AN EXPLORATION ON CELLULOSE AND WEED RESIDUES

FROM BIOMASS TO MYCELIUM COMPOSITE

RAPPORT

2019
17

FROM BIOMASS TO MYCELIUM COMPOSITE
AN EXPLORATION ON CELLULOSE AND WEED RESIDUES

RAPPORT
2019
17

ISBN 978.90.5773.851.7

stowa@stowa.nl www.stowa.nl
TEL 033 460 32 00
Stationsplein 89 3818 LE Amersfoort
POSTBUS 2180 3800 CD AMERSFOORT

Publicaties van de STOWA kunt u bestellen op www.stowa.nl

COLOFON

UITGAVE Stichting Toegepast Onderzoek Waterbeheer
Postbus 2180
3800 CD Amersfoort

PROJECTUITVOERING
Davine Blauwhoff, Centre of Expertise Biobased Economy, momenteel werkzaam bij The New Makers
Ilaria La Bianca, Centre of Expertise Biobased Economy

BEGELEIDINGSCOMMISSIE
Alice Fermont, Waternet
Chris Reijken, Waternet
Tim Pelsma, Waternet
Wouter Maatje, Staatsbosbeheer
Yede van der Kooy, Wetterskip Fryslân
Robert Kras, Waterschap Aa en Maas
Alexandra Deeke, Waterschap de Dommel
Cora Uijterlinde, STOWA

FOTO'S OMSLAG Centre of Expertise Biobased Economy
DRUK Kruyt Grafisch Adviesbureau
STOWA STOWA 2019-17
ISBN 978.90.5773.851.7

PREFACE

OPPORTUNITIES FOR THE PRODUCTION OF MYCELIUM COMPOSITES, BUT FURTHER DEVELOPMENT IS NEEDED

This research shows the potential of cellulose and certain types of roadside weeds to produce mycelium composites. The mechanical properties of the mycelium composite can be recognized as valuable, although more research and development is needed.

In the Netherlands, the Water Authorities want to contribute to the transition to a more circular and sustainable economy. Within the waste water treatment plants, they regard sewage as a source for energy and raw materials. One of focus areas looks at the potential of cellulose as a valuable resource. This project has explored the possibilities of using cellulose from sewage and roadside weeds to produce mycelium composites. The natural fibers are bound by the growth of the fungi. Mycelium composites can be used as sustainable building materials and / or insulation material.

Several recipes in combination with different types of fungi have been tested. The materials produced from the processing experiment have been studied for their material properties (compressive strength, bending strength and thermal insulation).

Joost Buntsma
Managing director STOWA

SUMMARY

In the Netherlands the waterboards want to contribute to the societal transition towards a more circular and sustainable environment. Within their waste water treatment facilities they regard wastewater as a source for energy and new raw materials. One of the focus areas researches the potential of cellulose as a valuable material. This project investigates the possibility of using cellulose from wastewater treatment facilities and roadside weeds to produce mycelium composites, completely natural materials that are bound by the growth of fungi.

The research is constituted by two phases: material development and material characterization. The material development is divided into two parts focusing on mycelium growth and processing techniques. For the mycelium growth substrates as raw cellulose (directly collected from the waste water treatment facility RWZI Aarle Rixel), reeds and hay are tested. The fungal species Ganoderma Lucidum and Pleurotus Ostreatus are used to produce the composites. The mentioned fibres are used as pure substrate and mixed with hemp, known for its growing capacities.

In addition to the ingredients, a small experiment has been executed with the processed cellulose (Recell®) in which different processing techniques have been applied after the growth of the material. The four variations are 1) non pressed, 2) cold pressed, 3) cold pressed + growth and 4) heat pressed. By applying these techniques the properties of the material can be altered, making them more suitable for certain product applications.

The materials from the mycelium growth have not been further tested, but the materials from the processing experiment have been studied on their material properties. For these tests the processed cellulose called Recell® from KNN Cellulose BV has been the main focus. Other fibres such as hemp, wood chips and straw are also considered as a reference materials, because of their known growing capacity. Besides the pure substrates, the Recell is also mixed with the three types of fibres to research the effect on the material properties. With these combinations of ingredients, different samples are produced to test the compressive strength, bending strength and thermal insulation of these composites.

The research on mycelium growth, showed that the reed does not grow when inoculated with either Ganoderma *lucidum* or Pleurotus *ostreatus.* Also in combination with hemp as an additional fibre no growth was present. The other two fibers, the raw cellulose and hay performed much better and showed colonization of the fungal hyphae. From both substrates, the raw cellulose grew the most dense as a pure substrate and in combination with hemp. Regarding the fungal species, Ganoderma *lucidum* performed the best.

When looking at the different processing techniques, the heat pressed samples present the highest compressive strength with a value of 0.43 MPa for the mixture of cellulose and hemp. In all compressive tests that contained a pure cellulose specimen, this material had a significant higher strength than the others. However, in comparison with the density, these samples also have the highest values. Ideally a low density and a high strength are desired.
Due to the processing techniques the mycelium composites have a large spread in their density, varying from 0.08 g/cm^3 to 0.61 g/cm^3 . This difference depends on the applied compression as the non-pressed samples have the lowest densities and the compressed samples have higher densities. From these different techniques it is however interesting to see that the samples that have been regrown after being cold pressed have slightly higher densities, possibly due to the additional growth of mycelium.
Compared to EPS (expanded polystyrene) and biofoam, defined as expanded PLA (polylactic acid), the mycelium composites perform accordingly and even higher on compressive strength: 0.1 MPa for EPS and 0.05 MPa for biofoam. However, their densities are much lower: 0.01 g/cm^3 (EPS) and 0.02 g/cm^3.

The bending strength of the produced composites shows 2.70 MPa as the highest value, by the substrate combination of cellulose and wood chips. This value can be seen as low when comparing to the 24.93 MPa of tested MDF. The density of the mentioned mycelium composite is lower than the tested MDF, however the difference in strength is more significant.
The thermal conductivity of mycelium composites is relatively low, with the lowest value of 0.05 W/Km from the pure hemp composite. This can be considered as a valid result, when comparing the mycelium to conventional foam, which presents a thermal conductivity of 0.03 W/Km. However, also in this case, the higher density of the mycelium composite decreases its value.

In conclusion, the research shows the potential of cellulose and certain types of roadside weeds to produce mycelium composites. The material mechanical properties of the mycelium foam can be recognized as valuable, even though more study needs to be performed in order to improve them and make them a biobased alternative for EPS. Regarding the mycelium board material, it would need significant improvement of strength to be applied as a structural material in comparison the MDF. With more research on heat pressing parameters and chemical reactions during this process, there is definitely potential for the mycelium to be a completely natural alternative without any adhesives.
From economic perspective these mycelium composites are not yet feasible as the conventional materials are in a very low price range. At this moment the mycelium process has not yet been industrialized and optimized. With the focus on circular economy and the need for new biobased materials, mycelium composites are interesting but need further research to achieve their potential.

THE STOWA IN BRIEF

The Foundation for Applied Water Research (in short, STOWA) is a research platform for Dutch water controllers. STOWA participants are all ground and surface water managers in rural and urban areas, managers of domestic wastewater treatment installations and dam inspectors.

The water controllers avail themselves of STOWA's facilities for the realisation of all kinds of applied technological, scientific, administrative legal and social scientific research activities that may be of communal importance. Research programmes are developed based on requirement reports generated by the institute's participants. Research suggestions proposed by third parties such as knowledge institutes and consultants, are more than welcome. After having received such suggestions STOWA then consults its participants in order to verify the need for such proposed research.

STOWA does not conduct any research itself, instead it commissions specialised bodies to do the required research. All the studies are supervised by supervisory boards composed of staff from the various participating organisations and, where necessary, experts are brought in.

The money required for research, development, information and other services is raised by the various participating parties. At the moment, this amounts to an annual budget of some 6,5 million euro.

For telephone contact number is: +31 (0)33 - 460 32 00.
The postal address is: STOWA, P.O. Box 2180, 3800 CD Amersfoort.
E-mail: stowa@stowa.nl.
Website: www.stowa.nl.

