore size can be kept constant. Because of this, the materials can easily be modelled. When these models are linked to empirical values, new materials can then have their acoustic properties predicted with good accuracy. The other less frequent and more irregular material types include felt, plaster, wood wool and wood fibres. Fibres can be made with layers of increasing density, with all or most fibres in a certain direction, with all fibres in a completely random direction, etcetera. Foams often end up with a certain amount of closed cells, even in an open cell structure. Even with these differences and small uncertainties the material can still be treated as homogenous or isotropic.

An example of a material with a different structure and a slightly lower absorption is a granular rubber material made from discarded tyres by Pfretzschner and M^a. Rodriguez (1999). Besides a different pore structure, it also has a lower porosity than the fibrous materials or foams. Instead of the common maximum absorption of almost 1, the maximum is 0,8. As shown in Figure 412, with an increasing thickness the absorption curves approach the 0,8 value. The lower absorption results in more sound being reflected at the hard surface behind the absorber. Because of interference with the incident soundwave, this results in the maxima and minima as seen in the graph. (Pfretzschner, 2002) The same effect can also be seen in the impedance tube tests with mycelium done for this paper. The impedance tube uses sound with a normal incidence. When tested in a reverberance chamber, with a diffuse sound field, the fluctuations are lower, see Figure 413.

With completely irregular materials the acoustic properties are only gotten from measurements, because modelling of the material structure is not possible. When the flow resistivity and porosity are constant through the cross-section of the material, these two measured properties can be used for calculations. Although, predicting how a change in the structure affects the absorption will be difficult. Materials that are difficult to predict with models can however still be understood when looking at material characteristics. The theoretical arguments for certain material behaviour can then be compared to acoustic measurements and microscopic imaging, as is done in this paper.

4.4. PREDICTING MYCELIUM MATERIALS

4.4.1. MATERIAL CHARACTERISATION

Predicting the acoustic behaviour of a mycelium composite is difficult because of the biological growth process. Firstly, the growth is uneven or at least so in

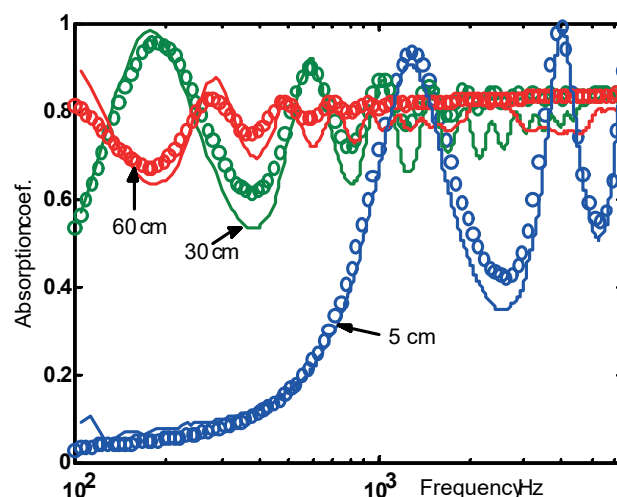


FIGURE 412 RUBBER SAMPLES MEASURED IN IMPEDANCE TUBE (CONTINUOUS LINES) (PFRETZSCHNER, 2002)

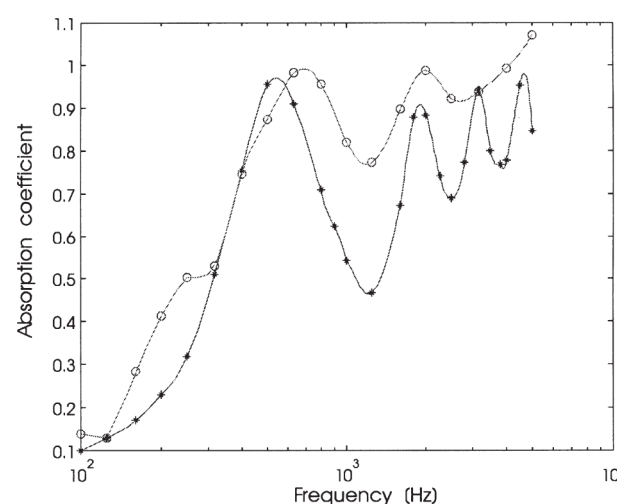


FIGURE 413 RUBBER SAMPLES OF 9 CM MEASURED IN IMPEDANCE TUBE (*) AND REVERBERATION CHAMBER (o) (PFRETZSCHNER & M^a. RODRIGUEZ, 1999)



FIGURE 414 MICROSCOPIC IMAGE OF A HEMP/STRAW SAMPLE CROSS-SECTION

the beginning. This is mainly at the surfaces against the growth shape and in a different way on top where the container is open. Secondly, the material in general can have differences in growth, because of the spawn used for inoculation, differences in airflow, the type of natural particles, temperature differences and nutrients. So, compared to fibrous materials or foams it is very inhomogeneous, or at least there is a difference between surface and internal growth. For the internal structure it can probably be assumed to be isotropic and homogeneous on the larger scale, although not as constant as the synthetic materials.

Typical for mycelium composites as an acoustic absorber is the combination of materials, a substrate and a fungus. The substrate probably makes up for the largest part of its mass, where the fungus mainly acts as a binder. The scale of the air cavities is also different from the regular foams and fibres. The substrate creates larger gaps, but the mycelium might fill this up and work on a much smaller scale.

4.4.2. THEORY FORMING

When forming a hypothesis, two questions have to be answered: 'How to maximise the absorption?' and 'How does the absorption change when changing the material?'

To maximise the porosity, and hopefully also the tortuosity, thick substrate particles are unwanted. Large particle shapes might cause reflection and too small particles might close off the material. To find out how to maximise the absorption and how this absorption changes, a range of particle sizes and densities can be tried out.

A closed surface is unwanted for porous absorption. However, surfaces of the panel can act as a resonant absorber. Low frequencies below 250 Hz are difficult to achieve in porous absorbers but are still in the frequency range of human speech. First a good openness has to be found and then a trade-off might be made for the lower frequencies.

The properties of the structure, and thus also the shape of the air cavities, depend on the substrate, the mycelium and the interaction between those two. Comparing mycelium samples with different substrates or fungal growth might give some insight. In general, the material structure needs to be rigid and the panel needs to be anchored to a rigid surface. The substrate particles and the mycelium especially are, to different degrees, elastic and therefore might reduce absorption. Stiff substrate particles are preferred, although the fibres on which the white-rot fungi grow contain lignin, which provides stiffness.

Other factors that still have an unknown effect on the absorption are thickness, density, shape of the growth container and biological factors, such as growth time, moisture content, temperature and nutrients.

4.4.3. HYPOTHESIS

The expectation is that the air in between the structure and the accessibility of this air at the surface have the biggest influence on the overall acoustic absorption. Different materials, substrates and fungal strains, should not matter too much for the absorption properties, more for on how the samples will grow. How the absorption will change when the mycelium composite is change is still unknown and simply has to be tried out.

5. IMPEDANCE TUBE TESTS

5.1. METHOD

A good method for finding the absorption coefficient of a material is by using an impedance tube. Here a sample of the material is placed at the end of a tube. At the opposite end a speaker produces a standing wave inside the tube. Placed in the wall of the tube are two microphones with a fixed distance to each other and to the sample surface, see Figure 51. The absorption then is calculated with a transfer-function method, which compares the measured sound levels at the two microphones for every frequency. From this information, and by knowing how much sound is produced by the speaker, the incident and the reflected sound waves can be derived, which can be used to calculate the absorption coefficient.

The advantage of this method is that the measurements are done on a small scale. Where the other method used in this thesis, the reverberation chamber test, is a more realistic, but more laborious method. A downside is that sound incidence is only perpendicular to the surface, where in reality there is usually a diffuse sound field.

The tests are done according to the ISO norm 10534-2: 'Acoustics - Determination of sound absorption coefficient and impedance in impedances tubes - Part 2: Transfer-function method' (Nederlands Normalisatie-instituut, 1996; 2001). The Building Technology department had an impedance tube available for use together with software for measurement and data processing. The next subchapter will describe the sample choice and growth process after which there is a subchapter for the discussion of the results.

5.2. SAMPLE SELECTION

The selection of the substrates and fungal strain for the samples is based on the hypothesis that the air cavities and the access to it are most important for acoustic absorption. For this, the size and shape of the substrate particles are expected to be more important than for example the substrate type and fungus used. Although it might have an effect on how good the mycelium will grow. In addition, different substrates and growth conditions will have to be explored. The effect of the following properties on the acoustic absorption will be tested:

- Density
- Boundary layer
- New substrate materials
- Growth time
- Thickness
- Surface shape effects

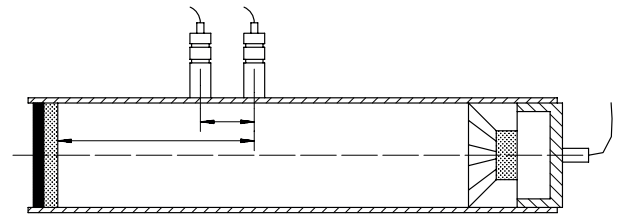


FIGURE 51 IMPEDANCE TUBE LONGITUDINAL SECTION (NEDERLANDS NORMALISATIE-INSTITUUT, 1996; 2001)



FIGURE 52 SAMPLES WITH HEMP/STRAW, CATTAIL AND CACAO SUBSTRATES

Changing the exact particle size and shape would be ideal to test these properties, although changing this requires a lot of work per material. A simpler solution is to look at what materials are available and base the selection on the preferred properties mentioned earlier. Furthermore, the samples will also be compared to conventional products. To do this, different existing bio-based and regular products will also be measured next to the mycelium samples.

Readily available materials were hemp and straw. Less common materials were wood curls, cattail and cacao. These were picked because of either their particle shape, hydrophobic properties or unknown growth behaviour. To explore the surface effect one sample will undergo an extra growth phase, in which it will be placed in a humid environment with a relative humidity of 95%. Different surface shapes will also be tested, see Figure 54. Growth time, thickness and density were varied in the regular sample of hemp/straw to see if and how much these properties effect the acoustic absorption. Finally the products are compared to existing material samples of conventional products, both bio-based and petroleum based materials, and mycelium products.

For a detailed description of the growth process, see chapter 2.2. The fungal strain used for most mycelium samples is *Pleurotus ostreatus*. After growing the samples, the material had to be cut to size to fit a 100 and a 29 mm diameter impedance tube. For this a belt-saw was used, which had the advantage of a continuous downward motion of the saw blade's edge instead of a up and down motion of a regular saw. For the smaller size cutting samples was sometimes difficult and not all samples were of good quality because of this. For a complete overview, see the sample documentation in the appendices.

5.3. MEASUREMENTS AND PROCESSING THE DATA

For the impedance tube tests a Brüel & Kjær Impedance Tube Kit was used in combination with their PULSE software for measurement and data processing. First the two microphones had to be calibrated. Then the background noise was compared to the measured sound of the impedance tube speaker to check if it was low enough. After these steps the transfer function could be calibrated to eliminate phase and amplitude mismatches between the two microphones.

After these preparations, multiple measurements could be done as long as the conditions stayed the same. The frequency range was set to be measured in small steps of 2 Hz, as this still did not affect the measurement time too much. This resulted in a smooth curve, different from the one-third-octave-bands used in the reverberation chamber tests. The samples were measured in two different tubes, with a 100 mm and a 29 mm diameter, to measure over a broad frequency range. Although the norm suggested to fill gaps at the edges with lube, this was not done because most samples fitted well. In addition, not using lube for all

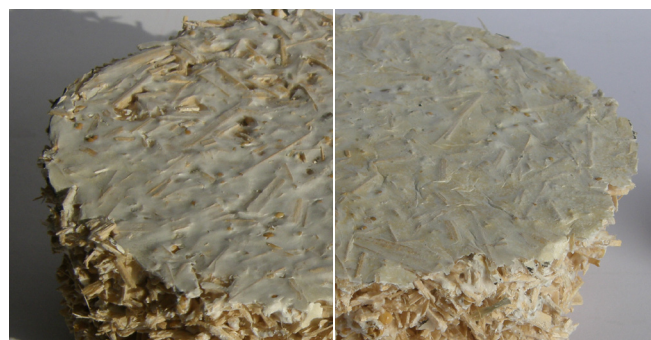


FIGURE 53 SAMPLE WITH AND WITHOUT EXTRA SURFACE GROWTH



FIGURE 54 SAMPLES WITH DIFFERENT SURFACE SHAPES



FIGURE 55 EXISTING MYCELIUM PRODUCTS: ECOVATIVE AND GREENSULATE, ALSO TESTED WITH OPEN/CLOSED SIDE



FIGURE 56 EXISTING ACOUSTIC PRODUCTS

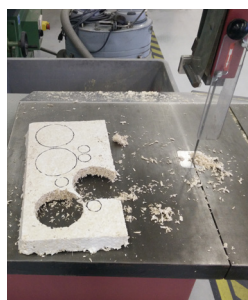


FIGURE 57 CUTTING THE MYCELIUM MATERIAL TO SIZE WITH A STATIONARY BELT-SAW

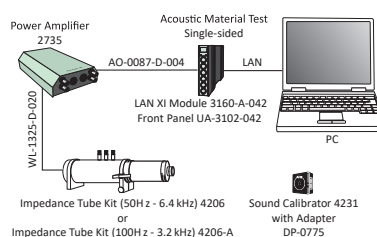


FIGURE 58 PRODUCTS USED FOR THE IMPEDANCE TUBE MEASUREMENTS (DIAGRAM ADAPTED FROM WWW.BKSV.COM)

samples made the results more consistent. However, the smaller samples did not always fit well or were of lesser quality because of the difficulty of making them. The small gaps were filled with loose substrate particles. For a more detailed description, the sample documentation is included in the appendices.

After the measurements the materials that had multiple samples of the same size could be averaged and then the results of the small and large tube could be stitched together. Although, most materials only had one large and one small sample. Stitching together results of the small and the large tube was done in the range of 500 to 1600 Hz. It was not possible to measure with only one tube. The working frequency range of a tube is

$$f_l < f < f_u$$

where

f_l is the lower working frequency of the tube;

f is the operating frequency;

f_u is the upper working frequency of the tube.

The lower working frequency is limited by the equipment used, but the upper working frequency depends on the diameter of the impedance tube. (Nederlands Normalisatie-instituut, 1996; 2001) This relation is:

$$f_u < \frac{0,58 \times c_0}{d}$$

where

c_0 is the speed of sound in m/s;

d is the diameter in m.

In normal conditions this means the small tube has an upper working frequency of 6860 Hz and the large tube one of 1990 Hz. Because the accuracy already seemed to drop after 1700 Hz, the highest frequency used for the large tube was set to 1600 Hz. The lowest frequency measured was limited by the equipment and set to 50 Hz. The highest frequency measured was set to 6400 Hz.



FIGURE 59 LARGE IMPEDANCE TUBE OF 100 MM DIAMETER

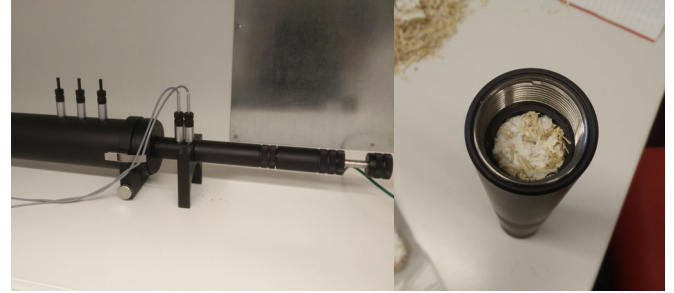


FIGURE 510 SMALL IMPEDANCE TUBE OF 29 MM DIAMETER

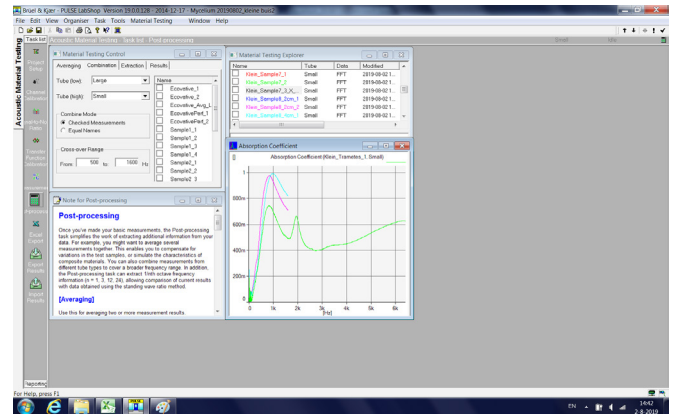


FIGURE 511 SCREENSHOT OF THE POST-PROCESSING TAB IN THE IMPEDANCE TUBE SOFTWARE

5.4. RESULTS AND DISCUSSION

The overview in Figure 512 shows all graphs of the measured samples together. The red line is the 4cm thick hemp/straw sample with which all samples will be compared with. This already shows that the mycelium performs well.

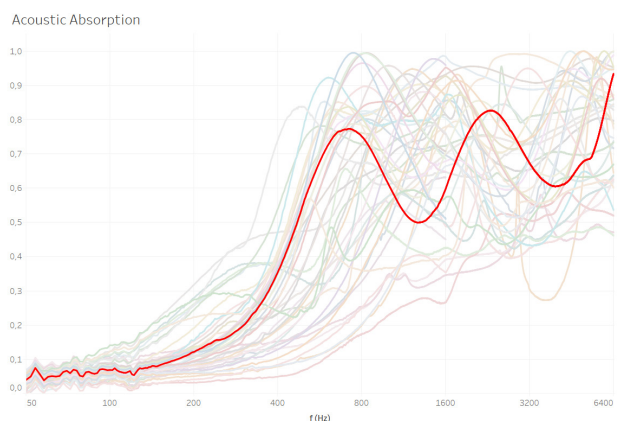


FIGURE 512 BANDWIDTH OF MEASURED SPECTRA, INCLUDING MYCELIUM AND EXISTING PRODUCTS.

When looking at the different substrates used, the cattail and cacao are a lot denser but might be interesting for lower frequencies. Just straw, not combined with hemp, is probably too light/open. Hemp/straw seems like a good choice.

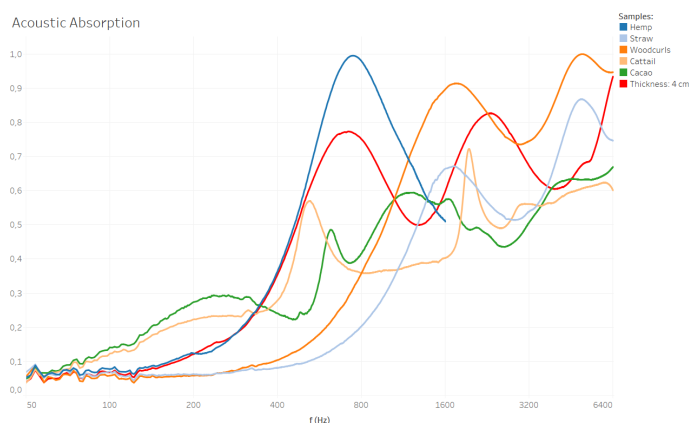


FIGURE 513 MYCELIUM WITH DIFFERENT SUBSTRATES

Growth time seems to be of no big difference, most of the mycelium growth already took place. It is also difficult to predict the growth based on the parameter 'growth time' alone. Nutrients, moisture, temperature, etcetera have not been varied for the samples in this thesis.

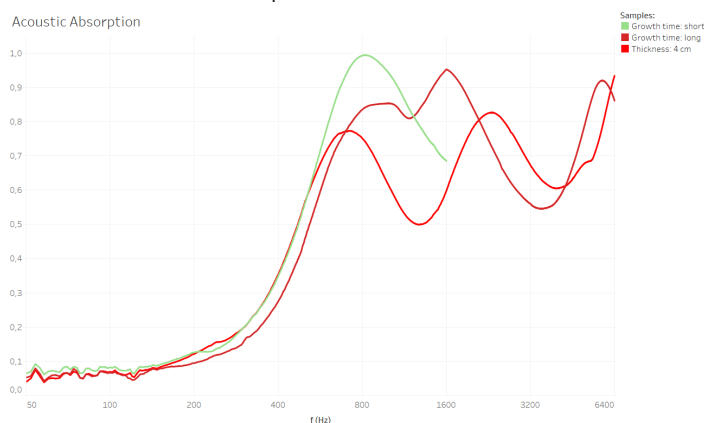


FIGURE 514 MYCELIUM WITH 3 DIFFERENT GROWTH TIMES

With increasing thickness, absorption of lower frequencies increases and/or absorption in general seems to increase. The 4 cm samples seem to be on the heavy side when looking at the documentation.

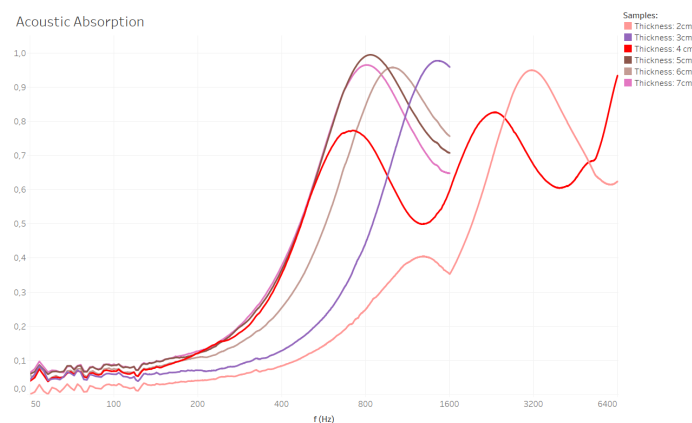


FIGURE 515 SAMPLE THICKNESSES RANGING FROM 2 TO 7 CM

With increasing density, absorption of lower frequencies increases. 'Extra compressed' was found out to have a lower measured density than 'Compressed' when weighed afterwards. The samples were made by either distributing the substrate lightly or pressing it by hand when putting it in the growth shapes.

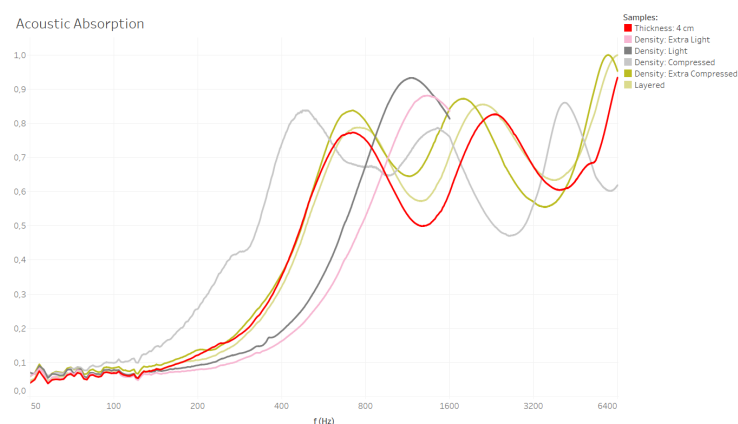


FIGURE 516 MYCELIUM WITH DIFFERENT DEGREES OF COMPRESSION

Changing the shape of the surface, on this scale, does not seem to make much of a difference compared to the regular samples. The extra growth phase seemed to slightly improve lower frequency absorption and decrease the higher frequency absorption. However, the quality of the small sample for higher frequencies was not very good, with the internal structure falling apart, see Figure 518. Looking at the separate graphs in Figure 519, the drop in the small sample for lower frequencies could be explained by the bad sample quality. Comparing only the large sample of with the regular mycelium sample, it seems to improve the absorption in the lower frequencies. If the absorption will go up again above 1600 Hz is not clear and requires more testing.

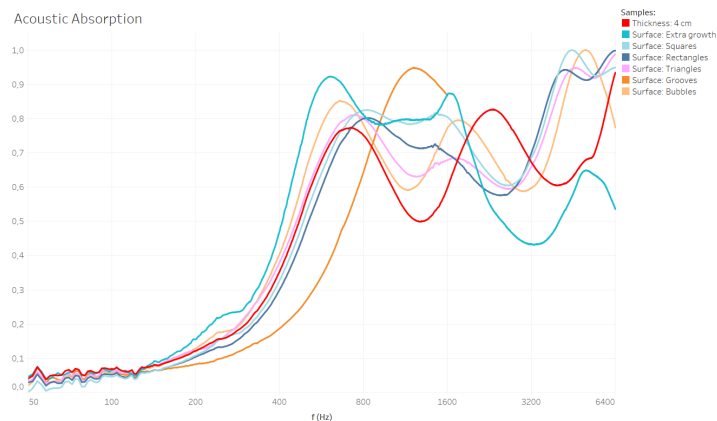


FIGURE 517 MYCELIUM WITH DIFFERENT SURFACE EFFECTS

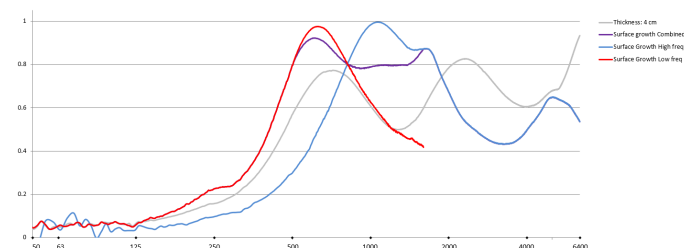


FIGURE 519 SMALL SAMPLE, LARGE SAMPLE AND COMBINED GRAPH EXTRA SURFACE GROWTH (INCLUDING REGULAR 4 CM SAMPLE)

Next to the samples grown for this thesis, Fungalogic also had some previously grown samples available, see Figure 520 and Figure 521. The samples with straw and hemp perform more or less the same, with both better and worse performers. Although the straw block and flax substrate perform better on lower frequencies, possibly because of the higher density.

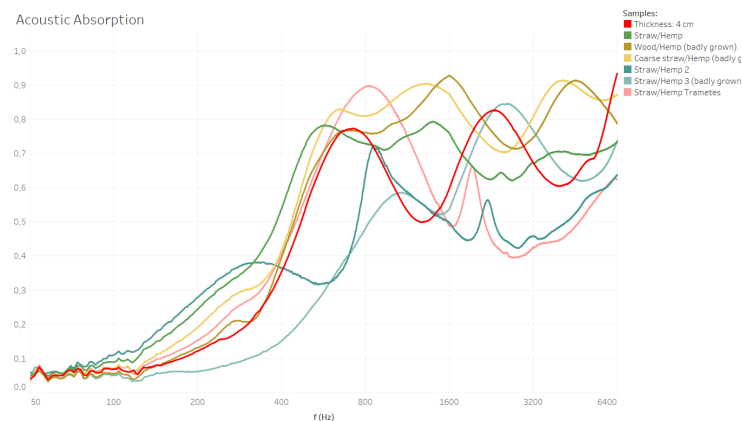


FIGURE 520 SAMPLES PREVIOUSLY GROWN BY FUNGALOGIC

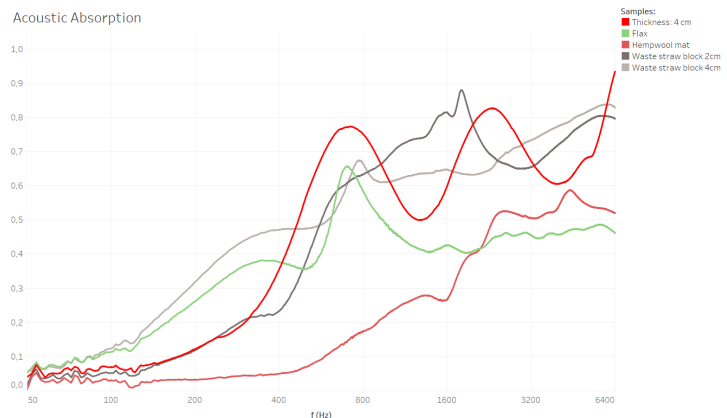


FIGURE 521 SAMPLES PREVIOUSLY GROWN BY FUNGALOGIC

Existing products that were tested also contained two mycelium products by Ecovative. The Ecovative GIY material is one of the worst performers. Greensulate is only 1 cm thick but shows the difference between an open and a closed surface with a shift to the higher frequencies when opened. For the conventional products there were both bio-based and petroleum-based products. They had a lot of different types and thicknesses, but in general the mycelium performs less in the higher frequencies. The rigid wood wool samples, Troldekt and Heraklith, perform a bit less than the other foam-like materials. Although this was to be expected, because these are often used in combination with mineral wool on top.

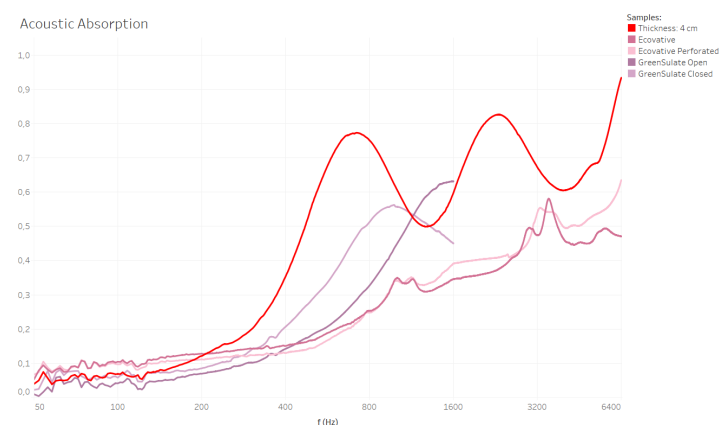


FIGURE 522 EXISTING MYCELIUM PRODUCTS

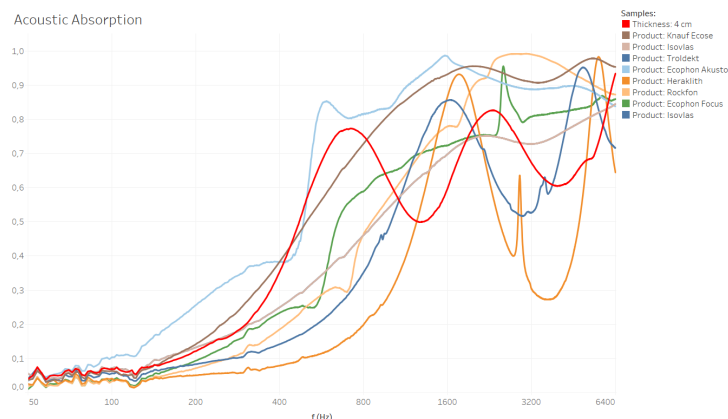


FIGURE 523 EXISTING ACOUSTIC ABSORBERS

either had a limited or unknown effect.

Material samples that were grown or delivered, but not measured, are included in the sample documentation in the appendices. This includes multiple samples with *Trametes* and *Métisse*.

5.5. CONCLUSION

In general, the mycelium has a good acoustic absorption. Most of the hemp/straw samples perform the same, although thickness and density has some effect. Better grown, dense or samples with a closed surface show a shift to the lower spectrum. Compared to other products the mycelium seems to have a similar acoustic performance, although foams are better in the higher frequencies.

Surface growth does not seem to affect absorption as much as expected. The extra growth phase only resulted in a slight focus on the lower frequencies compared to all the other hemp/straw samples from that batch. The absorption is both less broad and with a shift to the lower frequencies. After the measurements were done, all samples were weighed and the dimensions were measured. When looking at the calculated density, there seems to be a balance, as most samples seem to be a bit on the light side. Increasing density generally improves the absorption. Although this is only until a certain point, because cacao, the flax and the Ecovative GIY kit material are probably too dense.

The sinewave-like curve at the end can probably be attributed to a lower porosity, as described in chapter 4.3.2. Results from the reverberation chamber and real-life measurements will partially level this out.

The hypothesis expected that the air in between the structure and the accessibility of this air at the surface have the biggest influence on the overall acoustic absorption. This was tested by testing samples with different densities, boundary layers, substrate materials, growth times, thicknesses and surface effects. The most important conclusion is that the density can probably still be increased to improve the absorption. However, a balance has to be found, since the Ecovative samples are too dense. A denser material also has the advantage of being less fragile. How mycelium materials can be changed to improve the absorption is difficult to say from the impedance results. Growth, thickness, growth container shape and substrate

6. MICROSCOPIC IMAGING

To be able to better explain the acoustic behaviour of mycelium, the surface and sections of three impedance test samples were viewed under a microscope.

6.1. GOALS AND SAMPLE CHOICE

Predicting the acoustic behaviour exactly from the theory would be ideal, but for mycelium that is not possible. In addition to the impedance tube tests, the microscopic imaging should either verify or find possible explanations for the observed acoustic behaviour.

The growth of the mycelium in the samples seemed more or less of the same quality, but it is relevant to see what part of the acoustic behaviour is caused by the mycelium and what part by the substrate. With the naked eye there seemed to be no big differences in the fungal structure, but it might be worth knowing if there are any. The second goal is to see the effect of the surface openness and compare it to what can be seen with the naked eye. The third goal is to see if the mycelium growth is different at the surface compared to internal growth.

The regular hemp/straw sample was chosen as a basis to compare the other two with. The second sample was the worst performer, the Ecovative GIY material, and the third sample was the one with the extra surface growth.

The samples were viewed from the top and sides with different magnifications. With the views of the sides, the method of cutting the samples has to be considered, since it is not a perfect cut. You can see the direction of the saw in the alignment of some particles.

The Keyence VHX 7000 digital microscope is an optical microscope with digital picture processing and was in use at the Architecture faculty for research on glass fractures. The microscope can analyse and generate depth maps of surfaces, but for mycelium there was no distinct opening that could be pinpointed, only a complex three-dimensional structure of substrate particles connected by webs of hyphae.