FROM BIOMASS TO MYCELIUM COMPOSITE

AN EXPLORATION ON CELLULOSE AND WEED RESIDUES

CONTENTS

PREFACE
SUMMARY
THE STOWA IN BRIEF

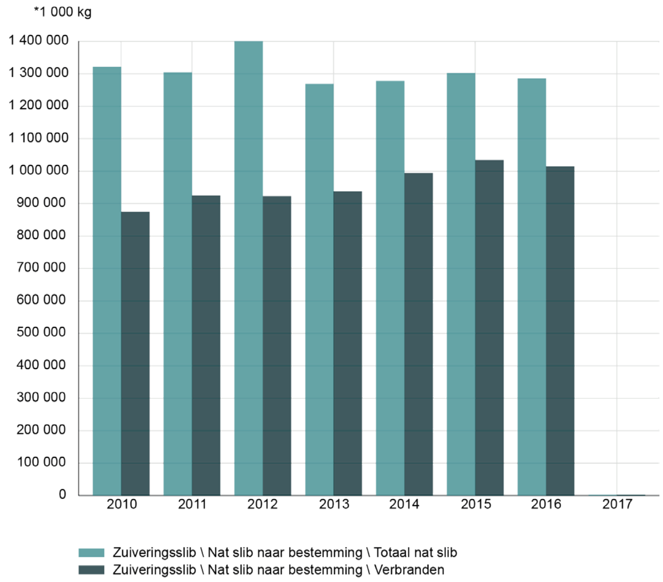
1

INTRODUCTION

1.1 GENERAL BACKGROUND

The Netherlands has 21 water boards who ensure dry feet, clean and sufficient water supply. These waterboards are responsible for the treatment of collected sewage water. Sewage water is the mixture of waste water that derives from households, companies and rainwater that flows into the sewage system. Annually they treat approximately 2 million tons of waste water (CBS statline, 2019). The treatment of waste water results in two products: clean water and sludge. Currently 79% of the "wet" sludge is incinerated (Figure 1).

FIGURE 1 **SLUDGE PRODUCTION URBAN WASTE WATER TREATMENT - NETHERLANDS (CBS STATLINE, 2019)**



In order to contribute to the wider societal transition towards a circular economy the water boards have set-up a collaborative network organization called Energy and Resources Factory (Energie- en Grondstoffenfabriek) (EFGF, 2019). "Water authorities in the Netherlands no longer regard wastewater as merely a by-product to be treated and processed, but as a valuable source of renewable energy, raw materials, and clean water (EFGF, 2019)." Intensive research is being done to recover valuable raw materials such as phosphate, polymers, Kaumera (neo-alginate), CO_2 and cellulose from waste water. For example, in the Netherlands approximately 140.000 tons of cellulose can be recovered, which can be reused by other companies as a raw material.

This project focusses on the reuse of cellulose (from the waste water treatment) and biomass from (roadside) weed residues. An innovation in the field of materials is the production of mycelium composites. These are completely natural materials composed from a natural fibre and fungal hyphae. In general, natural fibres such as cellulose, reed, hay and grass contain valuable nutrients for the growth of fungi, which could make them potential substrates for the production of mycelium composites.

With this in mind, Waterschap de Dommel initiated this research and formed a consortium with STOWA (Stichting Technisch Onderzoek Water) and the Centre of Expertise Biobased Economy (CoEBBE) to research the potential of cellulose and (roadside) weed residues for the production of mycelium composites.

Waterschap De Dommel is one of the 21 waterboards in the Netherlands and located in Boxtel in the province of Noord-Brabant. Just like the other waterboards they ensure clean, sufficient and safe water in the area. They manage the (ground) water level and treat sewage water to ensure clean water in surrounding brooks, ditches and rivers.
STOWA is the knowledge centre of the regional water boards in the Netherlands. They develop, gather, distribute and implement applied knowledge that water managers need to properly perform the tasks they face in their work. This knowledge can lie in applied technical, natural sciences, administrative, legal or social sciences.

Centre of Expertise Biobased Economy (CoEBBE) aims for an economy that runs on biomass as a raw material. They implement applied Biobased research that helps companies with their Biobased ambitions and ensure that Biobased education is given a place in all levels of education in the Netherlands. Within the research group Biobased Building, an extensive study is done on mycelium composites and their possible application for the building industry.

1.2 GOAL

The main goal of this project is to prove the technical value of residual biomass (cellulose and weed residues) for the production of mycelium composites. Within the production process there are multiple variables that have an influence on the material properties. An underlying goal is to optimize the material through a combination of these variables and parameters.

This goal is supported by three main research questions:

1. Is it possible to produce mycelium composites from cellulose and weed residues?
2. What are the material properties of the mycelium composite?
3. What is the economic value of the mycelium composite?

1.3 READING GUIDE

The following chapters describe the performed research. Chapter 2 explains the background knowledge needed to understand the concepts of mycelium composites. Chapter 3 displays the used methodology of research. Chapter 4 focuses on the material development, showing the used substrates and species of fungi, also showing the mycelium growth related to each used fibre. Chapter 5 presents the material processing, while chapter 6 shows the consequent tests on the produced materials, defined as material characterization. Chapter 7 focuses on the final conclusions of the research.

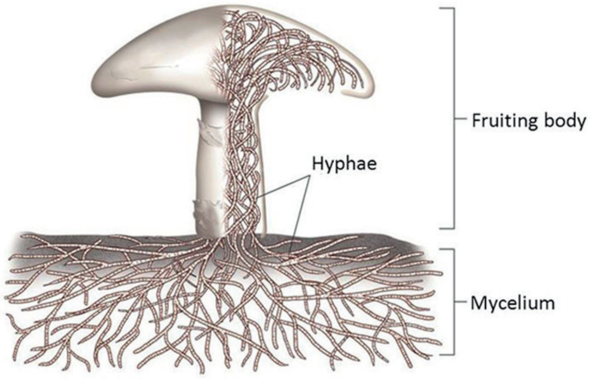
2

BACKGROUND KNOWLEDGE

2.1 MYCELIUM COMPOSITE

Mycelium is the vegetative part of fungi or "roots" of the mushroom, representing the structure which provides the necessary nutrition for fungal growth and development (Kavanagh, 2011). Mycelium is made of fibrous filaments called hyphae, which can be described as stretched/prolonged cells, mainly composed of chitin, glucans and proteins (Muhammad Haneef, 2017). Figure 2 shows the fungal composition, divided into mycelium, found underground, and the fruiting body. Hyphae growth is usually characterized by circular expansion.

FIGURE 2 FUNGAL MYCELIUM

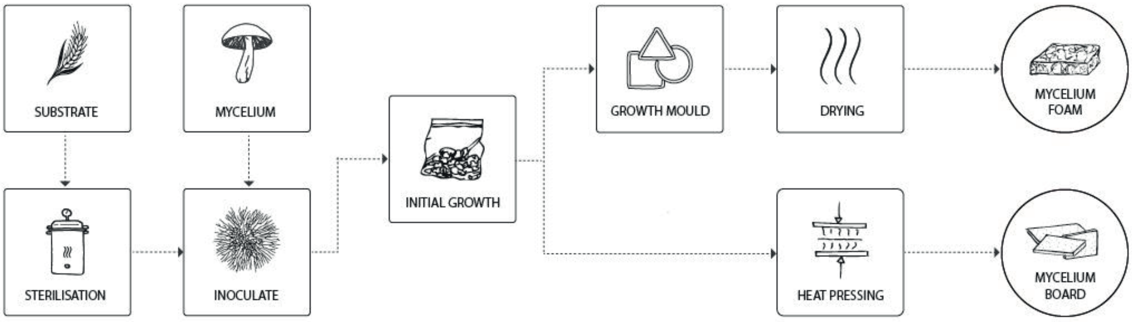


A complex enzymatic process enables fungi with a unique ability to digest highly stable molecules such as the structural polysaccharides of plants (Danai et al, 2012). The ability of fungal mycelium to digest and grow through organic materials makes mycelium feasible to produce composites. In fact it functions as natural glue holding the organic fibres or particles together and forms a natural, light weight bio-composite (Attias et.al 2017, Haneef et.al 2017).

2.2 PRODUCTION PROCESS

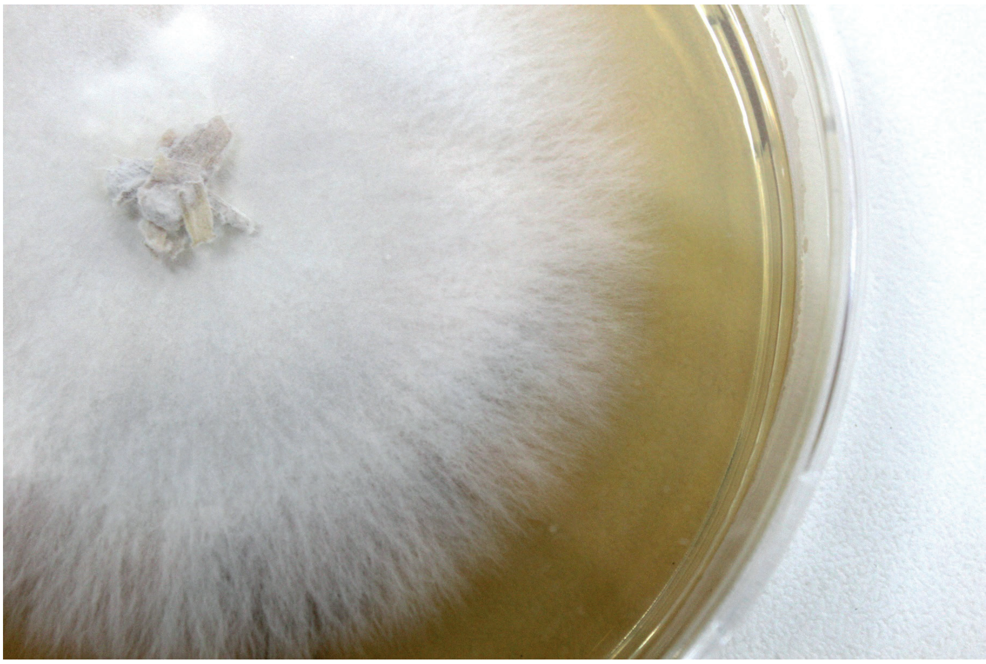
The production of mycelium composites comprises several steps. First the substrate needs to be sterilized and inoculated with fungal spawn (mycelium) to achieve the initial growth. After the initial growth (one week period), the composite is moulded into the desired shape. The composite is grown for another week period before being dried. The drying process ensures the killing of the microorganism and the end of the production process. An overview of this process is shown in Figure 3.