FIGURE 61 KEYENCE VHX 7000 DIGITAL MICROSCOPE AT THE FACULTY OF ARCHITECTURE AND THE BUILT ENVIRONMENT



FIGURE 62 MICROSCOPIC IMAGES OF 3 SECTIONS: REGULAR HEMP/STRAW, HEMP/STRAW WITH EXTRA GROWTH PHASE, ECOVATIVE

6.3. COMPARISON AND DISCUSSION

When comparing the surface images with each other, only at the regular hemp/straw sample the mycelium strands are visible. The other two samples have mycelium that is too dense to see any individual hyphae. When using the microscope to view the surfaces, the light could be seen to penetrate the mycelium of the extra surface growth sample, but not that of the Ecovative

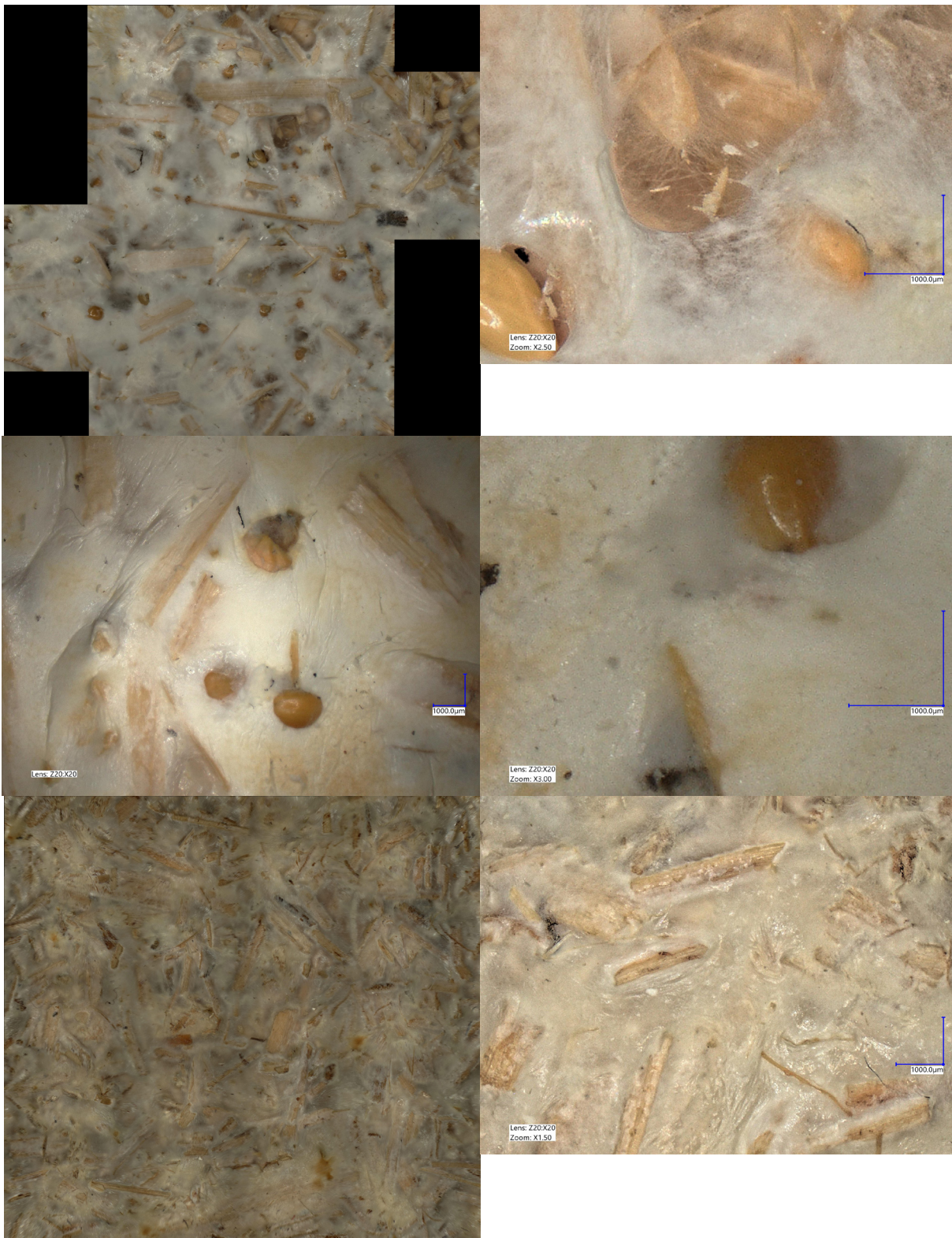


FIGURE 63 SURFACES: TOP: REGULAR HEMP/STRAW; MIDDLE: HEMP/STRAW WITH EXTRA GROWTH PHASE; BOTTOM: ECOVATIVE

one. This indicates also a large difference in density. The sections very clearly showed the differences in density again, but also a difference in density at the extra surface growth sample that could not be seen with the naked eye. The section of the Ecovative sample showed that the particle size played a large role to completely fill the material volume, not because the mycelium filled all the gaps.

Comparing the images with the impedance tests results

shows that the extra surface growth does not affect the absorption very much, indicating that it is possible to grow a denser mycelium composite when trying to increase the absorption in this way or to improve the mechanical properties. Although it is difficult to draw conclusions when the extra surface growth has a sample size of 1 and the bad quality of the small sample makes the absorption values above 1600 Hz less reliable. More impedance tube tests could be done to draw a more definitive conclusion.

7. DESIGNING WITH MYCELIUM

Using a novel building material such as mycelium does not only require material tests. Design and production are also different than when using conventional materials. Finding out the unknown qualities and possible issues of mycelium is less straightforward and needs to be done by exploration and trial and error. The knowledge from literature, existing applications, own acoustic research and hands-on experience was used as the starting point for this process. Different topics related to the upsides and downsides were then explored.

7.1. INSIGHTS FROM OWN RESEARCH AND HANDS-ON EXPERIENCE

Literature on mycelium already shows that a wide range of material properties is possible, although the performance might not be as good as is sometimes claimed or as good as conventional materials. However, the acoustic tests done with the impedance tube show that the mycelium material does have good acoustic absorption properties.



FIGURE 71 PHOTOS OF THE ECOVATIVE KIT WITH CONTAMINATIONS

More relevant for the design are the hands-on experiences with mycelium. Starting with the Grow It Yourself-kits from Ecovative and later making samples and panels at Fungalogue, the practical experience gave a more intuitive insight in the material. Especially in aspects that had to do with using a living organism during the production phase, uncommon with most raw materials used in building construction. Some early attempts to grow mycelium failed because of contamination, old mycelium or too low temperatures. Parameters like these make production less straightforward and sometimes difficult to determine why something failed to grow. A fitting analogy was made by Marc Postel, comparing the production with baking a cake. The geometry and material of the growth shape has a big effect on the growth. Some flexibility and an impenetrable surface helped getting the mycelium out in one piece. The shapes with straight surfaces were also easier to empty from the mould, although issues with more complex geometries mainly occurred on a smaller scale. The mycelium itself also pushed the substrate to

parts where the mould was empty, this roughened out the initial structure of the substrate, but also make it difficult to create air cavities by perforating the substrate. The air cavity in the growth shapes, below the plastic foil cover with air holes, also seemed to have an effect. For some samples this air gap was possibly too big, given the lower the moisture content in the substrate, resulting in less mycelium growth. In a similar way, the mycelium against the surface of the mould and on top was denser, possibly because the moisture and oxygen were able to reach these parts better. Drying the mycelium too long or with a too high temperature could result in asymmetric deformations. Above a certain thickness the designed shaped would need air holes to get all the moisture out.

The samples made for the acoustic impedance tests were made with different thicknesses, densities and changes in surface geometry. Still, the differences in absorption were a lot smaller than expected. The hemp/straw samples all having similar absorption curves is positive, because it shows that the results can be consistent. However, the current results do not provide a reason to focus on improving the material properties during the design phase, but rather on a proper application of mycelium.

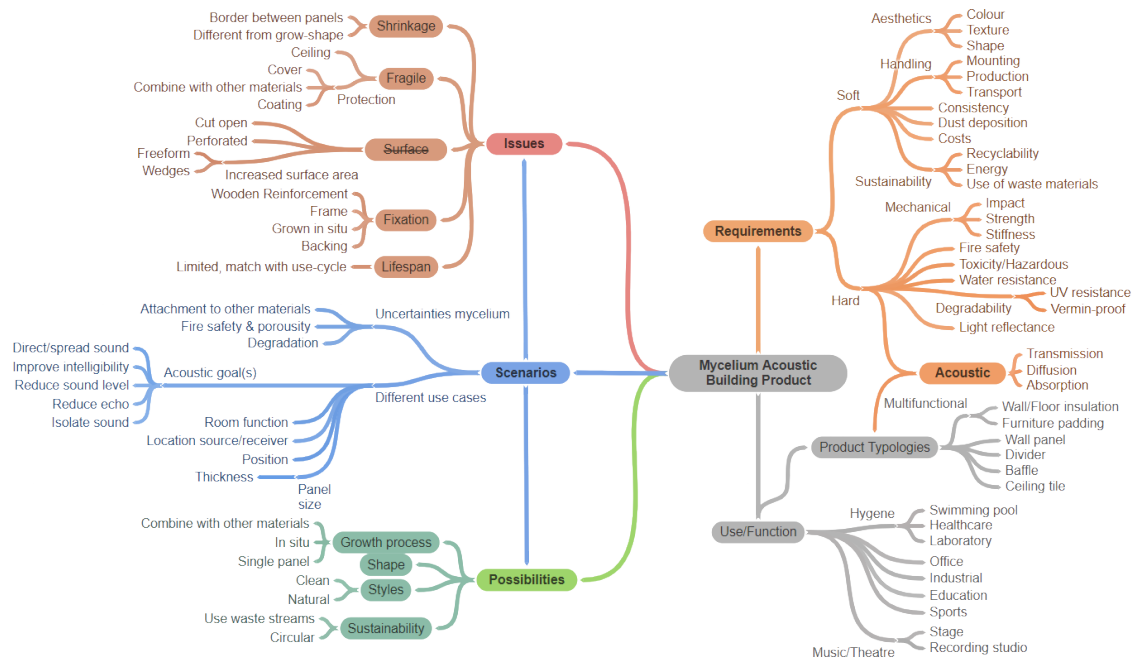


FIGURE 72 MINDMAP FOR DESIGNING A MYCELIUM ACOUSTIC PANEL

7.2. RELEVANT TOPICS WHEN DESIGNING WITH MYCELIUM

From the literature, acoustic research and own experiences with mycelium different topics emerged. The topics are related to issues specific to mycelium, uncertainties in what the final material properties are going to be, different possible scenarios related to use and configuration, possible opportunities with this new material and the range of what can be done in style and shape. The first topics focus more on expected issues, after which the focus shifts to possibilities and then also scenarios. The order is also slightly chronological, so some assumptions or scenarios have become less relevant after new insights from for example acoustic tests.

7.2.1. OPENNESS OF THE SURFACE

Before the impedance tests, the expectancy was that the openness of the mycelium surface would lower the acoustic absorption below an acceptable level. The initial idea was to raise the absorption by increase the openness of the surface. Later tests showed that the amount of absorption was sufficient.

The first impedance test was done with the open and closed surface of a single 10 mm GreenSulate sample. The results showed a slightly lower absorption with the closed surface, but also a shift towards the lower frequencies, making it possible a trade-off could be beneficial, since lower frequencies are often more difficult to absorb in practice. The amount absorbed however seemed insufficient at the time, when compared with conventional acoustic products. Furthermore, the tests were only done for frequencies up to 1600 Hz, which meant that for the higher frequencies, where absorption mainly works by porous absorption, it was difficult to say if the surface would be open enough to access the pores.

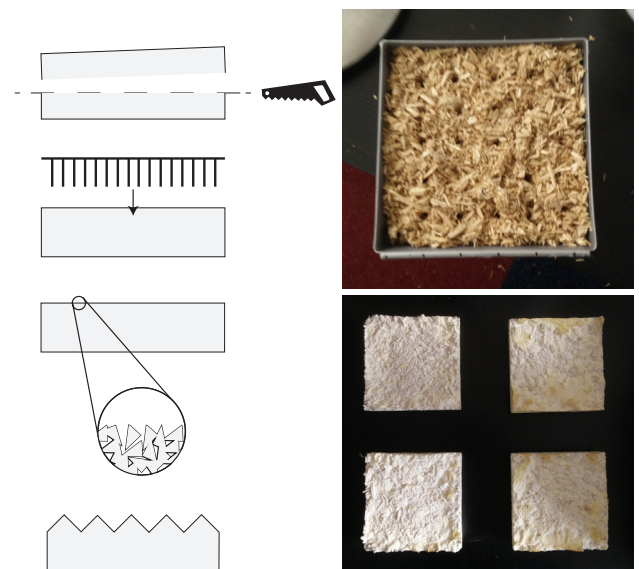


FIGURE 73 SURFACE TREATMENTS FIGURE 74 ECOVATIVE SAMPLE PERFORATED PRE GROWTH AND AFTER GROWTH (LEFT: REGULAR SAMPLES, RIGHT: PERFORATED)

Different options were explored to improve the acoustic absorption by changes in the surface treatment or shape, see Figure 73. The first option is to cut open the mycelium composite after growth. Beside an effect on acoustic absorption, the surface would also be less water resistant and more fragile. Although, this could be partially solved when the acoustic panel is hung with a distance from the wall or ceiling, the open side facing inward. Another downside is that this would require another production step, increasing the cost of the panel. The second option is to perforate the panel. This would either add a production step before or after growth. For either ways the idea is to partially open the surface, but also to get the sound deeper into the material. When trying out the Ecovative Grow-It-Yourself kit, two samples were made with perforations done before growth. The holes however closed during growth, with the mycelium pushing the substrate particles into them.

This can be seen when comparing the perforated samples with regular ones, see Figure 74. The impedance tests also did not show any clear difference or improvement. The third option is an untreated panel of a certain mycelium material. Here the surface properties would follow from the material. The material can be influenced by substrate particles of different sizes and combinations, but also from compression and mycelium growth. However, improving the surface openness could result in a material with a lower the general absorption. For this reason it is better to first look at test results for a complete picture. The fourth option is the use of the surface shape. The surface area and the angle of incidence are both important for how much sound enters the material, although absorption also depends on the pore structure behind it. More surface area means more open pores that can be accessed. The angle of incidence is relevant when the sound is no longer absorbed but reflected. In this way, a surface shape can trap the sound, reflecting it back to an opposite part of the surface. Using a sawtooth shape will greatly increase the surface area but creates a more fragile surface. Comparing the panel with a flat panel of the same average thickness will show if the increased absorption of the surface shape is worth it. The five different surface shapes tested in the impedance test did not perform significantly different from the standard 4 cm sample. Since the material did not grow into a very dense structure or surface, the openness at the surface is already quite high, and might not improve much from an increased surface area. Because the samples are very fragile and were more difficult to release from the grow shape it is better to not apply the same to the final design. It could be useful to test the same shapes at a bigger scale or with a denser material.



FIGURE 75 IMPEDANCE SAMPLES WITH SURFACE SHAPES

In conclusion, extra steps in production to alter the surface are probably not worth it, considering the downsides and because the impedance tests showed the acoustic absorption was sufficient. Improvements on the material level are a more logical first step. Additional measures can then still be taken.

7.2.2. FRAGILITY

It is not clear if mycelium panels with great acoustic absorption will also be strong enough to withstand incidental impacts. Besides this uncertainty there are also different scenarios where these impacts are or are not expected or accepted. For example, a panel in a ceiling is less at risk than one on a wall. Nonetheless, the solutions below, for protecting the mycelium, can be applied when necessary. Combining it with another stronger material can decrease the visibility of the mycelium, decrease the acoustic

absorption of the panel and introduce new issues regarding the connection to the mycelium. Four examples of panel types are given to be able to discuss these issues.

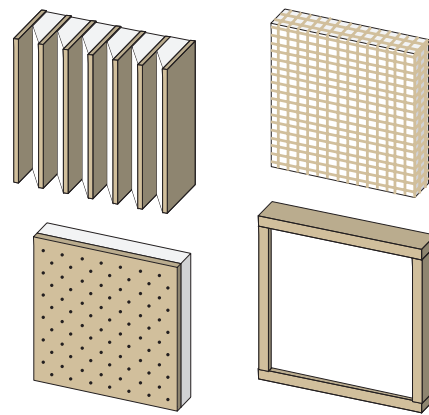


FIGURE 76 SHIELDING MYCELIUM FROM IMPACTS

The first type consists of vertical slats with mycelium in between. The mycelium is fully visible when standing in front of the panel but disappears when viewed from the sides. The slats could trap sound with small angles of incidence, which would normally be reflected back into the room.

The second type uses a perforated panel in front to protect the mycelium. This greatly reduces the accessible area for absorption, but this can be balanced by changing the perforation rate. When the mycelium is grown onto the panel, the small holes have a risk of being filled with mycelium. Larger holes can be used to show the texture of the mycelium.

The third type strengthens the surface with a net of natural fibres, like for example flax or hemp. Compared to the panel the surface area available for absorption should be larger. By growing the mycelium on the reinforcement material, the strength should come from the combination of materials, instead of only from the panel.

The first three types can be realised by growing the mycelium on the other material. Tests should be done for bonding strength and growth behaviour in small openings. When these show there are issues, the mycelium can also be attached after growth.

The fourth type is the use of a frame, which could be an easy solution when the bonding strength is insufficient. The mycelium in this type has a large accessible and visible surface area. While the large opening is also more susceptible to impacts, the size can be chosen in relation to the expected impacting objects, such as fingers, hands or people falling or leaning against the panels.

7.2.3. CONNECTIONS

The mycelium can be directly grown onto something, glued, drilled into, clamped or kept into place by a frame. Gluing and framing are simple solutions without

much effect on the mycelium panel. The other types are different for mycelium compared than for conventional products, for which the fixation depends on the strength of the mycelium composite.

Drilling, cutting and other mechanical manipulation types require the mycelium to be dense and strong. The cut or hole should be clean and able to transfer a certain load. The outer surface will be breached, and this will possibly result in the panel to be less moisture proof. But more importantly, the problem with acoustic materials is that they tend to be light and porous, which makes them less likely to be suitable for drilling and cutting.