FIGURE 3 **MYCELIUM COMPOSITE PROCESS**



To ensure mycelial growth, certain conditions need to be followed: fungi need an ambient temperature between 25 ˚C and 30˚C (Turković, 2015) (Mustafa Nadhim Owaid, 2015) and an air humidity from 60% to 90% to grow (Charles Alan Rocco, 2010) (Tisdale, 2004). The present project used the fungal species Ganoderma *lucidum* and Pleurotus *ostreatus* (also known as oyster mushroom). These strains both belong to the white rot fungi, also defined as wood decaying fungi (Raúl Castanera, 2012) (Suldbold Jargalmaa, 2017), which indicates their capacity to hydrolyse plant components, such as lignin (José Maria Rodrigues da Luz, 2012). This characteristic makes the selected fungi optimal for the production of composites.

FIGURE 4 **CIRCULAR MYCELIAL GROWTH ON AGAR PLATE**

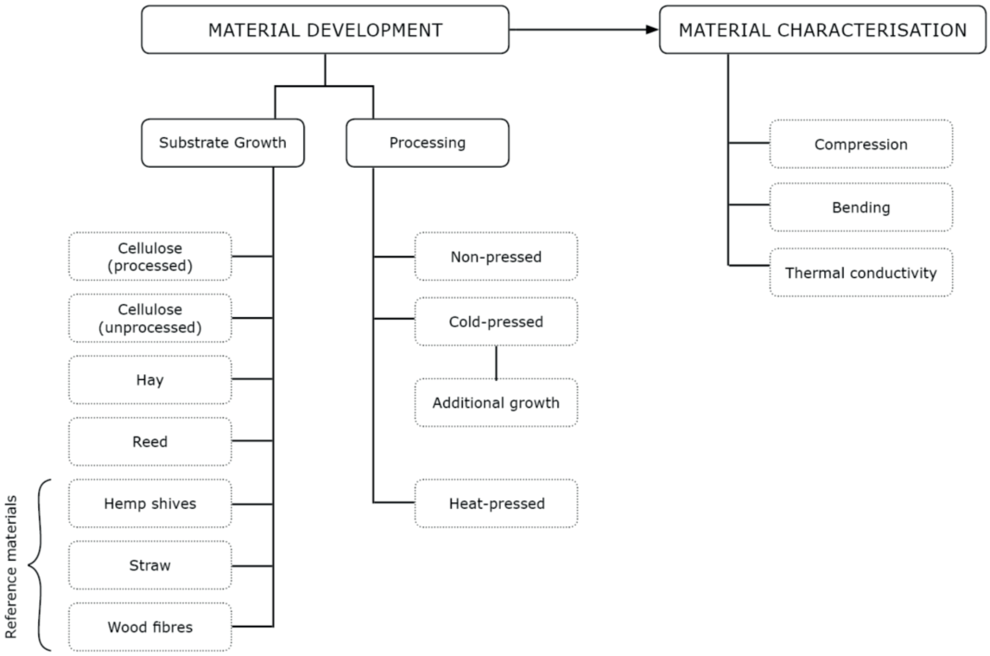


3

METHODOLOGY

The current project investigates the viability of cellulose and roadside reeds and hay for the production of mycelium composites. The research is divided into two main parts: 1) material development and 2) material characterisation. The material development focusses on the substrate growth and processing of the material. Several smaller experiments are done to define the viability of the mycelium materials. For the material characterisation three technical tests are performed to assess the material properties. Figure 5 gives an overview of the research areas that are considered.

FIGURE 5 **FLOW SCHEME RESEARCH AREAS**



As can be seen in the overview, seven different substrates are examined. The main focus lies on the upper four materials, but three fibres are added as a reference to provide proper results and conclusions. Two types of cellulose are used throughout the project. Raw cellulose can be defined as unprocessed, because it directly derives from the waste water treatment facility. No cleaning process is therefore applied apart from the sieving. The processed cellulose is a product provided by KNN Cellulose BV, called Recell®. It is processed and cleaned before reaching the laboratory facility. Both types of cellulose are thoroughly described in chapter 4.3.

For the processing three different techniques are applied with one additional procedure of extra growth to strengthen the material.

All the succeeded samples from the material development are tested on either of the three properties. These samples are tested in triplets to assure valuable results. Further details on both phases are given in the following chapters.

4

MATERIAL DEVELOPMENT

4.1 FUNGAL SPECIES

The considered types of fungi for this research are: Ganoderma lucidum (strain M 9720) and Pleurotus Ostreatus (var Spoppo), commonly known as Grey oyster, both species are used in the lab at the CoEBBE, and therefore already known in terms of growth (Figure 6). Furthermore, prior studies have proven that these are the most stable to produce mycelium composites. For the final tests just one type of fungi will be used, which is defined by its speed of growth, mycelium density and infection resilience. Both species have been initially grown with the same substrates and physical conditions (air humidity and temperature).

FIGURE 6A: GANODERMA LUCIDUM

FIGURE 6B: PLEUROTUS OSTREATUS

4.2 SUBSTRATES

As aforementioned, the study on substrate growth is centered on the growing viability of the fibres cellulose, reeds and hay as required by the project goal. Additionally, more substrates are included into the matrix, in order to compare their mycelial growth and to perform tests on mechanical properties. The added fibres include hemp shives, straw and wood chips. The latter substrates are used more frequently for the growth of mycelium composites. In general, they show good fungal colonization of the fibre and are therefore the most reliable as reference material. Due to this, these substrates are mainly used to study the material properties, only colonized by the Ganoderma species. This choice is done because of its faster growth rate, higher growth density and higher resilience to infections. The substrates that are used during this research project are shown in the Figure 7.

FIGURE 7 **OVERVIEW SUBSTRATES**

PROCESSED CELLULOSE **PROCESSED CELLULOSE** **HAY** **REED**

HEMP **STRAW** **WOOD CHIPS**

In addition to the pure substrates, several combination of fibres are made to test the effect on mycelium growth and its material properties. For example, raw cellulose, reeds and hay are combined with hemp to stimulate fungal growth due to the high lignin content. Furthermore, a combination of fibres can alter the strength of the material depending on the type of fibre and its dimensions. A smaller fibre would make the sample more brittle, while a longer fibre would spread the force over a larger surface area. Table 1 shows a summary of the used substrates in reference to the used fungi.

TABLE 1 **FIBRES OVERVIEW**

Pure fibres	**Ganoderma**	**Grey Oyster**
Raw cellulose	x	x
Reed	x	x
Hay	x	x
Processed cellulose	x	
Hemp	x	
Straw	x	
Wood chips	x	
Mixed fibres (50:50)		
Raw cellulose + hemp	x	x
Reed + hemp	x	x
Hay + hemp	x	x
Hemp + processed cellulose	x	
Straw + processed cellulose	x	
Wood chips + processed cellulose	x	

4.3 SUBSTRATES ANALYSIS

REEDS AND HAY

Both reeds and hay need to be processed before being used. In the current state, the fibres are too large and long to be used for the production of mycelium composites. With this length it makes it difficult to autoclave the material, and to eventually fill up shapes for the testing. The substrates are therefore grinded to dimensions of about 3-4 mm. Figure 8 shows the fibres before and after grinding.