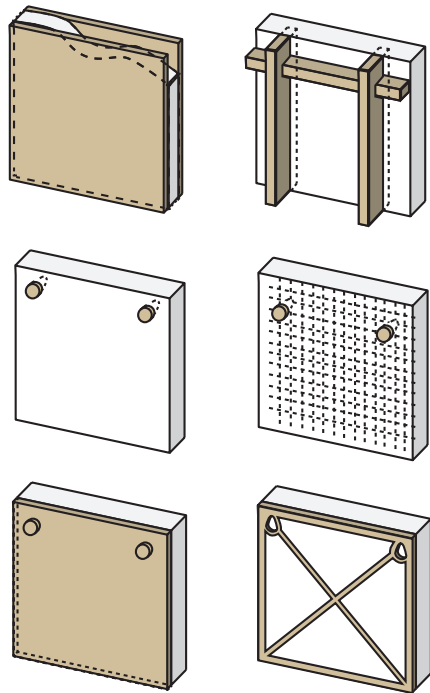


FIGURE 77 IN SITU, POINT CONNECTIONS, 'MAT' CONNECTION, BACKPLATE, LINE ELEMENTS, BACKPLATE ALTERNATIVE

It is even possible to grow the mycelium in situ, although this is not always practical. For a panel, mycelium can be grown on a stronger material that is easier to hang or fixate to a wall, ceiling or point in space. Transferring the load can be done through a point, line or surface. Where for a material that is or might be fragile the safest option would be a surface. This gives a larger surface area and does not introduce any internal points where the material can start to tear or wiggle loose. Attention does have to be paid to delamination, but this can be prevented by proper drying and materials that are known to have a good bonding strength, like certain wood or cardboard types.

7.2.4. NARRATIVE

The perception of a product or material results into different meanings or narratives for different people. This is especially the case for a new material like mycelium, as shown in Figure 78. Even though the narrative is subjective, it still can be taken into account when designing a product. The multiple connotations for mycelium relate to intended functions of a product and material characteristics, which can be discussed by looking

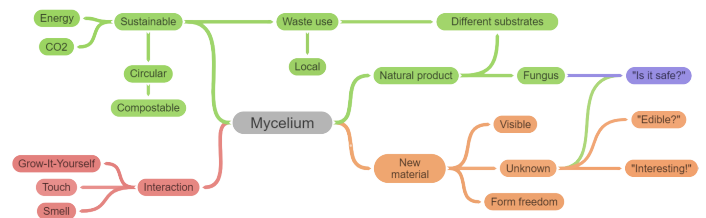


FIGURE 78 MINDMAP OF PERSONAL AND PUBLIC CONNOTATIONS OF MYCELIUM

at some existing mycelium products and projects. The use of waste plays an important role in the grow-kits of Rotterzwam, a mushroom farm in Rotterdam. By using your own used coffee-grounds you can grow oyster mushrooms at home. The product lets you experience recycling your own waste by interaction and seeing the mushrooms grow.



FIGURE 79 ROTTERZWAM SELLS GROW-KITS THAT TURN USED COFFEE-GROUNDS INTO OYSTER MUSHROOMS

The use of waste, like the coffee-grounds, can be part of a circular system. For circularity, the loop at the end of the product lifecycle must also be closed. It is possible to do this by composting mycelium products. A telling example of this is a UAV, unmanned aerial vehicle or drone, designed for the 2014 iGEM competition. Almost all parts are made of biodegradable materials, from a cellulose-based circuit board to a chassis of mycelium. Here the story makes sense, the drone looks natural, which could mean it is compostable, and a common use for drones is in remote areas, which could mean it cannot be retrieved after a crash. Another example of circularity and compostability is the mycelium packaging by Ecovative, such as wine shippers or breakaway corners.

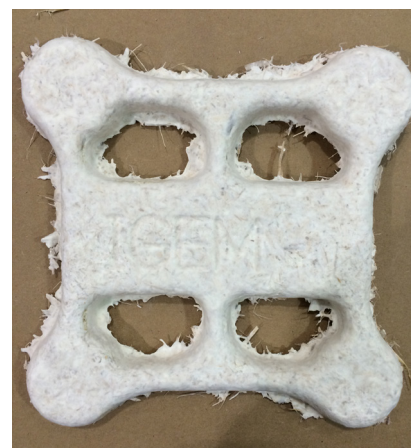


FIGURE 710 MYCELIUM DRONE CHASSIS BY STANFORD-BROWN-SPELMAN TEAM FOR IGEN



FIGURE 711 MYCELIUM WINE SHIPPER BY ECOVATIVE

Another narrative is that of the ‘new material’, which can be used to inspire people or explore possible future applications of mycelium. This can be anything from conceptual design to art installations. An example of this is the graduation project of Gianluca Tabellini, exploring the architectural tectonics of mycelium growing on suspended hemp fibres.



FIGURE 712 GRADUATION PROJECT GIANLUCA TABELLINI

The characteristic shape freedom of this new material is expressed by the 3D-printed chairs of Eric Klarenbeek, forming a freeform shape of a single material without nails or screws. In a same way the mycelium can also be used to grow in a wall cavity, although not visible.



FIGURE 713 3D PRINTED CHAIR BY ERIC KLARENBECK, 2018



FIGURE 714 WALL MOCK-UP WITH MYCELIUM INSULATION BY ECOVATIVE

With this new material the structural capabilities are still mostly unknown, especially in practice. With structure as an important part of the concept, architecture studio the Living designed a 13-meter-high tower, showcasing what is possible with mycelium. It is made of mycelium bricks that carry their own weight, although it is partially supported by a wooden structure.



FIGURE 715 HY-FI TOWER BY THE LIVING AT MoMA, 2014

People that interact with mycelium for the first time often make remarks about the touch or smell. It is possible to make it feel soft like velvet by having an additional growth phase after taking it out of the mould. It can also be made to look and feel like leather in texture, colour and flexibility.



FIGURE 716 MYCELIUM “LEATHER” BY MYCOWORKS

As a living material, mycelium can have both a positive and negative impression. Positive, often when it is seen as a new interesting material. Negative, when it is not known if there will be spores or if the material is dangerous.

Finally, when designing with mycelium, different strategies can be applied in relation to the narrative. After deciding what narrative is wanted and before testing how the product is perceived, in the design the mycelium has either to be shown, hidden or altered to exaggerate or soften certain characteristics. The acoustic panels of Mogu show the mycelium and have a soft white surface. The acoustic tiles, grown on cotton by-product, have a clean aesthetic, with the mycelium texture only visible close by. Another option is to completely hide the mycelium. This was done by Harry Allen in the Weave panels.

Here the product looks like it could be a conventional product, although it is completely compostable with the use of a biodegradable cover and adhesive. Letting the mycelium grow until it starts growing mushrooms will cause it to show discolouration. This emphasises it being a natural product. An example of this are the panels of Maurizio Montalti of Mogu.



FIGURE 717 PLAIN AND WAVE ACOUSTIC TILES BY MOGU

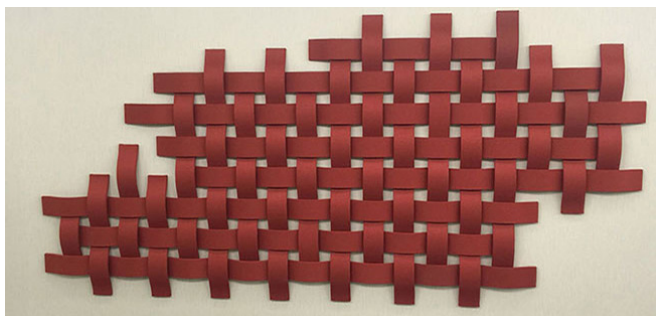


FIGURE 718 WEAVE ACOUSTIC PANELS BY HARRY ALLEN AND ECOVATIVE



FIGURE 719 WALL TILES BY MAURIZIO MONTALTI

7.2.5. LIFECYCLE AND SUSTAINABILITY

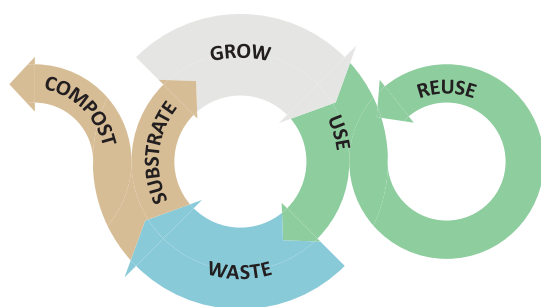


FIGURE 720 LIFECYCLE DIAGRAM

An important opportunity for a mycelium product is the use of waste biological fibres as a source material. Compared to conventional products however the lifespan is probably limited. Therefore, it is important to first look at the lifecycle of a mycelium product. A simplified representation of the lifecycle is shown in Figure 720. The different phases are: grow, use, waste and substrate.

First the mycelium product is grown. Depending on the

production method the number of steps and duration can be different. For this paper these are: treatment of the substrate, first growth phase, growth in growth shape and drying. Using natural fibres as a source material already results in a very low CO₂- and energy-footprint. It can be reduced even further with a local substrate source and panel production.

The use phase lasts as long as the product performance meets the demands. The performance can be directly related to the product properties, like for example the acoustic absorption or the surface colour, or be more indirect or contextual, as for example the economic value or aesthetic quality. The performance can for instance be lowered when a product is damaged or when it degrades over time. The demands can also change, for instance during a refurbishment or when the use of the room changes. Compared to conventional products mycelium acoustic panels are expected to be more fragile, because the material is less flexible, and will probably degrade faster, as the material is a natural composite of lignocellulose fibres and mycelium. Therefore, it is likely that the product will have a shorter lifespan and more attention has to be paid to how long the product is expected to be used. This can be done by focussing on temporary use and designing a disassemblable or compostable product. Cleaning, maintenance work or repairs extend the lifespan of a product. First it is important to make sure these are kept to a minimum. The amount of cleaning needed can be reduced by paying attention to surface orientation, surface roughness and electrostatic attraction. A rough mycelium surface collects more dust and is harder to clean compared to a smooth and straight surface. The water repellent properties also improve with a smooth and well grown surface, which prevents staining by fluids and makes it easier to clean. Repairing a mycelium panel can be done by filling gaps with a material with a similar look. It might be possible to do this by growing mycelium onto it, although the growth needs to be stopped. Relevant for reuse is the way the acoustic panel can be demounted and remounted. This is a lot harder when using adhesives instead of a mechanical connection. Of course, the quality of the panel still has to be high enough to fulfil the new demands.

The product is discarded as waste when the relevant demands are no longer fulfilled. The diagram in Figure 720 shows the cycle of a completely compostable product. The waste is either composted or recycled as substrate. It is possible that the product is also made of non-compostable materials, like for example metal clips or a polyester cover. It is important that these are easily separated from each other for recycling.

7.2.6. OTHER ACOUSTIC TYPES

Other acoustic functions than absorption are transmission shielding and reflection, where reflection can be further divided into diffuse and specular reflection. Hybrid products are also possible as rooms often need more than one acoustic function. This paper mainly goes into mycelium panels with absorption as the main function and diffusion as a possible additional function.

Panels that provide pure diffusion are often used in music studios and conference halls. The material the panels are made of needs to be hard, so mycelium is not a logical choice, even with compression and heat treatment. Only when a balance of absorption and diffusion is needed in one panel mycelium might become an option again.



FIGURE 721 ACOUSTIC DIFFUSOR BY RPG

Another common type are hard panels used for specular reflection, for example in concert halls and auditoria. Here the sound needs to be projected across the space and usually in a specific angle. Diffuse reflection is also needed in these kinds of rooms. Without much need for absorption, it does not make much sense to use mycelium here.

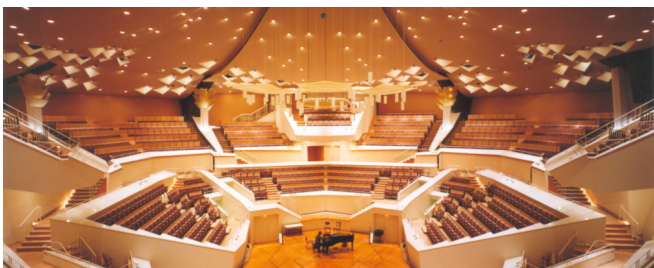


FIGURE 722 PHILHARMONIE BERLIN

Through transmission shielding is a function needed when the sound needs to be isolated and is usually done inside the walls, as for example in apartments or machine rooms. When this function is fulfilled with panels inside a room, it is often combined with absorption, like in open plan office dividers. The core of these dividers consists of a material that has a high through transmission shielding and is padded with material for absorption. As measured by Pelletier et al. (2017), high density mycelium can be used as a through-transmission shielding material. However, the costs of conventional materials used in floors and walls are already very low and will be hard to compete with. The lifespan also needs to be longer compared to acoustic panels placed in rooms. Using mycelium for panels that provide through-transmission shielding and absorption, such as in office dividers, can be done with multiple combinations. A core of mycelium is possible, although it might be better to use a stronger material to grow the porous mycelium on. Using mycelium as a core would also need a separate growth step, as it needs to be treated first. A wooden core with mycelium grown on it seems the best option, see



FIGURE 723 OFFICE DIVIDERS BY BEJOT

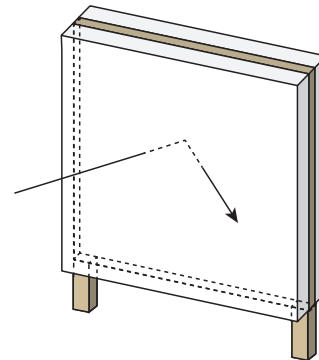


FIGURE 724 DIVIDER OF MYCELIUM GROWN ON A WOODEN PANEL

7.2.7. SHAPE

Designing with mycelium composites gives you a lot of freedom. Compared to regular materials and production methods, a mycelium panel can take a lot of different shapes, sizes and textures by only using a single material. Although it is also possible to grow it in-situ and in tailored shapes, this paper is focussed on standardised panels. The following factors were found to have the biggest limiting effect on the shape of mycelium acoustic panels: maximising the surface area for absorption, a good diffusion or at least no convex surfaces, no thin or sharp edges, being able to release the panel from the growth-shape and a maximum growable thickness.

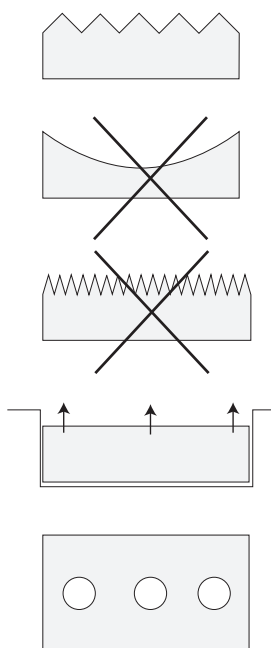


FIGURE 725 EFFECT ON SHAPE: MAXIMUM SURFACE AREA, NOT CONVEX, FRAGILE, DEMOULDING, THICKNESS

To improve the absorption of a porous absorber the surface

area can be increased, for example with a sawtooth cross-section or in two directions with an 'egg-carton' shape. A balance must be found between a maximum surface area and the sturdiness of the surface details. At a certain point the improvement in absorption per added surface area declines because the available volume behind it is limited, so it is advised to maximise the surface area sparingly. In addition, with a larger surface area, the maximum thickness increases when the volume does not change. Usually this is not a problem, unless the panels need to be very compact. With a porous material, the main acoustic function is absorption. Diffusion can be an added benefit when the surface already reflects a part of the incoming sound. With an optimal porosity and openness of the surface this is probably not the case. However, in the impedance tests mycelium did not have an absorption of 1, so changing the shape to get a more diffuse reflection is possible, although maybe to a limited extent. When a stronger panel is preferred the reflection can also increase and diffusion can become relevant again. Finally, the exact effect of a panel on the reflected sound field is best calculated or measured, although in general it is achieved with a wide mix of subdivided surfaces in different orientations or depths. Large convex shapes must also be avoided. Thin or sharp edges are possible for as long as the mycelium is strong enough. The mycelium grown for acoustic panels is probably relatively fragile. Greatly increasing the surface area or using large extruding details for other reasons can make parts too fragile. In a similar way complex shapes and thin parts will make the panel harder to release from the growth shape compared to a flat panel. The flexibility and material of the growth shape are also important, as mentioned in the beginning of this chapter. In addition to this the growth shape also needs to be tapered. The last factor that has an effect on mycelium panels is the thickness. The growth is affected by the refresh rate of the air, which is a lot higher at the surface of the shape. But more importantly, drying the mycelium panel will be really difficult or either gives problems with warping or tearing. This should not be a problem for regular acoustic panels, but when making bigger shapes this problem can be solved by making air-holes.



FIGURE 726 LARGE BLOCK WITH AIR HOLES, GROWN BY ECOVATIVE

7.3. CONCLUSION

The impedance tests do not provide a reason to focus on improving the material properties during the design phase, but rather on a proper application of mycelium.

The main issue is fragility. Therefore, it is best to keep the panels as a whole, so no drilling or cutting. The top layer then also keeps the moisture out.

The possibilities are large when looking at shapes and styles, although it is still too fragile for thin or sharp edges. As a typical showcase it makes sense to show the natural aspect of it in the final design, although a clean look is also possible. It can be a circular product, but also using non-compostable materials makes recycling more difficult.

There are different scenarios when looking at the possible applications and material uncertainties. The lifespan is probably limited. This makes mycelium products less flexible in application than conventional materials. It is best to match the design with use types with a specific duration.

There is a need to know how good mycelium attaches itself to other materials. Both for other parts of the panel, but also for releasing it from the mould.

Other acoustic types, transmission and reflection, are less suited for this mycelium type. Compressing and heat treating would be an option when not needing absorption. Diffusion can be an additional effect. When the material reflects a part of the sound, the shape can be designed to create a diffuse sound field.

8. MYCELIUM ACOUSTIC PANEL

For this thesis a regular panel was designed because of time restrictions. The initial idea was to also make a prototype to try out different textures to be able to play with contrast, the bonding strength to wood and what shapes and sizes are possible to grow and release from the growth shape. The chapter starts with the reasoning behind choosing for the emphasis on an application in office buildings. As this was related to the problems in open-offices, but also to the demand for more information on how to apply this in building construction.

First the standard panel is described and its production steps and installation are explained. Then multiple different design ideas are explored in text and with visual impressions of the products in use.

8.1. FOCUS: OPEN-PLAN OFFICES

For this graduation project an acoustic building product was chosen to be designed in testing out this new material. This mycelium design should not be a one-off, but a marketable product for the building construction industry. Krown and Fungalogic came with questions of how to use mycelium in this sector. Ecovative and Mogu already have mycelium acoustic panels for sale. The emphasis in this thesis will be on products that can be sold as a complete system and directly applied in spaces with acoustic problems. Although it might also be possible to use mycelium as a bulk material or market semi-finished products. Mass production means that, in order to lower the price it has now compared to regular products, the amount of labour and production steps need to be kept to a minimum. Although still popular because of greater communication, open-plan offices often present auditory problems. (Brennan, Chugh, & Kline, 2002; KRO-NCRV, 2020) The product will therefore be designed with offices as the main area of application. Open-plan offices can be mainly improved with absorption. Diffusion is of lesser importance but can play a larger role when panels are used in conference rooms. Wall panels and ceiling tiles are the most common product typologies for indoor sound absorption. Most of the applied products are cheap and simple panels for in suspended ceilings. The wall panels are less common but can be more expressive. Margins on ceiling tiles are much lower, currently making it more difficult to replace existing products with mycelium alternatives. This thesis will concentrate on designing a wall panel, but most requirements are the same as for ceiling tiles. The acoustic tests are also relevant for both applications.

8.2. STANDARD PANEL

The design consists of a simple panel with a backplate and leaves the mycelium exposed, see Figure 81. Although the material might be more fragile compared to regular products, the upside is that the mycelium is now fully visible, showcasing the novel building material. The backplate gives some extra stiffness, although this is mainly relevant when in transport or when handled during installation. The main upside is that it provides for a durable connection to the wall while maintaining a porous material for acoustic absorption. The open backside lets sound through, so that when mounted with a distance to the wall the backplate does not reflect sound. In this way the sound is reflected by the wall or ceiling instead of being absorbed there, which improves the absorption at lower frequencies.

The dimensions of the standard panel are 60 by 60 by 4 cm³. The edges of the mycelium are rounded so that it can be easily released from the growth shape. The laser-cut thin wooden backplate is completely recyclable and even compostable. Applying an eco-friendly fire proofing coating could improve the fire-safety, but it is not known how much this influences the compostability.



FIGURE 81 STANDARD MYCELIUM PANEL

8.2.1. PRODUCTION

The growth shape can be made by using a vacuum forming machine. This can be done by using transparent polystyrene sheets to be able to see the panels during growth. After the first growth phase, the substrate particles with mycelium are inserted in the growth shape and the backplate is put on top of it. After this the top of the growth shape is clamped on top. The top has air holes and two extrusions that make sure the two holes for inserting screws are not filled with mycelium. When drying the panel, the backplate can delaminate when this is done too fast because of differences in shrinkage. The growth shape can be cleaned and then re-used for making the next panel.

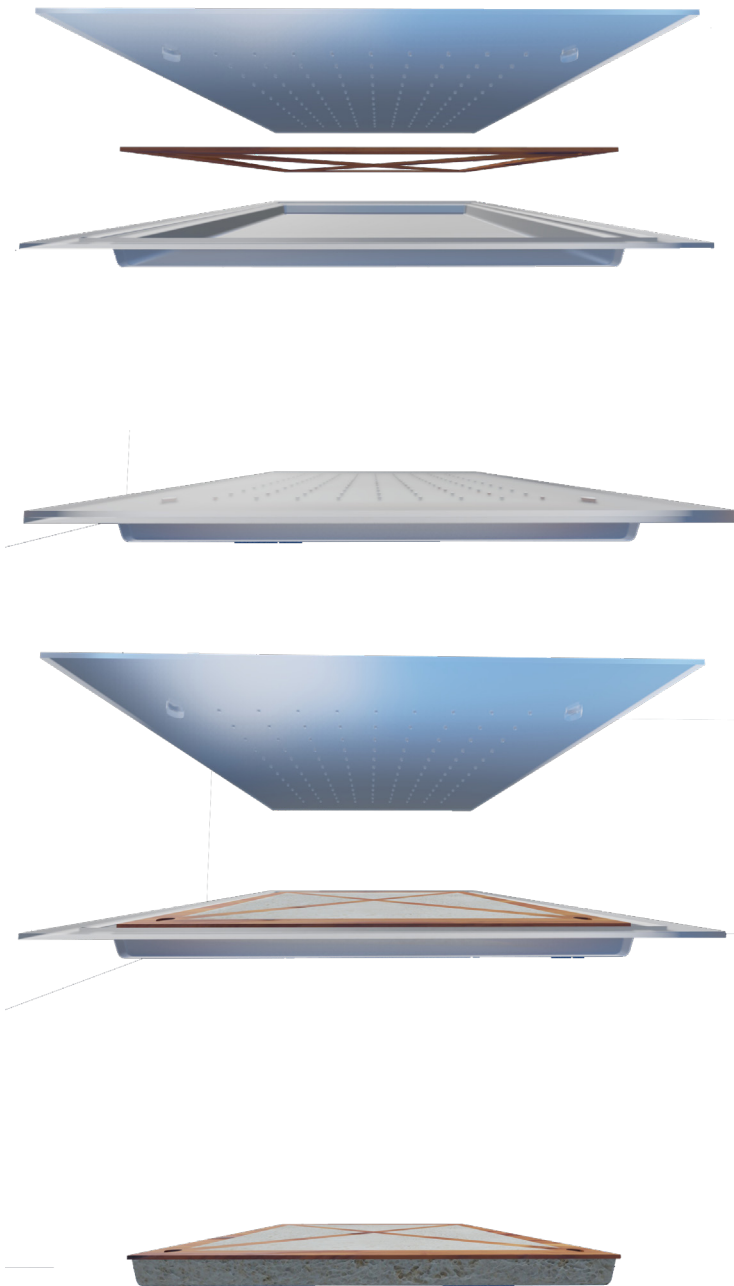


FIGURE 82 TOP AND BOTTOM OF GROWTH SHAPE WITH BACKPLATE: BEFORE GROWTH, DURING GROWTH, AFTER GROWTH AND AFTER DEMOULDING

8.2.2. INSTALLATION

The panel can be hung on the wall individually or together in a row. A single panel is hung on the wall with on two screws at the top. The panel can be hung onto them lightly or tightly clicked onto them.

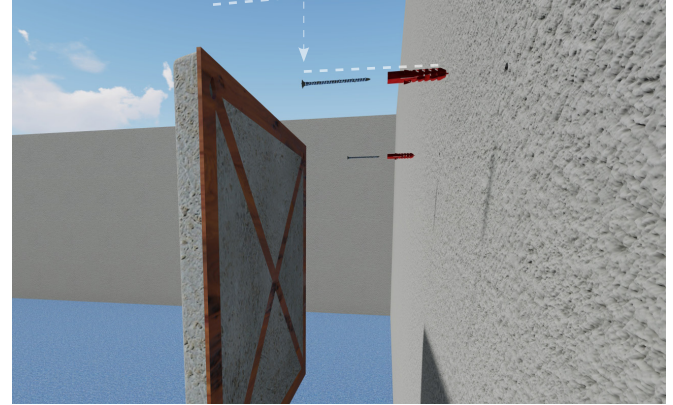


FIGURE 83 INSTALLING A SINGLE PANEL WITH 2 SEPARATE SCREWS

A row of panels can also be connected by installing a rail first. Spacing the drill holes is then not necessary and installation can be done in a shorter time. The panels can then be hung onto it in a similar manner as the single panels connect to the screws.

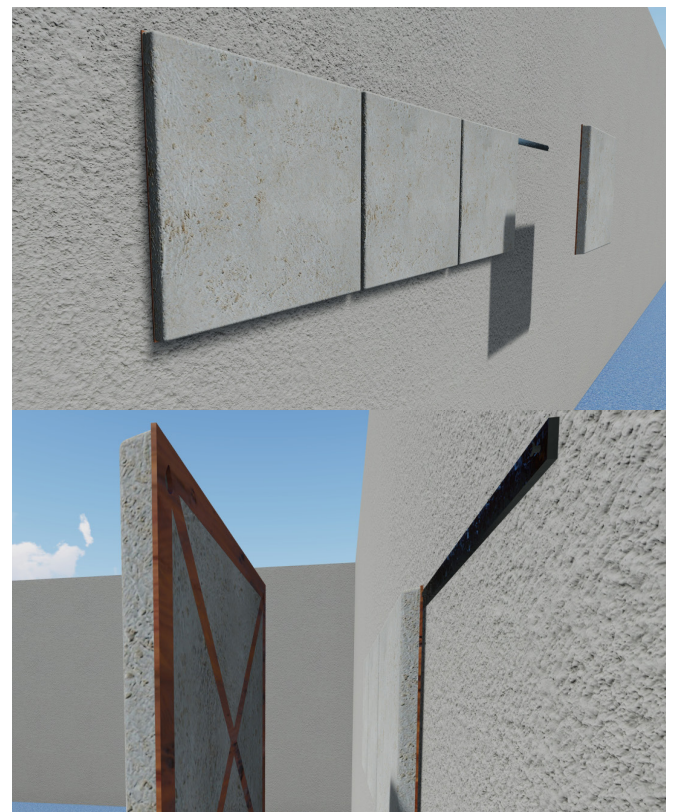


FIGURE 84 INSTALLING A ROW OF EVENLY SPACED PANELS WITH A RAIL

8.3. OTHER DESIGNS

The standard panel can be used to make different configurations. An important thing is that a spacer can hang the panel with a distance from the wall, similar to connecting it with two screws, but here an additional connection point is needed at the bottom. It is also possible to use different substrates or use colouring to get different types of panel and make a more alternating or collage-like installation.

The main use for the regular panels is to reduce reverberation and improve intelligibility. It is also possible to use mycelium to reduce noise inside a room. This can for example be done by a divider. This can be made with a wooden panel as the core with mycelium grown on both sides. Dividers can be placed around printers or coffee-machines, but also in between desks.

Ceiling tiles from mycelium are an option too. Although the lifespan is somewhat shorter and therefore more suitable for products that are replaced or moved anyway during refurbishments or relocations. The ceiling is a good method of installation when users are more prone to touching or bumping into the walls.

Diffusers of mycelium or even an absorption/diffusion combination are possible when using mycelium with a higher density. These can reduce echo and improve intelligibility. They can be applied in for example a conference room.

A playful solution for protecting the mycelium is placing it in between slats. When walking past it, the mycelium is gradually revealed. The slats also reflect sound with a large angle of incidence into the mycelium, making it suitable for different types of applications such as a long hallways or opposite to coffee corners or printers.



FIGURE 85 THE REGULAR PANEL: SINGLE PANEL AND PANELS WITH DISTANCERS FOR BROAD-BAND ABSORPTION



FIGURE 86 MYCELIUM ON BOTH SIDES OF A WOODEN DIVIDER



FIGURE 87 CEILING TILES MADE OF MYCELIUM

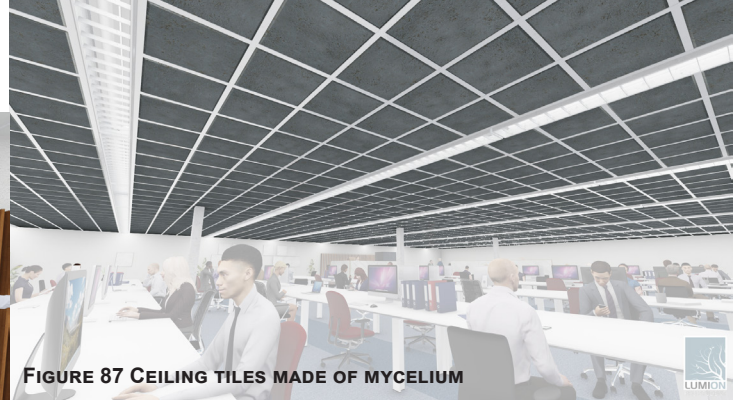


FIGURE 88 DIFFUSING PANELS WITH A DENSER TYPE OF MYCELIUM



FIGURE 89 MYCELIUM IN BETWEEN WOODEN SLATS ALONG A WALL

9. REVERBERATION ROOM TESTS

9.1. METHOD

Measurements in a reverberation chamber are different from impedance tube tests. In a reverberation chamber there is a diffuse sound field, where the sound incidence in an impedance tube is only perpendicular to the sample surface. This, together with the larger scale, results in measurements that are more alike to what can be seen in real-world situations. The downside to this is that it is difficult to keep the conditions exactly the same. Therefore, norms are important to be able to compare and replicate measurements. The European norm followed in this thesis is “*Acoustics - Measurement of sound absorption in a reverberation room (ISO 354:2003)*”. (Nederlands Normalisatie-instituut, 2003) Also relevant for the correction of absorption by the air in the reverberation chamber is “*Acoustics - Attenuation of sound during propagation outdoors - part 1: Calculation of the absorption of sound by the atmosphere (ISO 9613-1:1993)*”. (Nederlands Normalisatie-instituut, 1993)

The absorption coefficient of the panels (α_s) is calculated by measuring and comparing the reverberation times in the room, with and without the panels. The formula used is written below. The calculation steps are explained in more detail in chapter 9.4. The area of the panels (S) and volume of the reverberation room (V) are constant. For both situations the reverberation time (T_n), temperature, relative humidity and ambient atmospheric pressure have to be measured. The last three values are used to calculate the propagation speed of sound in air (c_n) and a coefficient to account for the sound absorption of air (m_n).

$$\alpha_s = A_T / S$$

$$A_T = A_2 - A_1$$

$$= 55.3V \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_2 - m_1)$$

For the reverberation chamber tests of this thesis around 4 m² of mycelium panels are grown, instead of the 12 m² minimum stated in the norm, which required too much material. The growth shapes were open at the top, so they have a rough surface on top and a smooth surface at the bottom. To improve the absorption of low frequencies, which seemed relevant when looking at the impedance tube results, panels can be hung in a distance from the wall or ceiling. A common mounting configuration for ceiling tiles is with a distance of 400 mm. (Adams, 2016) When using an E-mount, at least E200, E300 or E400 has to be used. Other distances can be tested in addition. The panels are tested for both sides and with and without the E400 mounting. The tests are done in the reverberation chamber of the TU Delft.



FIGURE 91 REVERBERATION CHAMBER, WITH DIFFUSERS, MICROPHONE AND OMNIDIRECTIONAL LOUDSPEAKER, AT THE FACULTY OF APPLIED SCIENCES, TU DELFT

9.2. GROWING THE PANELS

The panels for the reverberation chamber tests were grown by the method described in chapter 2.2. The substrate mix of straw and hemp was the same, but this time the fungal strain used was *Trametes versicolor*, because it showed improved growth and resulted in a sturdier panel compared to *Pleurotus ostreatus*.

The pasteurisation of the substrate initially was too short. After the first growth phase in the bags, the substrate showed some dark spots with clear transitions to areas where the fungus did manage to grow, see Figure 93. After the growth phase in the growth shapes, a large part of the substrate appeared to be contaminated. Because this was not specific for any bag or panel, the batch was probably not pasteurised properly, causing bacteria and fungi already present in the straw and hemp to be active in the growth phase.



FIGURE 92 MIXING STRAW AND HEMP AND PUTTING THEM IN SEALED BAGS



FIGURE 93 FILLING THE GROWTH SHAPES AFTER PASTEURISATION WITH ALREADY VISIBLE COLOUR DIFFERENCES



FIGURE 94 40 x 40 CM² PANELS WITH AND WITHOUT CONTAMINATION

After increasing the pasteurisation time in the second try, the *Trametes* was able to grow unhindered, also resulting in a more even spread and denser growth. Instead of growing panels of 400 by 400 by 40 mm³ this time two containers of 2150 by 1000 by 40 mm³ were filled to make up for the same area surface area of mycelium. After drying, the panels shrunk to a size of 2125 mm by 972 mm and 2128 mm by 965 mm.



FIGURE 95 MYCELIUM AFTER THE GROWTH PHASE IN BAGS, SECOND TRY



FIGURE 96 THE TWO WOODEN CONTAINERS AT THE START OF THE FIRST GROWTH PHASE



FIGURE 97 THE TWO LARGE PANELS BEING AIR-DRIED

The E400-mount was constructed according to ISO 354. This required it to have sides with a surface density of at least 20 kg/m². This was realised by using a double layer of 18 mm MDF wood. The panels were laid on top of two metal rebar grids, which were supported at the sides and by an MDF beam.