FIGURE 8 REEDS BEFORE (LEFT) AND AFTER GRINDING (RIGHT)

CELLULOSE

As aforementioned, throughout the project development, two types of cellulose are used: processed cellulose Recell® provided by the company KNN Cellulose BV, deriving from the waste water treatment facility Hollands Noorderkwartier, and raw cellulose from the waste water treatment facility RWZI Aarle-Rixtel. The former type has been treated through the Cellvation method. The sievings are hygienised through thermal process (temperature concealed by company secrecy) to reach the EPA class A rating (making it bacteria free), and then dried (Cellvation BV, 2018). For the raw cellulose the contained water needs to be taken into acount when producing mycelium composites, but for the processed dry cellulose the usual amount of ($60_{wt}\%$) water needs to be added to the composite. This aspect makes its use easier to produce mycelium composites, because the standard amount of water is needed. Figure 9 shows raw cellulose and processed cellulose in comparison.

FIGURE 9 PROCESSED (LEFT HAND SIDE) AND RAW CELLULOSE (RIGHT HAND SIDE)

RAW CELLULOSE WATER CONTENT

The raw cellulose is collected from the water treatment. Of the total weight the amount of fibres of dry solids is 30%, while the water content is 70%. This information is given by the water treatment facility.

The high cellulose content accompanied by hemicellulose and lignin compounds, indicates the suitability of this waste stream as substrate for mycelium composites production (more details relating its chemical composition can be found in Table 3 in the following chapter). Due to the raw cellulose intrinsic water content a few considerations need to be done when producing a mycelium composite. To grow a mycelium based composite of 120 grams (after drying), the composition of the ingredients is prepared as follows:

Total weight: 100% (400 grams)
Water: 65% (260 grams)
Fibres: 30% (120 grams dry weight)
Spawn: 5% (20 grams)

When preparing the substrate, the **dry fibre weight** is used to create the proper mixture. In this case 30% of 200 grams is 60 grams in total, which refers to the dry weight of the raw cellulose fibres. Therefore, when using the raw cellulose as pure substrate, no water needs to be added. However, when a different fibre is added, for example hemp, and the fibres are 50% hemp and 50% cellulose, the sample composition will be as follows:

Total weight: 400 grams (100%)
Fibres: hemp = 60 grams (15%)
cellulose = 200 grams → 60 grams dry fibre (30%) + 140 grams water (70%)
Water: 120 grams to be added (35%)
Spawn: 20 grams (5%)

The amount of raw cellulose which needs to be added is equal to 200 grams. This is because of the wanted dry fibre content of 120 grams total (60 grams of hemp plus 60 grams of cellulose). The added 200 grams contain 120 grams of water, therefore, only 140 grams of water need to be added to the sample. Table 2 shows a summary of the explained calculation, with a comparison between a standard mycelium composite, one containing raw cellulose only and one containing both hemp and raw cellulose.

TABLE 2 **WATER CONTENT RAW CELLULOSE SAMPLES**

	PURE RAW CELLULOSE *70% water content raw cellulose*		**HEMP AND RAW CELLULOSE** *70 % water content raw cellulose*		**STANDARD SAMPLE**
Initial total weight	400 g		400 g		400 g
Hemp fibres	/	/	60 g	15%	120
Dry fibre raw cellulose	114 g	30%	60 g	15%	(30% total weight)
Raw cellulose	380 g	80.3%	200 g	50%	-
Water in raw cellulose	266 g	70.8%	140 g	35%	260 g
Water to be added	/ g	/ %	120 g	30%	(65% total weight)
Spawn	20 g	5%	20 g	5%	20 g
Final total weight	400 g	100%	400 g	100%	400 g

SUBSTRATES CHEMICAL COMPOSITION

The fibers' chemical composition indicates the availability of the necessary chemical compounds to mycelium growth. Generally, white rot fungi, such as Ganoderma and Grey Oyster require high lignin, hemicellulose and cellulose content to provide the required nutrition for mycelium growth. The lignin, hemicellulose and cellulose dry weight percentage of each used substrate is displayed in Table 3.

TABLE 3 **CHEMICAL COMPOSITION OF DIFFERENT FIBRES**

Fibre	**Lignin (dw%)**	**Hemicellulose (dw%)**	**Cellulose (dw%)**
Raw cellulose	7	7	56
Reed [1]	26.20	23.80	30
Hay [2]	14.40	14.00	29.60
Processed cellulose [3]	<10	<15	65-80
Hemp shives [4]	22	24	40
Straw [5]	17.70	26.90	32
Wood chips [6]	27	26.90	40.70

1: (Suk-Jun Jung, 2015)
2: (Phyllis, 2003)
3: (Recell BV, 2018)
4: (Phyllis, 2003)
5: (José C. del Río, 2012)
6: (Tommi Räisänen, 2013)

4.4 SUBSTRATE GROWTH

This chapter shows the growth of both Ganoderma and Grey Oyster in three different substrates: hay, reed and raw cellulose. The following pictures display the mycelial growth in different intervals. The first pictures represent the composite at the moment of inoculation, while the second and the third pictures respectively represent day 3 and day 9 of mycelium growth. Mycelium development can be individualized by the white coating covering the substrate, which characterizes the hyphal network. When mycelium is developed, the whole fibres can present a white color.

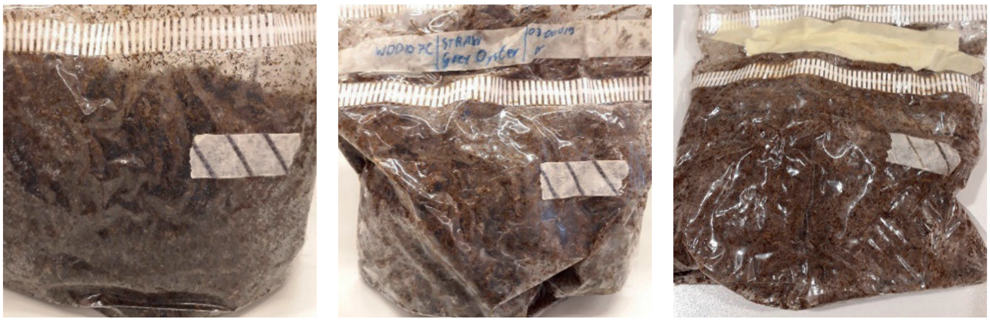
REEDS

FIGURE 10 REED AND HEMP MIXTURE GANODERMA GROWTH

FIGURE 11 REED AND HEMP MIXTURE GREY OYSTER

FIGURE 12 PURE REED GANODERMA GROWTH

FIGURE 13 PURE REED GREY OYSTER GROWTH



When pure reed (Figure 12 and 13) is used as a substrate, no mycelium growth can be seen throughout the whole specimen by both Ganoderma and Grey oyster. The former fungi shows a scattered development throughout the substrate, while the latter does not present any growth. When mixed with hemp (Figure 10 and 11), both Ganoderma shows more developed growth, in fact mycelial filaments are spread thoroughly over the substrate.

HAY

FIGURE 14 **HAY AND HEMP MIXTURE GREY OYSTER GROWTH**

FIGURE 15 **HAY AND HEMP MIXTURE GANODERMA**

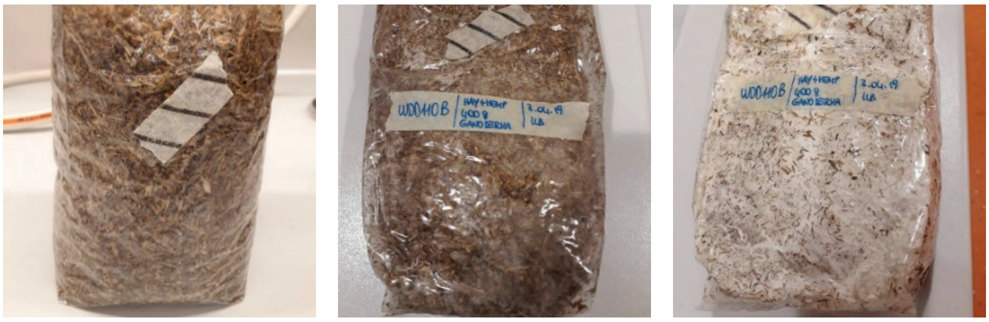


FIGURE 16 **PURE HAY GANODERMA GROWTH**

FIGURE 17 **PURE HAY GREY OYSTER GROWTH**

Differently from reed, hay shows well developed mycelium when used as pure and mixed substrate. However, when mixed with hemp, the fibres show higher growth. Ganoderma presents more developed growth than Grey oyster when looking at both pure and mixed substrates.