FIGURE 98 CONSTRUCTION OF THE E400 MOUNT AT FUNGALOGIC AND ASSEMBLY IN THE REVERBERATION CHAMBER (MIDDLE PHOTO BY M. BILOW)

9.3. PERFORMING THE MEASUREMENTS

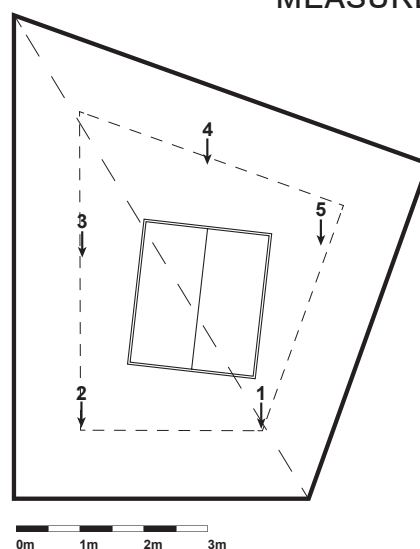


FIGURE 99 FLOORPLAN REVERBERATION CHAMBER WITH MICROPHONE/SOURCE POSITIONS AND MYCELIUM PANELS

The measurements were done in the reverberation chamber of the TU Delft at the faculty of Applied Sciences. The volume is 200 m³, which is also the volume recommended by ISO 354. The enclosing concrete surfaces of the room are constructed so that none are parallel to each other, which can be seen in Figure 99. The room has a pointed ceiling. The microphone and loudspeaker were placed at one of the 5 locations, which are picked to be at a distance of at least 1m to the wall and 2m to each other, which is demanded by the norm. The microphone was placed at a height of 1,05m and the loudspeaker at 1,3m. After every measurement the relative humidity and temperature are also measured, which can change during the day and because of people moving around the equipment. The ambient atmospheric pressure level was measured once.



FIGURE 910 MEASUREMENT SETUP: LAPTOP CONNECTED THROUGH A HOLE IN THE WALL TO A MICROPHONE AND A LOUDSPEAKER



FIGURE 911 OMNIDIRECTIONAL LOUDSPEAKER



FIGURE 912 DIGITAL TEMPERATURE AND HUMIDITY METER AND ANALOGUE BAROMETER

In total a number of 84 measurements were performed. This is a combination of 7 panel configurations and the required 12 microphone plus loudspeaker positions. The panels were placed with the rough side or smooth side facing up and in the E400 mount or on the ground. The mountings were also measured without the panels and the room was measured without anything in it. A few things also had to be taken into account when putting the panels into place. No sides of the panels are parallel to the walls. Gaps were filled with pieces of MDF and duct tape. These gaps mainly occurred because of the slightly different panel sizes and an uneven part in the concrete floor.



FIGURE 914 GAPS BETWEEN THE MOUNTING AND THE FLOOR OR THE PANELS ARE FILLED WITH MDF OR COVERED WITH DUCT TAPE



FIGURE 913 ALL SITUATIONS MEASURED, EXCEPT FOR THE GROUND EDGES

9.4. PROCESSING THE DATA

As mentioned at the start of this chapter, in order to get the absorption coefficient, the reverberation time, temperature, relative humidity and ambient atmospheric pressure had to be measured. According to ISO 354 and ISO 9613-1 the following calculations were made.

According to ISO 354 (Nederlands Normalisatie-instituut, 2003), the sound absorption coefficient of a plane absorber is

$$\alpha_s = A_T/S$$

The equivalent sound absorption area of a reverberation room, in m², is

$$A = \frac{55.3V}{cT} - 4Vm$$

The equivalent sound absorption area of the test specimen, in m², is equal to the difference between the room with (A_2) and without (A_1) the test specimen.

Here the power attenuation coefficient m , in m⁻¹, is used to correct for the sound absorption of air and is mainly relevant at high frequencies.

$$m = \frac{\alpha}{10 \log_{10}(e)}$$

For temperatures between 15 °C and 30 °C, the propagation speed of sound in air, in m/s, is

$$c = 331 + 0.6t$$

where

- c is the propagation speed of sound in air in m/s;
- S is the area covered by the test specimen in m²;
- V is the volume of the reverberation room in m³;
- T is the reverberation time in s;
- t is the temperature in °C;
- a is the attenuation coefficient in dB/m, see below.

According to ISO 9613-1 (Nederlands Normalisatie-instituut, 1993), this attenuation coefficient, in dB/m, is

$$\alpha = 8.686f^2 \left(\left(1.84 \times 10^{-11} \left(\frac{p_a}{p_r} \right)^{-1} \left(\frac{T}{T_0} \right)^{\frac{1}{2}} \right) + \left(\frac{T}{T_0} \right)^{-\frac{5}{2}} \times \left(0.01275e^{-\frac{2239.1}{T}} \left(f_{ro} + \left(\frac{f^2}{f_{ro}} \right) \right)^{-1} + 0.1068e^{-\frac{3352.0}{T}} \left(f_{rN} + \left(\frac{f^2}{f_{rN}} \right) \right)^{-1} \right) \right)$$

The two relaxation frequencies, in Hz, for oxygen (f_{ro}) and nitrogen (f_{rN}) are

$$f_{ro} = \frac{p_a}{p_r} (24 + 4.04 \times 10^4 h \frac{0.02+h}{0.391+h})$$

$$f_{rN} = \frac{p_a}{p_r} \left(\frac{T}{T_0} \right)^{-\frac{1}{2}} \times \left(9 + 280he^{-4.170 \left(\left(\frac{T}{T_0} \right)^{-\frac{1}{3}} - 1 \right)} \right)$$

From Sengpiel (2020), the molar concentration of water vapour in % is

$$h = h_r \left(\left(\frac{p_{sat}}{p_r} \right) / \left(\frac{p_a}{p_r} \right) \right) = h_r \left(\frac{p_{sat}}{p_a} \right)$$

and the saturation vapour pressure, in kPa, is

$$p_{sat} = p_r \times 10^{(-6.8346 \times \left(\frac{T_{01}}{T} \right)^{1.261} + 4.6151)}$$

where

- f is the frequency of the sound in Hz;
- p_a is the ambient atmospheric pressure in kPa;
- T is the ambient atmospheric temperature in K;
- p_r is the reference ambient atmospheric pressure: 101.325 kPa;
- T_0 is the reference air temperature in K: 293.15 K;
- T_{01} is the triple-point isotherm temperature in K: 273.16 K.

The reverberation time is defined as the time it takes for the sound pressure level to decrease 60 dB after the sound production has stopped. The direct microphone feed is shown on the left in Figure 915. This impulse response is converted into an echogram, shown on the right. From this the decrease in sound pressure level is calculated and shown in the Schroedercurve in red. Here it can be seen that the measurement stops before the sound pressure

level has decreased 60 dB, from around -20 to -80 dB. A way to solve this problem is to extrapolate the slope of the curve at an earlier moment to get to the actual reverberation time (T_{60}). The processed measurements by Matlab gave the values for $T_{5 \rightarrow 25}$, $T_{5 \rightarrow 35}$ and $T_{5 \rightarrow 45}$, where the first one was the most reliable and was finally used in the formulas above. The results are plotted in a graph and can be seen in the next subchapter.

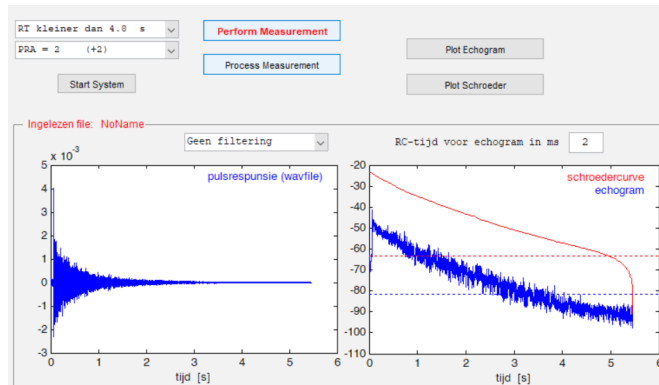


FIGURE 915 USER INTERFACE OF THE MATLAB BASED SOFTWARE MATLAUS

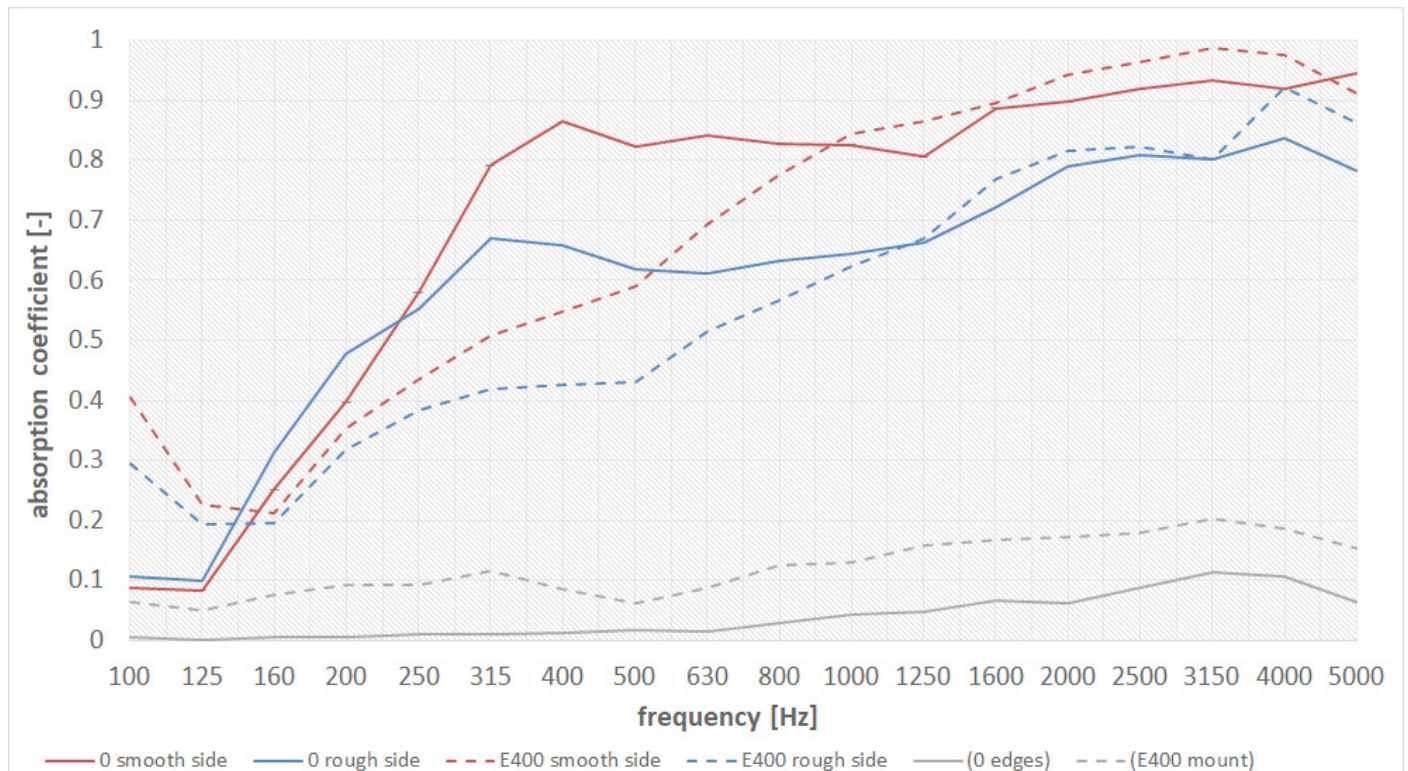


FIGURE 917 ABSORPTION SPECTRUM FOR BOTH SIDES OF THE MYCELIUM PANELS AND WITH OR WITHOUT THE 40 CM DISTANCE TO THE FLOOR

9.5. RESULTS AND DISCUSSION

The results are plotted with the continuous lines for the panels measured on the floor and the red lines for the panels with the smooth side up. The dotted and blue lines are for the E400 mounting and the panels with the rough side up respectively. The measurements without any panels, grey lines, are done to have an indication of what the effects of the mountings are and are not to be subtracted from the coloured curves.

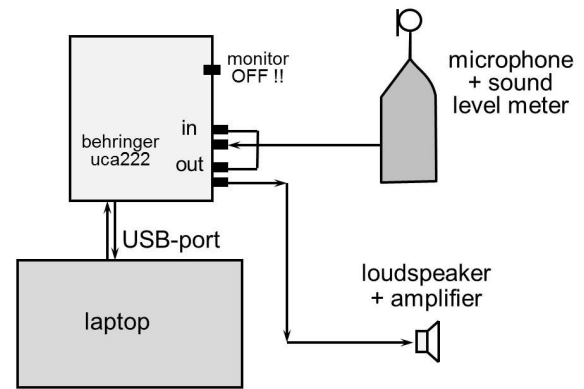


FIGURE 916 BEHRINGER UCA222 INTERFACE IN BETWEEN LAPTOP, MICROPHONE AND LOUDSPEAKER (MANUAL MATLAUS)

In general, the results are very good. When looking at the best performer, the smooth side without a distance to the floor, the absorption values are all above 0.8 from the one-third-octave-band 315 Hz and up. For a porous absorber the absorption in the lower frequencies is also good. However, the panels in the E400 mounting perform worse, where it would be expected to perform better or at least shift the curve towards the lower frequencies. It was not possible to explain this result and why this is mainly in the range of 200 to 800 Hz. The addition of the MDF mounting should even have a positive effect on the absorption, because of panel absorption, which could explain the difference between the grey curves. On the other hand, there is a possible explanation for

the difference between the rough and smooth sides of the panels. Mycelium can continue to grow on top of the panel at the open side of the growth container. This could form an extra layer, which might block the porous absorption in the higher frequencies and improve the membrane absorption in the lower frequencies. The first effect can be seen in both the panels on the floor and the raised panels. The second effect can be seen in the panels on the floor, where the continuous blue curve is above the continuous red curve in the lower frequencies.

Comparing the results to those of the impedance tube tests shows the sinewave-like curve has disappeared, as could already be seen in a comparison by Pfretzschner and M^a. Rodriguez (1999) described in chapter 4. They tested the exact same material in both the impedance tube and a reverberation chamber. Most of the impedance tests on mycelium were done with mycelium grown with *Pleurotus ostreatus* with only a single sample with *Trametes versicolor*. Furthermore, the test in the small tube for high frequencies also had a lesser sample quality. This makes a good comparison difficult when only looking at the tests with *Trametes*. However, the impedance samples with *Pleurotus* have a similar curve, which is more reliable because it is an average of multiple samples. More tests need to be done in the impedance tube with *Trametes* to see what the exact relation is between both type of tests and how to influence the material. However, the results show it mycelium materials can perform well as an acoustic absorber. When looking at the best performer tested for this thesis, the Ecophon Akusto, mycelium performs even better.

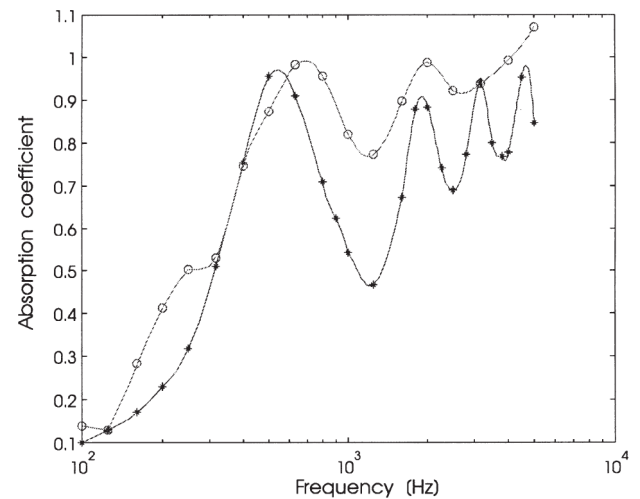


FIGURE 918 RUBBER SAMPLES OF 9 CM MEASURED IN IMPEDANCE TUBE (*) AND REVERBERATION CHAMBER (o) (PFRETZSCHNER & M^a. RODRIGUEZ, 1999)

In conclusion, although it is unknown why the E400 mounting did not increase the absorption or shift it to the lower frequencies, the results are very good compared to other porous acoustic absorbers. The results also show that the impedance tube tests were not too optimistic and that the acoustic absorption in reality is or can be even higher.

Acoustic Absorption

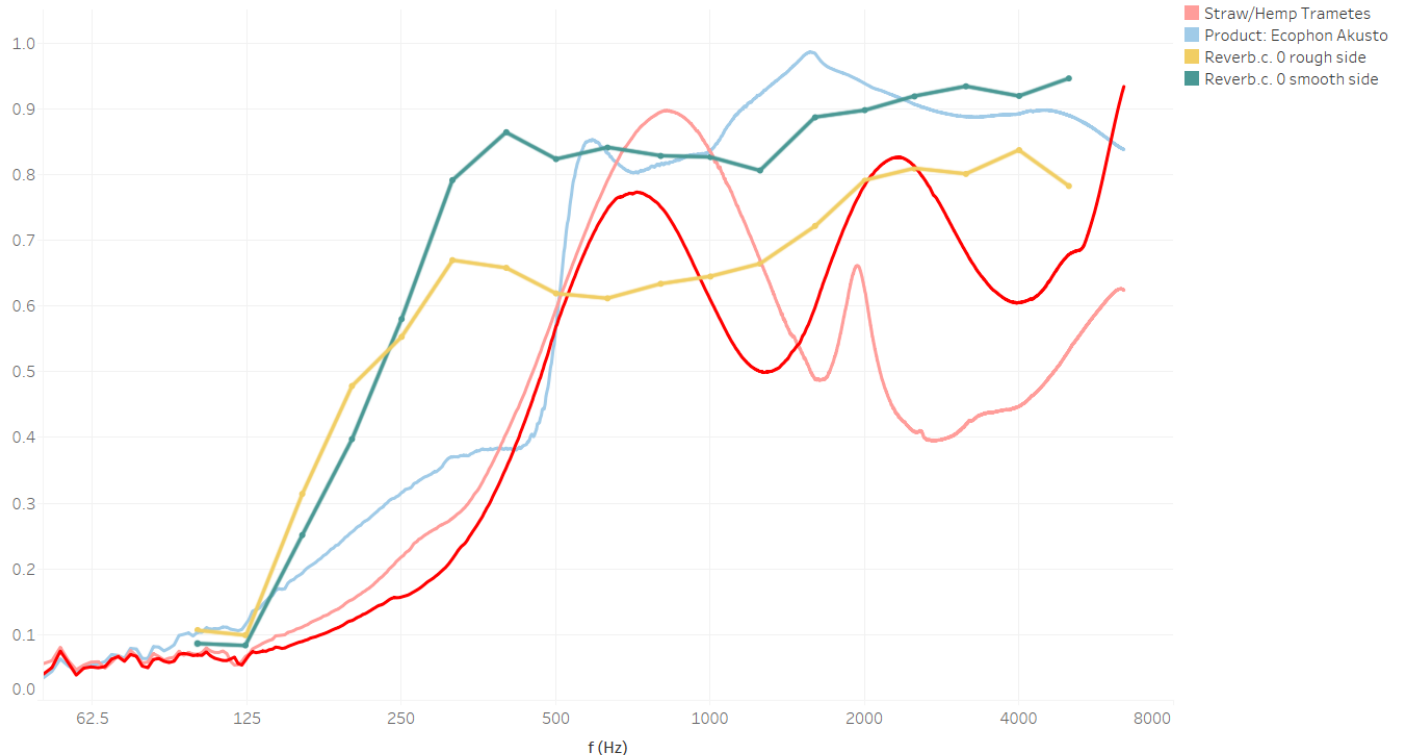


FIGURE 919 ACOUSTIC ABSORPTION COEFFICIENT OF THREE IMPEDANCE TUBE SAMPLES PLUS TWO REVERBERATION CHAMBER RESULTS

10. COMPARISON WITH OTHER ACOUSTIC PRODUCTS

10.1. SELECTION OF REPRESENTATIVE PRODUCTS

In order to see if the designed mycelium panel will perform well, it will be compared with other acoustic building products that can be applied to improve the sound absorption of a room. The products are selected to have a range of different materials. Most conventional products are made from petroleum-based materials or are hard to recycle. Some bio-based products are on the market, of which a few also use mycelium. The products contain simple panels, but also panels with more expressive shapes and colours. Most available acoustic products come in different types: wall panels, ceiling tiles and as separate insulation sheets. Most sold products on the market are ceiling tiles, although some can also be used as a wall panel when framed. The bio-based materials are often limited to just separate acoustic insulation sheets. Alternatives are different absorber types, such as Helmholtz panels, or different types of application, such as acoustic plaster.

The comparison made here was limited to wall panels: two mycelium panels by Ecovative and Mogu, two other bio-based panels by Baux and Métisse and two conventional products by Kvadrat and Ecophon.

10.2. PERFORMANCE CRITERIA

The panels are compared by their shapes and appearances and by properties for acoustic performance, safety, health, durability, sustainability and price.

For each product a representative image is shown, but some products are available in different colours and shapes. For every panel the dimensions of a single panel from the image is listed. All existing products except the Ecovative Sinewave are available in different versions or sizes. Bio-based products are at the moment not available in different colours. It is possible to add bio-based colouring or use a different substrate like cacao for the mycelium.

The acoustic performances are compared by looking at a measured spectrum, see Figure 108. Although not every product was tested in the same mounting or with the same method. For this thesis some products were measured in the impedance tube. The Ecovative Sinewave and Ecophon Akusto graphs show the results from the impedance tube measurements. The own mycelium panel is measured at the TU Delft, the rest is data from the manufacturer. There was no available data for the Kvadrat Clouds. Most panels have an average acoustic performance or better. Only the Ecovative Sinewave does not absorb much



FIGURE 101 MYCELIUM PANELS GROWN FOR THIS GRADUATION PROJECT



FIGURE 102 ECOVATIVE SINEWAVE MYCELIUM PANEL



FIGURE 103 MYCELIUM PANELS BY MOGU: WAVE, KITE, FIELDS AND PLAIN



FIGURE 104 BAUX PULP, BIO-BASED AND LASER PERFORATED PANELS

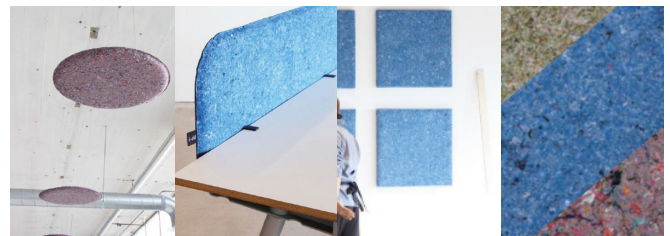


FIGURE 105 MÉTISSE ACOUSTIC C-SERIES: ISLAND, DIVIDER, PANEL, FELT COLOURS



FIGURE 106 KVADRAT CLOUDS MODULAR PANELS

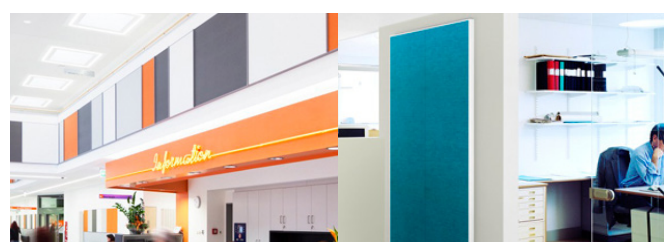
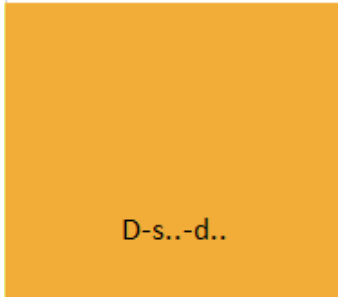
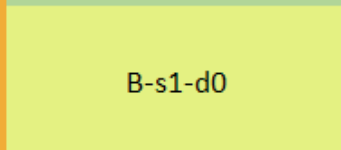
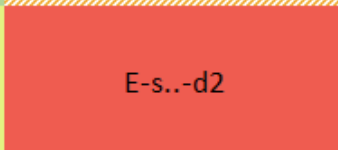
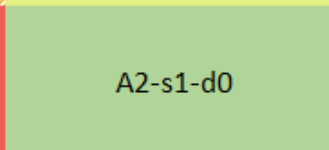
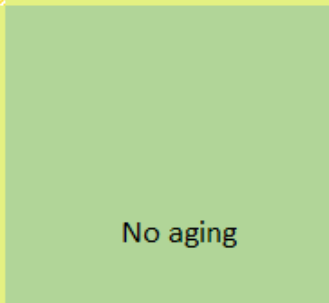
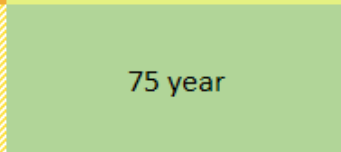
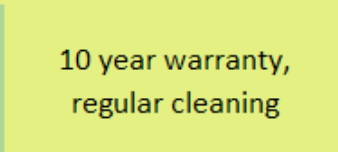
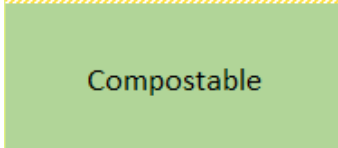
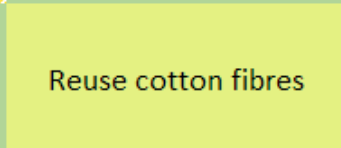
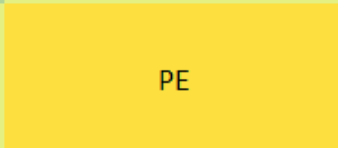
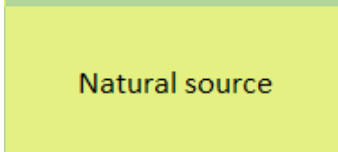
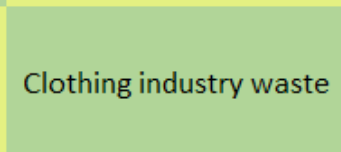
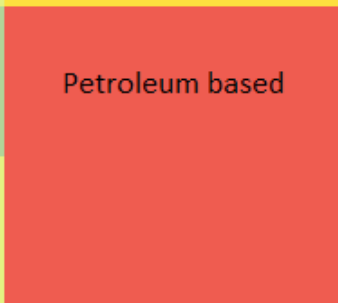
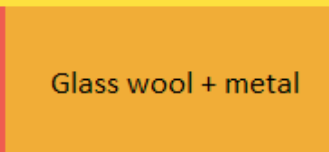
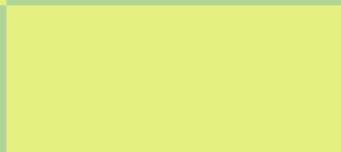
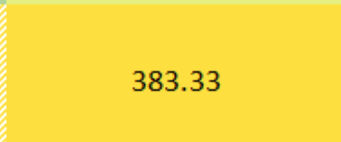
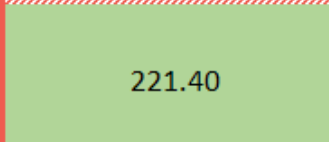


FIGURE 107 ECOPHON AKUSTO PANELS

TABLE 3 OVERVIEW OF ACOUSTIC PANELS WITH THEIR PERFORMANCE CRITERIA

Performance:

Best Good Average Bad Worst	(Estimate) (Estimate) (Estimate) (Estimate) (Estimate)		Mycelium panel	Ecovative Sinewave	Mogu Kite
					
		Dimensions (mm ³)	400x400x40	407x407x51	Kite: 500x500x40-75
		Absorption spectrum (See Figure ..)			
		Fire safety (class/smoke/droplets)	D--> B?	US class A - flame spread 20, smoke emmision 50	B-s1-d0
		Hygiene (mold/micro organisms)		mold resistant	
		Indoor air quality (VOC emmision µg/m2h)	010		
		Impact resistance			
		Water resistance			
		Aging			
		Recyclability	Compostable	Compostable	Compostable
		Source material	Agricultural waste	Agricultural waste	Clothing industry waste
		Biodegradability			
		Price (€/m2)		211.29	

Baux Pulp	Métisse C Panel	Kvadrat Clouds	Ecophon Akusto
			
500x1000x20	600x600x45	8 mm thick, 1 panel= 0.09m2	2700x1200x40
			
			
			
			
			
			
			
			
			
			

sound. The Métisse panels perform the best according to the graph, although these are measured with a distance to the wall. In reality it is a bit lower, but still probably very good.

Fire safety ratings are from A to F, s1 to s3 and d0 to d2. A-s1-d0 is the highest possible rating, where the material is incombustible and forms no smoke or droplets. All products were tested according to EN 1350, except for the Ecovative Sinewave, which got the highest rating according to US standards. The designed mycelium panel already has a rating of D but is estimated to perform in the same way as the Mogu and Ecovative ones, where chitin adds to the fire proofing of the material (M. Jones et al., 2018). Mogu used an eco-friendly coating to improve the fire proofing performance. All products, except for the Baux Pulp and polyethylene Kvadrat Clouds, perform well in terms of fire safety.

For hygiene, only Ecovative did tests on mold forming. The other mycelium panels are estimated to perform the same and the rest of the inert materials should not give much problems regarding hygiene.

In the emissions of volatile organic compounds, the natural materials perform better than the conventional materials, having almost no emissions.

Impact resistance tests are sometimes done by manufacturers, but as most foams are flexible, this should not be much of a problem. Only for the more fragile mycelium panels this can be an issue in some situations. The Kvadrat Clouds are held together by rubber bands, which make the total somewhat fragile, but the panels themselves are flexible.

Water resistance can be given as a resistance to humidity or as a water contact angle. The mycelium panels perform the best in the last category, because of the hydrophobic properties of the surface. Completely inert materials, such as the Ecophon Akusto perform better in the first category. For Baux Pulp it was advised to “avoid humid and dirty environments”.

Aging depends on temperature, humidity and UV. Most products have test reports for those or a warranty. The mycelium panels and Baux Pulp are estimated to not last as long as the conventional products.

The first criteria regarding sustainability is recyclability, being able to easily extract raw materials or otherwise close the circular lifecycle. The mycelium panels and the Baux panels are fully compostable, although cotton from the clothing industry might take more time. Polyethylene is in principle recyclable, but it is difficult to extract the materials and keep the quality the same every time it is recycled. The Ecophon panel has glass wool, which can be recycled for 70%. The metal frame is in principle recyclable.

The source material for all panels is graded from upcycled material to natural sources to non-renewable sources. All

products except for the Kvadrat Clouds and partially the Ecophon Akusto do not need non-renewable sources.

Biodegradability of the panel is possible with the non-conventional products. The Kvadrat Clouds are certainly not biodegradable and the Ecophon Akusto possibly is not too because of the binder in the glass wool. Biodegrading the industrial waste cotton might take longer too.

The price was calculated for 1 square meter of panel. The Kvadrat Clouds stand out, although it is more of a high-end product. The price of mycelium panels was estimated to be the same as the Ecovative Sinewave.

10.3. CONCLUSION

The own mycelium panel is the best performer in acoustics, although the most fragile and with unknown aging. Ecophon Akusto is more impact proof and lasts long, but it is not very sustainable. Métisse and possibly Mogu are good sustainable candidates when a higher lifespan is needed.

Like the other products, the mycelium panel passes the minimum requirements regarding safety and health. Durability is the biggest concern with a relatively low impact resistance and unknown aging. The price is similar to conventional products, although this is when lifespan has not been taken into account. A lower price will make it an interesting alternative when the long lifespan is not needed.

Mycelium composites are still being developed. This means the material properties can be improved and more products can be developed to have a greater variety. In general, it is difficult to compare the to be developed bio-based products with conventional products that have existed for a long time.

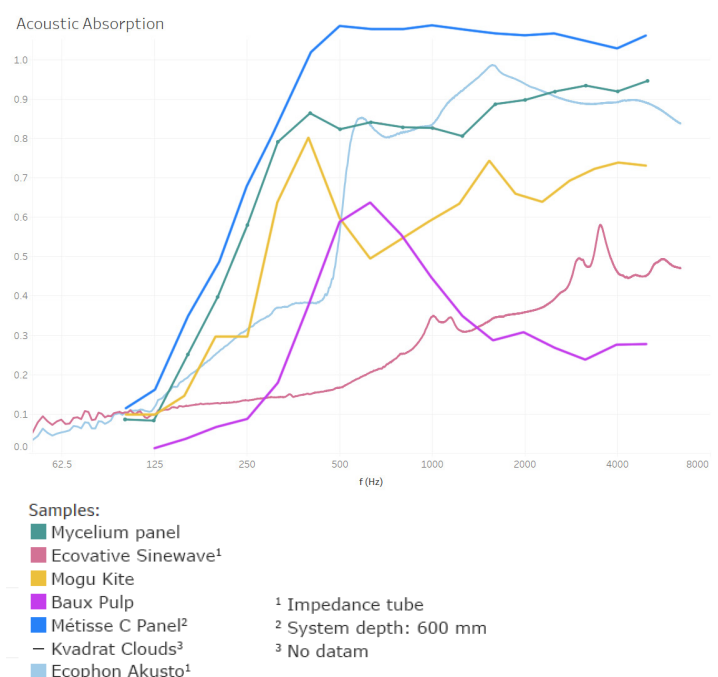


FIGURE 108 ACOUSTIC ABSORPTION SPECTRA OF THE PRODUCTS IN THE COMPARISON

11. CONCLUSIONS

As a novel building material, the sources for information on material properties are limited. Examples of marketed products are scarce and most designs found were conceptual or one-offs. This meant that it was necessary to find out answers to questions yourself. Different from existing materials in design and engineering was the biological background of the composite. Having a different production method also had an effect on the design phase.

The main research question was: “How can the new material, mycelium grown on biological (waste) substrates, be produced, designed with and perform in an (acoustic) building product?”

The first step to answering this question was a literature study on its material properties, from which thermal insulation and acoustic absorption both came out as logic applications. Other properties, such as mechanical and fire safety, would still be relevant when applying mycelium as an acoustic absorber. Predicting how mycelium as a porous absorber would behave was difficult, because mycelium composites are inhomogeneous and anisotropic. This was an important reason to perform acoustic tests on the material.

The first tests in the impedance tube showed promising results, although it was not sure how this related to the performance in use. The tests also indicated that increasing density could probably improve the absorption. Other properties, such as surface effects, thickness, growth time and fungal strain, did not seem to affect the absorption that much. The tests in the reverberation chamber showed even better results and showed that the sinewave-like curve indeed disappeared. This insight is useful when testing new materials, not having to do full scale tests again. The lower results for the E400 could not be explained however, although without the mount the absorption values are already very good. Microscope imaging clearly showed the difference between the regular hemp/straw material, the same material with an extra growth phase and the Ecovative material.