RAW CELLULOSE

FIGURE 18 **GREY OYSTER GROWTH ON RAW CELLULOSE**

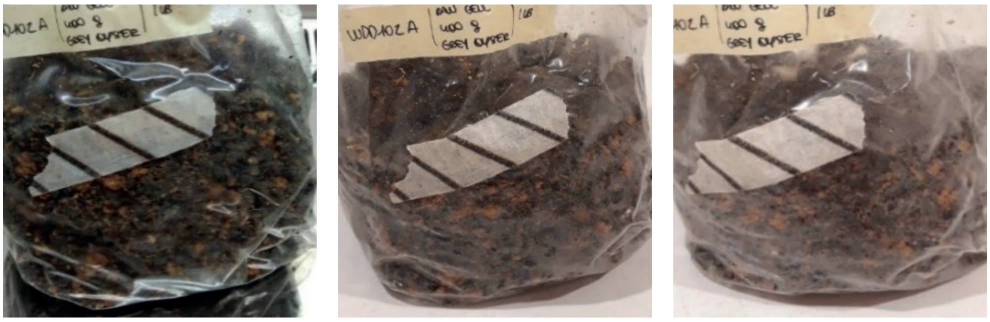


FIGURE 19 **GREY OYSTER GROWTH ON RAW CELLULOSE AND HEMP**

FIGURE 20 **RAW CELLULOSE PLUS HEMP GANODERMA GROWTH**

FIGURE 21 **GANODERMA GROWTH ON RAW CELLULOSE AND HEMP**

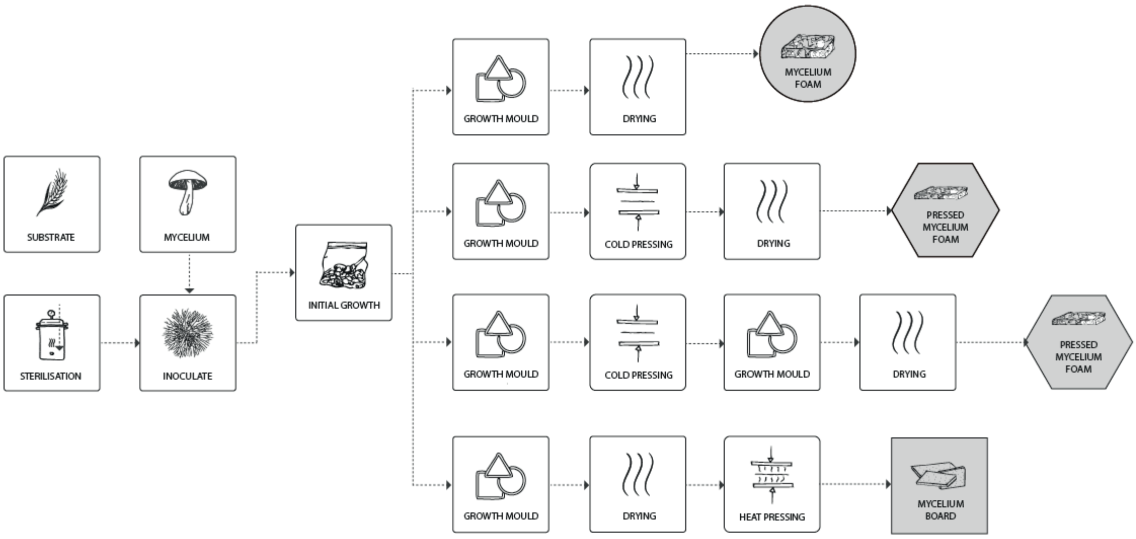
The above pictures show the growth of both Ganoderma and Grey oyster on raw cellulose. Ganoderma shows well developed growth with both pure and mixed substrates. While the Grey oyster does not show much growth when looking at both pure and mixed substrates. Compared to the growth on processed cellulose (Recell®), which generally starts developing hyphae after day 2 from inoculation, raw cellulose presents slightly slower growth, starting from day 4. This can be due to the difference in chemical composition between raw cellulose and processed cellulose.

5

MATERIAL PROCESSING

As mentioned before, the production of mycelium composites complies multiple different parameters and variables, of which one is the processing of the material after growth. These different processes are studied in order to understand their influence on the technical material properties. We mainly distinguish a foam and a board material, which are achieved by either 'non pressing' or 'heat pressing' the material. In addition to that two stages in between are considered with 'cold pressing' allowing the pressure to deform the material, however without heat to slightly alter the material properties. Next to the cold pressing an additional period of growth is performed. The following figure describes the applied processes.

FIGURE 22 **OVERVIEW DEVELOPMENT PROCESSES**



These four processes have been applied to cylindrical samples to test their influence on the compression strength of the material. However, the thermal insulation is only tested for the non-pressed samples and the bending test is only applied to heat pressed samples. In general, for insulation materials encapsulated air would be preferable as this functions as a heat/cold barrier. By compressing the material you would press out all the air and decrease the insulating capabilities.

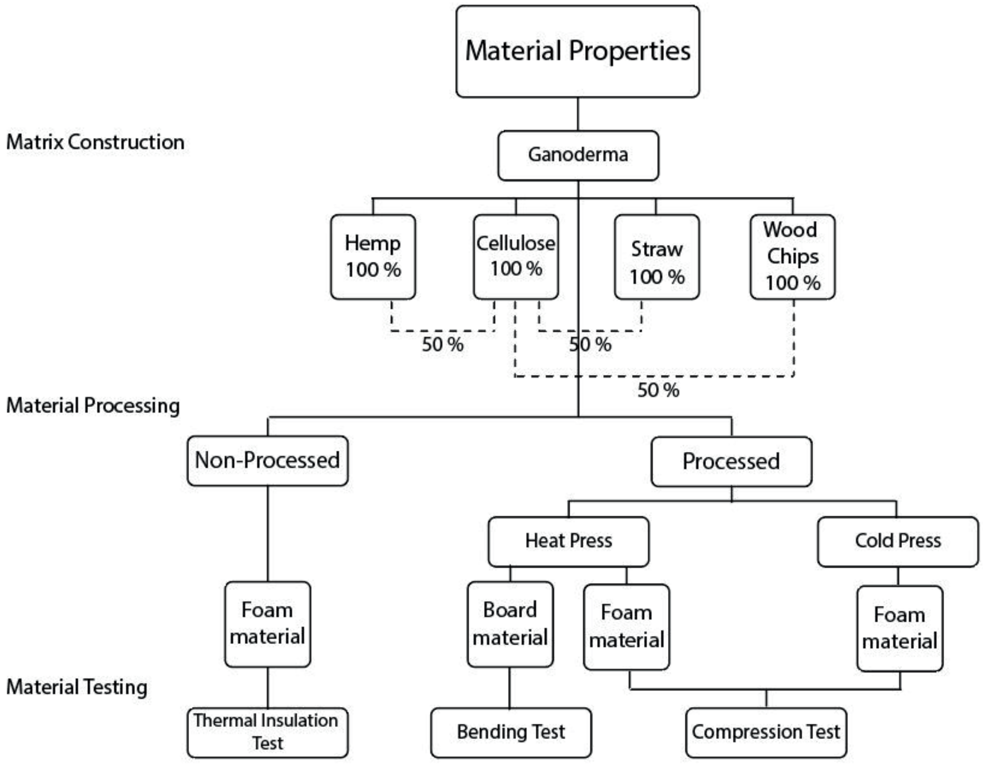
For the bending strength samples are required with a small thickness, which is not achievable without the heat compression. When growing these samples a higher mould is required to be able to compress the material into its final shape. All the moulds are produced using PET-G or PVC plastics, with a vacuum form machine.

6

MATERIAL CHARACTERISATION

The study on material properties is centered on the investigation of the compressive strength, bending strength and thermal conductivity of the produced mycelium composites. As aforementioned, the research is performed on the fungal species Ganoderma. Figure 23 summarizes the steps characterizing this part of the research.

FIGURE 23 GENERAL FLOW SCHEME OF THE STUDY ON MATERIAL PROPERTIES



The substrates that are used for this material characterization are the following: hemp, cellulose and straw. Both hemp and straw are also used in a combination with cellulose and an additional mixture of cellulose and wood chips is added to the samples. The experiments are performed using series of triplo's, to ensure reliable results. Table 4 summarizes the final matrix, showing an overview of the substrates in reference to the performed tests.

TABLE 4 **TESTS OVERVIEW ON DIFFERENT SUBSTRATES**

Pure fibres	Compression test	Bending test	Thermal insulation test
Raw cellulose			
Reed			
Hay			
Processed cellulose	x	x	x
Hemp	x	x	x
Straw	x	x	x
Wood chips			
Mixed fibres (50:50)			
Raw cellulose + hemp			
Reed + hemp			
Hay + hemp			
Hemp + processed cellulose	x	x	x
Straw + processed cellulose	x	x	x
Wood chips + processed cellulose	x	x	x

As can be seen in the table, raw cellulose, reed and hay are not used to study the material properties as the main focus at first was on the processed cellulose. The combinations of fibres are determined using cellulose as a base, because of its growth boosting nature. Hemp and straw are also used as pure substrates, in order to function as a control group in terms of both mycelium growth and mechanical properties. Wood chips are not used as pure substrates, because of its limited growth.

6.1 COMPRESSION TEST

The compressive strength is tested on a matrix of six samples with the same ingredient mixture, but undergoing four different processes. The studied processes are heat press, cold press, cold press with further growth. Moreover, the produced samples are compared to non-pressed samples in order to determine the efficacy of the applied procedures.