Insight in designing with mycelium relied on performing the production steps yourself. It was crucial to experience the effect of the biological growth process and the possibilities and the limits of using growth shapes. Fragility, connections and limitations in shape have to be taken into account, while fully taking advantage of the opportunities regarding its narrative, sustainability and the possibilities in freeform shapes. With limited time a simple design was made to show what a mycelium acoustic product can look like, although this is just an example of what is possible, as illustrated by the

impressions of other designs.

The comparison with existing products showed that it performs well in terms of acoustics, safety, health and sustainability. Durability can be an issue, if it is too fragile, or uncertain, when in a longer use phase the aging becomes relevant. Further development could be useful to make it perform well on all fields. The price per square meters is comparable with existing products. With improved durability and when regulations for sustainability increase it can become an even better alternative.

12. RECOMMENDATIONS

The first recommendations are for future research on material properties or development of new mycelium materials. The tests showed mycelium can be a good acoustic absorber, but when tinkering with mycelium composites, in reality all properties are related. Finding a good balance between acoustic, mechanical and other properties is important. After switching from *Pleurotus ostreatus* to *Trametes versicolor*, the samples seemed to have improved in growth quality and in rigidity. The *Pleurotus* samples also seemed slightly more brittle. Finding the right fungal strain seems to matter a lot. How mycelium will age is still unknown. The effect of UV, temperature and moisture in the long term will have to be researched. There is a lot of value of interdisciplinary research. Coming from building technology/architecture, I had questions the acoustic experts, biologists/mycologists and material scientists also could not answer. Figuring out these questions together seems very important.

The E400 mounting in the reverberation chamber shows lower values, where it was expected to improve absorption. Finding an explanation could be useful. Testing the material with 12m² instead of 4m² can also be done to see if the results change. The impedance tube tests still had some samples which could be measured. Especially the *Trametes* samples are relevant for comparing it with the reverberation chamber results.

When designing with mycelium, hands on experience is essential. Some things have to be experienced to understand how they work. It is a good way to find out possible issues during production.

For making a real circular product, it was difficult to find data on available waste streams. Most information was about biomass suitable for use in energy plants. Having a platform where relevant information can be found would be useful for a transition to a real circular economy. Using waste streams also means being dependent on what is available. For example, when making the impedance

tube samples, it was not easy to get specific particle sizes or shapes. It is better to see what the properties of the waste stream materials are.

13. REFLECTION

In general, I found working with this new material very interesting. Especially combining parts of biology, acoustics and material science. I learned that, while planning and sticking to it is not my forte, it can be improved with a lot of structuring. This helped with combining the different topics of testing, designing and making. Choosing what parts of the plan have priority was sometimes very important. Especially when tests or growth processes did not go as planned.

Process

How is your graduation topic positioned in the studios?

Developing a biodegradable acoustic panel which uses agricultural waste streams, encompasses the focus of the Climate Design & Sustainability chair on closing material cycles and acoustic user comfort. Making and designing acoustic panels by growing mycelium composites, encompasses the focus of the Building Product Innovation chair on materialisation and fabrication of building products.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The approach of literature research, acoustic testing, designing panels and making panels did give answers to the research questions. Although the broad approach made it difficult to combine all three, where the acoustic testing took the most time. This resulted in the design part not always getting enough attention.

If applicable: what is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

Not an official method of the chair, but the Building Product Innovation chair has a tradition of a more hands on approach to designing, with prototyping and 1:1 models in for example the Bucky Lab course.

How are research and design related?

The acoustic tests are not directly related to the design process. The tests more or less give a go/no-go for using the material in a design. However, making the samples and panels resulted in knowledge on production methods, more or less serving as prototypes.

Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

Not really ethical issues, but working together with companies required an awareness of them not necessarily

having goals in line with the educational goals of the TU Delft. Krown and Fungalogue wanted to help, but also wanted to know what they would gain from it. This required me to think ahead, to be able to make it plausible that the end result would probably be also useful for them.

Societal impact

To what extent are the results applicable in practice?

To the full extent, although for a mass-produced panel, development and some research is still necessary.

To what extent has the projected innovation been achieved?

Finding out if it is possible to use this material has been successful, both in finding good acoustic absorption values and in a general indication of applying it in an acoustic panel. The last step of making a more complete prototype was however not successful.

Does the project contribute to sustainable development?

Yes, as the panel as such does not yet exist on the market. It shows better absorption values are possible and gives more insight in growing sustainable panels like this. In total only a few compostable products like this exist that re-use waste materials.

What is the impact of your project on sustainability (people, planet, profit/prosperity)?

Large, mycelium panels are a typical product of a circular economy, combining the upcycling of waste materials with a marketable product.

What is the socio-cultural and ethical impact?

It connects the participants in a future local circular economy. A local farmer might have a large volume of waste fibres, providing a cheap material for a nearby office refurbishment. As the open-plan office is a popular concept for supposedly improving productivity, it is not very good for the people who work there. Acoustic absorption can be used as a quick fix or be used in more hybrid office plans.

What is the relation between the project and the wider social context?

A mycelium acoustic panel mainly has effect on a small scale, not so much a wide social context. Although for sustainable production on a large scale a change of mindset needs to happen too.

How does the project affect architecture / the built environment?

Sound absorbing panels can improve the working environment of for example offices. But the built environment also needs to use products in a smart way if circular products become mainstream. The lifespan might be less than the old products, requiring a new approach with regard to maintenance.

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APPENDIX: DOCUMENTATION IMPEDANCE TUBE SAMPLES

(See next pages for photographs)

	L/S	#	Weight (g)	Density (kg/m³)	Thickness		Remarks	Surface	Growth	L/S	#	Weight (g)	Density (kg/m³)	Thickness		Remarks	Surface	Growth
					Lower	Upper								Lower	Upper			
Hemp	L		23		78	37	38											
Straw	L		6	51	30		Very bad, falling apart	Missing	Very bad	S						Very bad, Completely fell apart		
Woodcurls	L		16	136	30		Bad	No surface	Bad	S						Very bad, Completely fell apart	Some surface growth	
Cattail	L		30	153	20	30	Very good, rigid	rough, cl	Good, dense	S			22	25				
Cacao	L		52	214	28	34	Very good, rigid	Flat, close	Good, dense	S	1		30					
Growth time: short	L		24	87	30	40	Good	Few small	Average	S						Bad, partially fell	Good	
Growth time: long	L		16	58	33	37	Good	Smooth	Average	S						Bad, partially fell	Good	
Thickness: 2cm	L		10	77	14	19	Good	Few small	Average	S						Bad, partially fell	Good	
Thickness: 3cm	L		12	59	24	28	Average	Open part	Average	S								
Thickness: 4 cm	L	1	20	81	29	34	Average	Few small	Average	S	1					Bad, partially fell	Bad, after handling	
	L	2	25	83	37	40	Good	Few small	Good	S	2		36			Good, broke in 2	Good	
	L	3	29	97	36	40	Good	Open part	Good	S	3		36			Average	Partially	Good
Thickness: 5cm	L		26	70	46	48	Good	Open part	Average	S								
Thickness: 6cm	L		27	64	52	56	Average, although	partially	Average	S								
Thickness: 7cm	L		33	66	65	62	Average, although	Half open	Average	S								
Density: Extra Light	L		16	55	34	40	Average	Partially	Average	S								
Density: Light	L		19	60	38	42	Average	Half open	Average	S								
Density: Compressed	L		32	109	35	40	Good	Smooth, Average/Good	S							Bad, partially fell	Good	
Density: Extra Compressed	L		29	91	37	44	Average, although	Open part	Average	S						Bad, partially fell	Partially	Average
Layered	L		20	63	39	42	Good	Smooth	Good	S						Bad, partially fell	Good	
Surface: Extra growth	L		18	62	36	38	Good	Good, ve	Good	S						Bad, partially fell	Good	
Surface: Squares	L		25	72	43	45	Good	Good, sh	Good	S						Bad, partially fell	Average	
Surface: Rectangles	L		25	72	43	45	Good	Good, sh	Good	S						Bad, partially fell	Bad,	Good
Surface: Triangles	L		18	48	45	50	Good	Good, sh	Good	S						Average, partially	Average, Good	
Surface: Grooves	L		12	36	40	45	Good	Partially	Good	S								
Surface: Bubbles	L		19	59	38	44	Good	Smooth	Good	S						Average, partially	Good	Average
Straw/Hemp	L	1	17	67	30	35	Good	Smooth, Good, full	S	1		30				Good, broke in 2	Good	
	L	2	23	90	30	35	Good	Smooth, Good, full	S	2		30				Good	partially	Good
	L	3	22	84	32	35	Good	Smooth, Good, full	S	3		25				Good	Good, cl	Good, loose
	L	4	20	76	30	37	Good	Smooth, Good, full	S									
Flax	L	1	22	119	20	27	Good	Smooth, Good, full	S	1		30				Good	Good	Good
		2	22	100	27	29	Good	Smooth, Good, full	S	2		30				Good, broke in 2	Good	Good
		3	24	102	24	36	Good	Smooth, Good, full	S	3		32				Good	Good	Good
		4	23	101	27	31	Good	Smooth, Good, full	S	4		20				Good	Good	Good
Wood/Hemp (badly grown)	L	1	20	82	25	37	Good	Good, fe	Good, bit more	S	1		30			Good	Good	Good
	L	2	18	69	32	34	Good	Good, fe	Good, bit more	S	2		30			Good, broke in 2	Good	Good
	L	3	16	65	30	33	Good	Good, fe	Good, bit more loose	S								
Coarse straw/Hemp (badly grown)	L	1	19	63	37	40	Good	No surface	Good, bit more	S	1					Bad, broke in 2/p	Few holes, no surface	
	L	2	17	65	30	37	Good	No surface	Good, bit more	S	2					Good, broke in 2/	No surface growth	
	L	3	15	63	28	33	Good	No surface	Good, bit more loose	S								
Straw/Hemp 2	L		22	100	26	30	Good	Smooth, Good, full	S							Good, partially fe	Good	
Straw/Hemp 3 (badly grown)	L		10	54	20	27	Good	Few hole	Average, bit	S						Bad, partially fell	Average	
Hempwool mat	L	1	8	146	6	8	Good	No surface	Good	S	1		4	6	Good	Little sur	Good	
	L	2	9	229	4	6	Good	No surface	Good	S	2		5	6	Good	No surface	Good	
	L	3	5	116	5	6	Good	No surface	Good	S	3		8		Good	No surface	Good	
Straw/Hemp Trametes	L	1	24	73	40	44	Good	Partially	Good	S						Average, partially	Good	
	L	2	22	69	40	41	Good	Not muc	Good	S								
Waste straw block 2cm	L	1	17	111	19	20	Little growth	Little sur	Almost no ir	S	1		21			Little growth	Little sur	Almost no in
	L	2	16	123	13	20	Little growth	Little sur	Almost no ir	S	2		14	21		Little growth	Little sur	Almost no in
Waste straw block 4cm	L	1	31	105	35	40	Little growth	Little sur	Almost no ir	S	1		38			Little growth	Little sur	Almost no in
	L	2	30	102	37	38	Little growth	Little sur	Almost no ir	S	2					Average, partially	fell apart	
Ecovative	L	1	39	134	36	38	Good	Closed, s	Very good, v	S	1		36			Good	Closed, s	Very good, v
	L	2	42	141	36	40	Good	Closed, s	Very good, v	S	2		36			Good	Closed, s	Very good, v
Ecovative Perforated	L	1	39	126	37	42	Good	Closed, s	Very good, v	S	1		36			Good	Closed, s	Very good, v
	L	2	35	114	37	41	Good	Closed, s	Very good, v	S	2		36	42		Good	Closed, s	Very good, v
GreenSulate Open	L		14	178	9	11	Good	Closed, s	Good	S								
GreenSulate Closed								Open										
Product: Knauf Ecose	L		5	21	60		See sheet			S			60					
Product: Isovlas	L	1	10	46	55		See sheet			S	1		55					
	L	2	13	26	60	65				S	2		65					
Product: Troldekt	L		110	800	35		Fibre: Extreme fine 0,5 mm, white (from S			S			35					
Product: Ecophon Akusto	L		20	127	40		See sheet			S			40			Internal splits after cutting, probably no		
Product: Heraklith	L		124	1263	25		See sheet, decorative A2, nature tone, s			S			25					
Product: Rockfon	L		14	178	20		See sheet			S			20					
Product: Ecophon Focus	L		17	216	20		See sheet			S			20					
Not measured:																		
Most interesting:							Mycelium:										Existing products:	
Métisse Cotton (4,5 cm PMA?)							Fungalocic: well grown wood										Troldekt Fine	
Métisse Cotton (5,0 cm PM?)							Woodchips										Troldekt Ultrafine	
Everuse							Houtkrul en hennep										Heraklith with rockwool	
multiple Trametes samples							Stro beetje houtkrul										Mogu	
							Thickness: 1cm										AMF Thermatex Acoustic	
																	AMF Thermatex Silence	



Hemp1.JPG



Straw1.JPG



Woodcurls1.JPG



Cattail1.JPG



Cacao1.JPG



Growth time short 1.JPG



Growth time long 1.JPG



Thickness 2cm 1.JPG



Thickness 3cm 1.JPG



Thickness 4 cm 1.JPG



Thickness 4 cm 2.JPG



Thickness 4 cm 3.JPG



Thickness 5cm 1.JPG



Thickness 6cm 1.JPG



Thickness 7cm 1.JPG



Density Extra Light 1.JPG



Density Light 1.JPG



Density Compressed1.JPG



Density Extra Compressed 1.JPG



Layered1.JPG



Surface Extra growth 1.JPG



Surface Squares 1.JPG



Surface Rectangles 1.JPG



Surface Triangles 1.JPG



Surface Grooves 1.JPG



Surface Bubbles 1.JPG



StrawHemp1.JPG



StrawHemp2.JPG



StrawHemp3.JPG



StrawHemp4.JPG



Flax1.JPG



Flax2.JPG



Flax3.JPG



Flax4.JPG



Coarse strawHemp badly grown1.JPG



Coarse strawHemp badly grown2.JPG



Coarse strawHemp badly grown3.JPG



WoodHemp badly grown 1.JPG



WoodHemp badly grown 2.JPG



WoodHemp badly grown 3.JPG



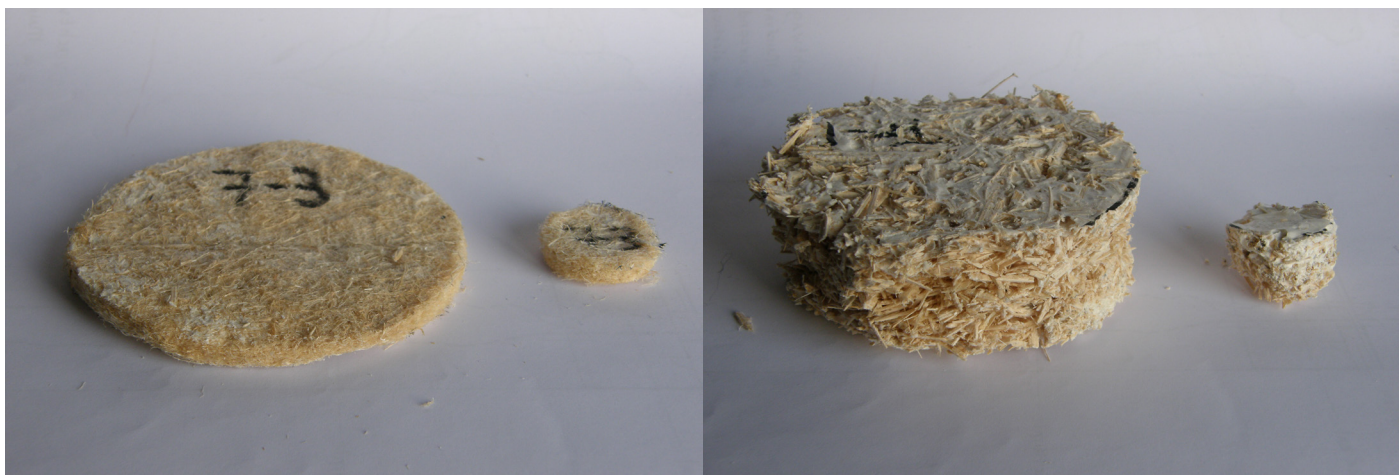
StrawHemp 2 1.JPG

StrawHemp 3 badly grown1.JPG



Hempwool mat 1.JPG

Hempwool mat 2.JPG



Hempwool mat 3.JPG

StrawHemp Trametes 1.JPG



StrawHemp Trametes 2.JPG

Waste straw block 2cm 1.JPG



Waste straw block 2cm 2.JPG



Waste straw block 4cm 1.JPG



Waste straw block 4cm 2.JPG



Ecovative1.JPG



Ecovative2.JPG



Ecovative Perforated 1.JPG



Ecovative Perforated 2.JPG



GreenSulate Open 1.JPG



GreenSulate Closed 1.JPG



Product Ecophon Akusto 1.JPG



Product Ecophon Focus 1.JPG



Product Heraklith 1.JPG



Product Isovlas1.JPG



Product Isovlas2.JPG



Product Knauf Ecosse 1.JPG



Product Rockfon1.JPG



Product Troldekt1.JPG