The test is performed according to the standard ISO 844, which provides the required samples measures. It indicates the relevant values to consider from the performed test. In fact, the 10% relative deformation of the initial cross sectional area is the value of interest and it can be derived from the executed compressive test. The compressive strength, in Mega Pascals (MPa) can be calculated with the following formula:

$$\sigma_m = \frac{F_m}{A_0}$$

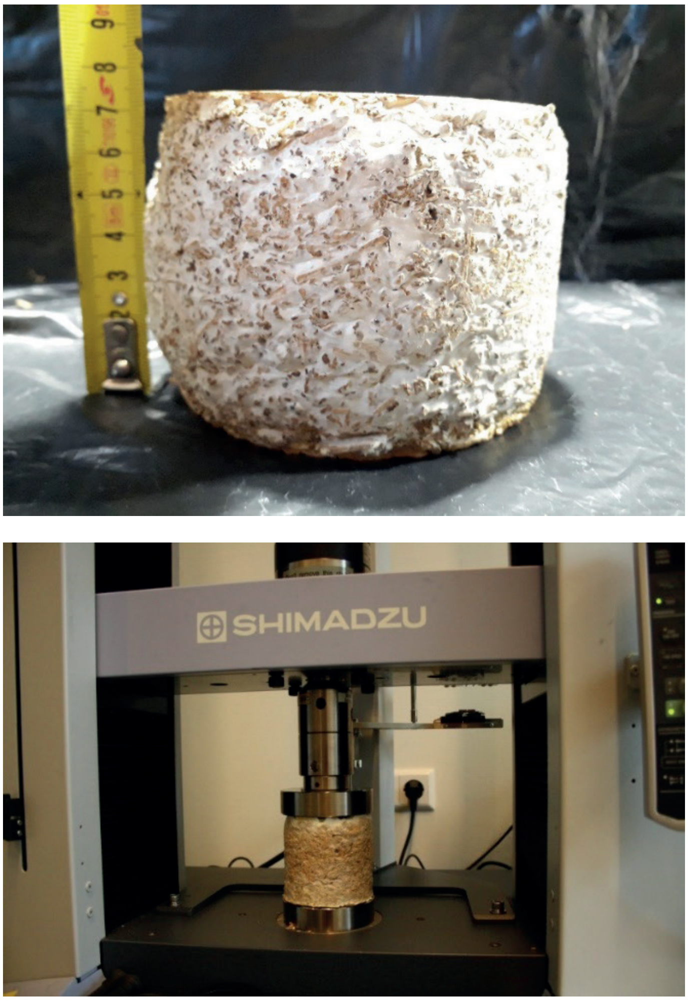
Where F_m is the maximum reached force and A_0 is the initial cross sectional area in square millimeters. F_m is the value directly shown from the testing machine. The 10% relative deformation value is then obtained considering the maximum force on the displacement responding to the 10% of the sample. When looking at this property higher values mean more valuable material, therefore the higher the compressive strength the better the material. Table 5 shows the matrix of the created and tested samples.

TABLE 5 **OVERVIEW OF FIBRES' DIFFERENT PROCESSES**

Fibre(s)	Non-press	Cold press	Cold press + growth	Heat press
Cellulose	x	x	x	/
Hemp	x	x	x	x
Straw	x	x	x	/
Cellulose + hemp	x	x	x	x
Cellulose + straw	x	x	x	x
Cellulose + wood	x	x	x	x

When producing the samples of the matrix, the structure of the pure cellulose got damaged by the heat pressing process (Figure 24, top). As the cellulose has a higher shrinkage when drying, the diameter of the sample was a bit smaller than the mould used for heat pressing. This caused the material to move outward, deforming the cylindrical shape. Therefore no test is performed for this combination of ingredient and processing technique. Pure straw samples are not heat pressed, because straw alone is not considered as a valuable substrate in terms of compressive strength, as it will be shown in the next chapters.

FIGURE 24 **DEFORMED HEAT PRESSED SAMPLE (TOP) AND PRESSURE TEST (BOTTOM)**

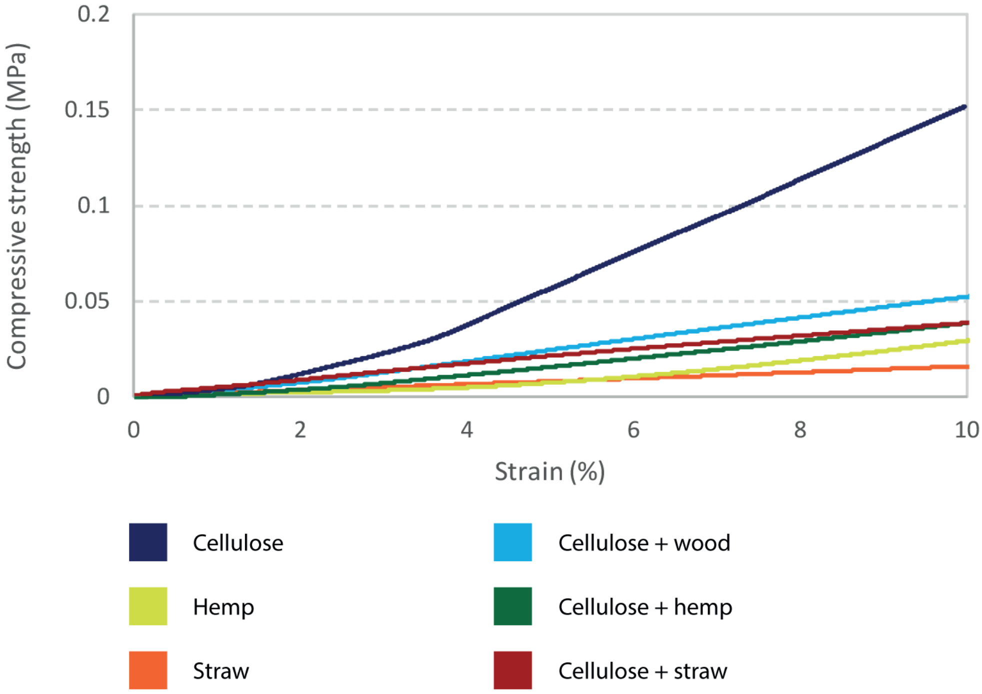


RESULTS:

NON PRESSED

Hereby a comparison between the compressive strength of non-pressed samples is shown. The compressive strength, expressed in MPa on the 10% relative deformation is displayed. In Appendix 1 graphs relating each series of triplets can be found.

GRAPH 1 **COMPRESSIVE STRENGTH NON-PRESSED SAMPLES**



From the figure the following considerations can be drawn:

- Pure cellulose samples present the highest compressive strength
- Pure straw samples present the lowest compressive strength
- The combination between cellulose and wood fibres shows the highest compressive strength between the mixed substrates

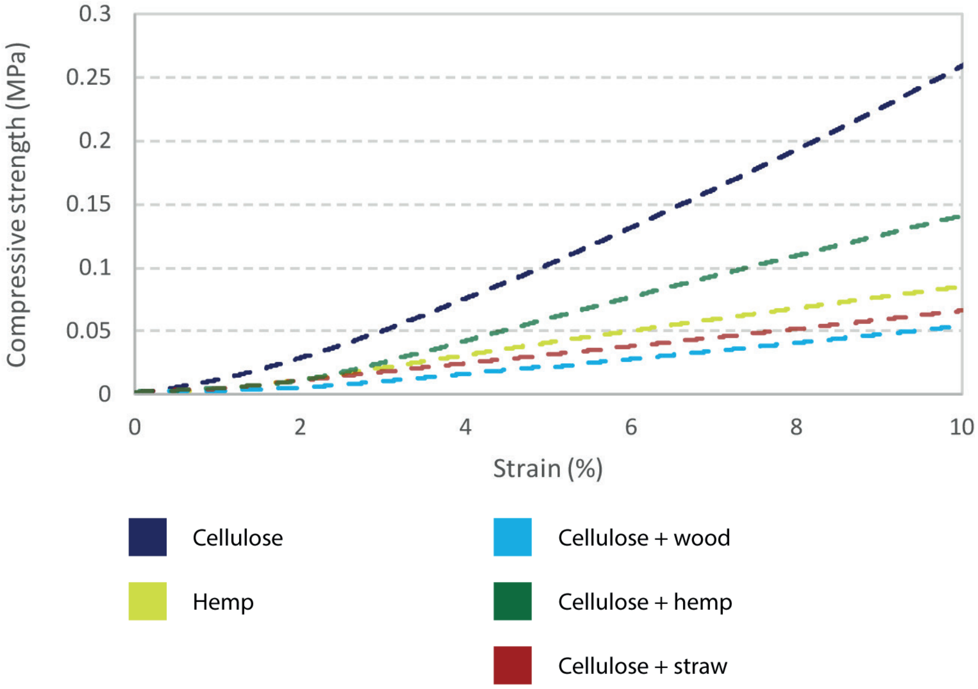
The following conclusions can be done:

- The adding of different fibres to cellulose does not improve the compressive strength of the material
- Materials deriving from pure straw and hemp present poor compressive strength

COLD PRESSED

Graph 2 presents a comparison of the compressive strength between the different used substrates that have been cold pressed after growth. Graphs of each series of triplets are shown in Appendix 2.

GRAPH 2 **COMPRESSIVE STRENGTH COLD PRESSED SAMPLES**



From the graph the following considerations can be drawn:

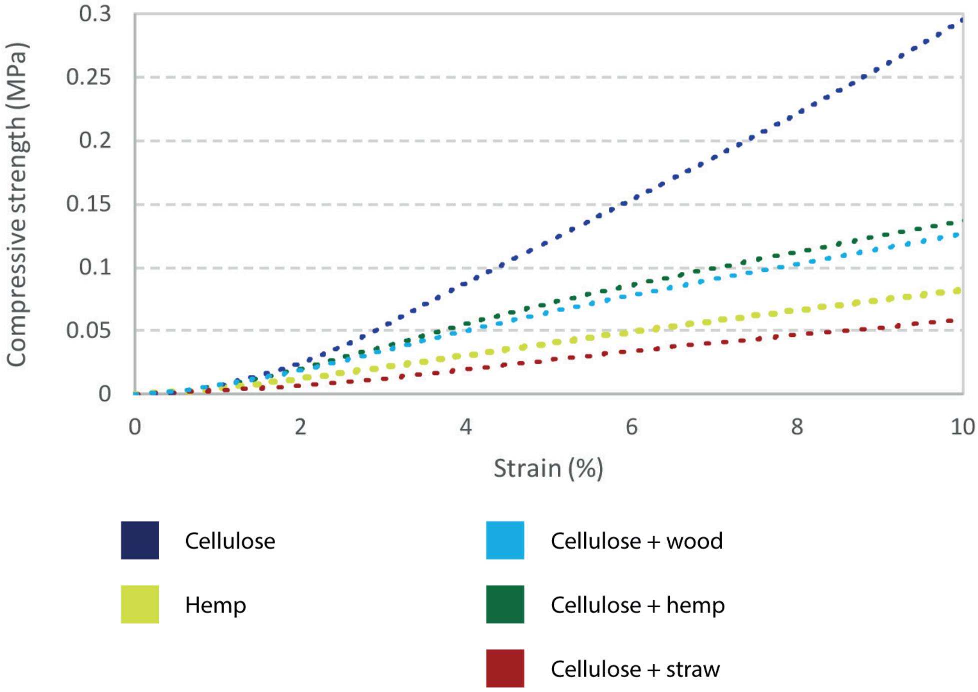
- Pure cellulose samples present the highest compressive strength
- The combination of wood fibres and cellulose presents the lowest compressive strength
- The combination between cellulose and hemp fibres shows the highest compressive strength between the mixed substrates

From the graph it can be understood that the adding of different fibres to cellulose does not improve the compressive strength of the material. This could be due to the higher mycelium growth which characterises the pure cellulose samples. The pure cellulose samples present higher density, this can derive from two factors: the finer particles constituting the cellulose substrate itself and the higher density caused by the higher and thicker mycelium growth.

COLD PRESSED + GROWTH

The compressive strength of the samples that have been cold pressed with an additional period of growth is presented. Graph 3 shows a comparison of the compressive strength between the different used substrates. Graphs related to each series of triplets are shown in Appendix 3.

GRAPH 3 COMPRESSIVE STRENGTH COLD PRESS WITH FURTHER GROWTH SAMPLES



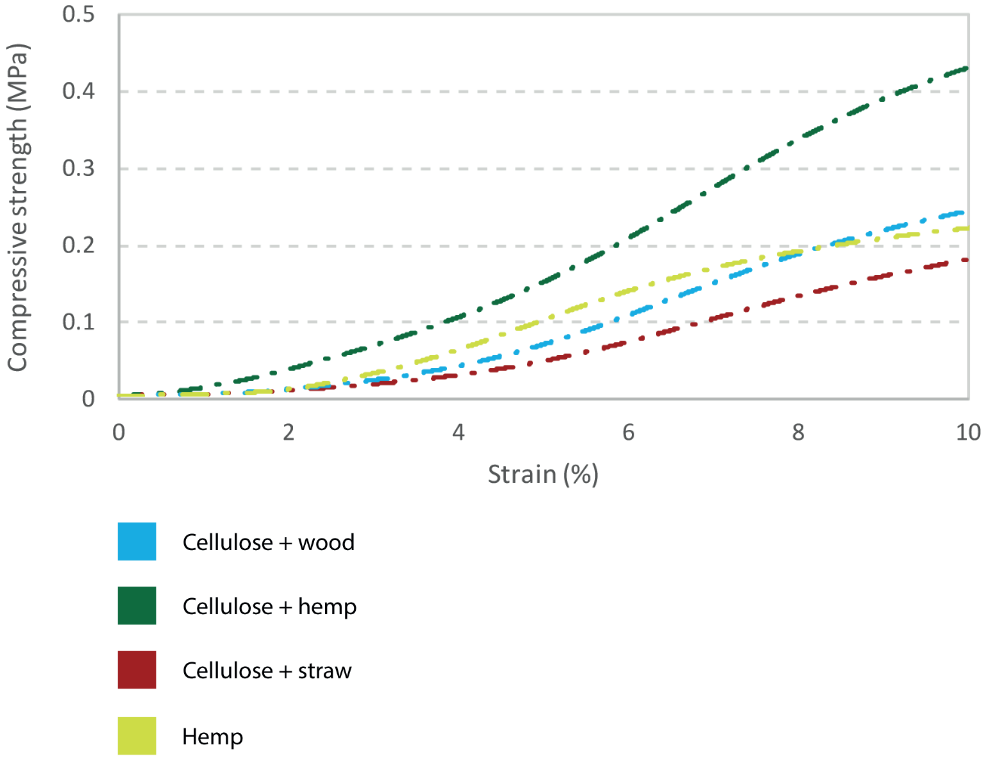
From the graph the following considerations can be drawn:

- Pure cellulose samples present the highest compressive strength
- The combination of straw and cellulose presents the lowest compressive strength
- The combination of cellulose and hemp fibres together with the combination of wood fibres and cellulose show the highest compressive strength between the mixed substrates

HEAT PRESSED

The compressive strength of the heat pressed samples is shown. Graph 4 presents a comparison of the compressive strength between the different used substrates. Graphs related to each series of triplets are shown in Appendix 4.

GRAPH 4 **COMPRESSIVE STRENGTH HEAT PRESSED SAMPLES**



From the graph above the following considerations can be drawn:

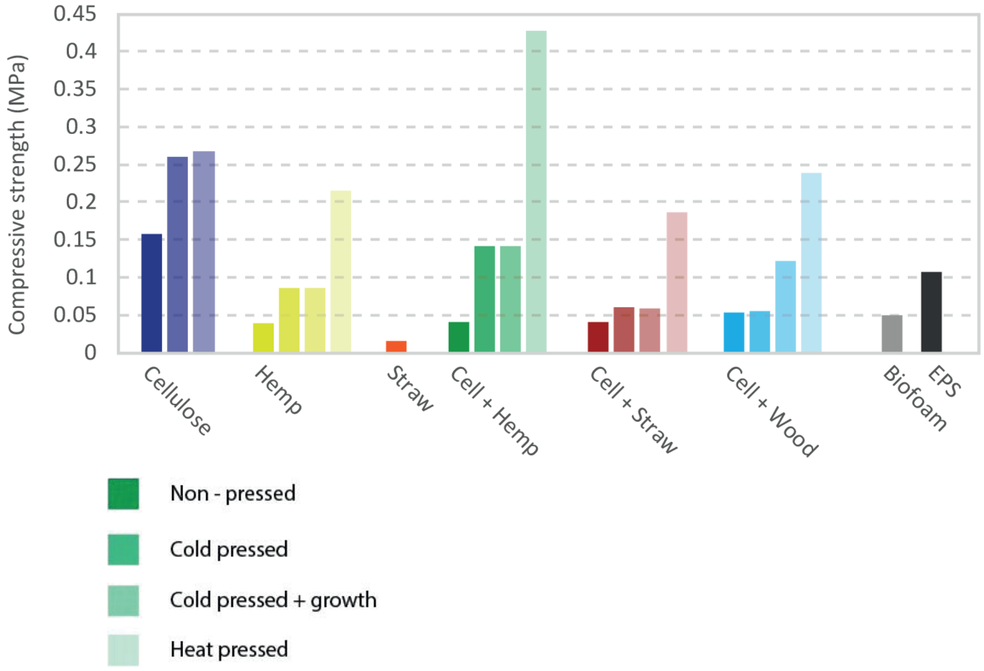
- Samples made of the combination of cellulose and hemp show the highest compressive strength
- Samples composed of cellulose and straw present the lowest compressive strength
- Pure hemp samples initially perform better than the combination of wood chips and cellulose, but the 10% deformation compressive strength is finally lower.

As previously mentioned, samples made of pure cellulose are not tested because they were deformed when heat pressed. This was due to the smaller cross sectional area presented by the samples after being dried. Pure straw samples are also left out from the heat press matrix, due to their poor performance observed in all the rest of the processes (non-pressed, cold pressed and cold pressed with further growth).

OVERVIEW COMPRESSION TEST

Hereby, an overview of the final results relating to the compressive strength corresponding to the 10% relative deformation of the initial cross sectional area is shown. Graph 5 shows a summary of the average compressive strength from each triplets. The graph shows a clear comparison of the applied processes to each used substrate.

GRAPH 5 OVERVIEW OF COMPRESSIVE STRENGTH OF DIFFERENT FIBRES AND PROCESSES



The compressive strength of heat pressed samples is higher when compared to the other applied processes. Non-pressed cellulose specimen show high compressive strength when compared to the fibres mix of both non processed and processed samples, not considering the heat pressed ones. This indicates that the addition of other, longer fibres does not add to the compressive strength of the material. The performance of the non-pressed cellulose samples can be regarded as valuable, since no further process is applied to increase their compressive strength.

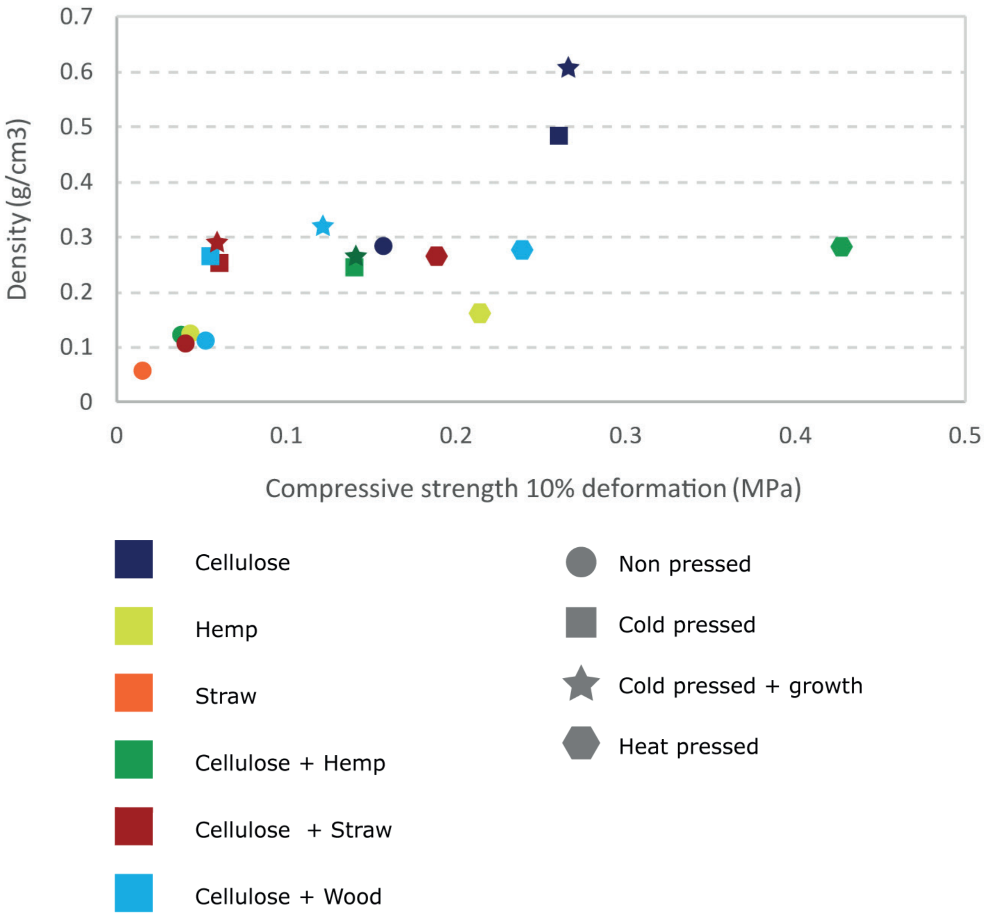
Furthermore, the graph clearly indicates that the difference between cold pressed and cold pressed + further growth is not significant. Only for the sample of cellulose + wood there is a larger difference between these two processing techniques.

In comparison to conventional materials the mycelium samples perform quite well. A large part of the samples, mainly the heat pressed variant, perform significantly better in terms of strength compared to EPS (expanded polystyrene) and biofoam, defined as expanded PLA (polylactic acid). The following subchapter compares the compressive strength to the densities of the samples.

OVERVIEW DENSITY VS COMPRESSIVE STRENGTH

The following figure presents an overview of the relation between the average densities of each series of triplets and their relative compressive strength.

GRAPH 6 DENSITIES AND COMPRESSIVE STRENGTH RELATION



From the graph it can be understood that:

- As it is expected, the processed samples (considering all the three used processes) present higher density than the non-processed specimens. Only the non-pressed pure cellulose sample shows higher density than some fibres combinations, also showing a better performance in terms of compressive strength. In fact, the mix of cellulose and hemp, cellulose and straw and cellulose and wood (looking at the cold pressed and cold pressed plus growth) show lower values than the non-pressed pure cellulose samples.
- No noticeable difference is present between the cold pressed and cold pressed with further growth samples. All the specimens, both pure and combinations, present close values in terms of both compressive strength and density. For instance cellulose and hemp samples show the same compressive strength of 0.14 MPa and densities of respectively 0.24 g/cm^3 and 0.27 g/cm^3 for cold pressed and cold pressed with further growth specimens. Only wood and cellulose samples present a large difference of density and compressive strength.
- Regularity can be seen when looking at the densities of pure and combined fibres of the three applied processes. For instance the cellulose and straw combination respectively presents 0.25 g/cm^3, 0.29 g/cm^3 and 0.26 g/cm^3 for cold pressed, cold pressed plus growth and heat pressed samples. This can be observed for all the samples but the pure cellulose ones.

- Higher density does not always mean higher compressive strength. The heat pressed samples made of cellulose and hemp present in fact the highest value of compressive strength (0.43 MPa) while presenting an average density of 0.28 g/cm^3. The second highest compressive strength value is shown by the cold press with further growth pure cellulose samples (0.27 MPa), which however present the highest density of 0.61 g/cm^3.
- Generally speaking, heat pressed samples of both fibre combinations and pure hemp show higher compressive strength when compared to the other applied processes. Pure hemp samples show higher value (0.22 MPa) compared to the pure cellulose non-pressed samples (0.16 MPa) and the fibres combinations of cold pressed and cold pressed with further growth processes. When comparing the pure heat pressed hemp samples average density to the pure cellulose non-pressed samples, a noticeable difference can be seen. In fact the former triplet presents an average density of 0.16 g/cm^3, while the latter samples present a value of 0.29 g/cm^3. The cold pressed samples and cold pressed with further growth specimens also present higher density, with values ranging from 0.26 g/cm^3 to 0.32 g/cm^3 (values respectively relating to cold press and cold press + growth of wood and cellulose combination)
- Non-pressed samples present both lowest densities and lowest compressive strength, with the exception of the pure cellulose triplet, which presents a higher value than the fibres combinations of cold pressed and cold pressed with further growth samples. However, also the sample density is higher than the mentioned samples, except for the cold pressed plus growth cellulose and wood combination.

DISCUSSION

When looking at the results and the considerations from above, it can be noticed that the compressive strength is more influenced by the undergone process than by the density of the samples. In fact all the heat pressed samples present high compressive strength and relatively low densities.

Heat pressing is performed at 200 ° C and with a force of 30 kN, it is possible that these parameters influence the final compressive strength of the specimens. High temperature can in fact cause chemical reactions to occur in the molecular composition of the mycelium cell membrane, possibly resulting in stronger molecular bonds, hence determining its higher compressive strength. In fact, because of its chemical structure, when heat pressed, lignin is the molecule responsible of the higher bonding force between the cells wall of mycelium composites (Mizi Fan, 2014). It can therefore act as a binder adding up strength to the already present mycelium bond. Moreover, lignin being a large molecule, the mycelium can degrade it through more effort than when breaking down cellulose and hemicellulose. This can result in a stronger bonding between mycelium and lignin.

Furthermore, the force applied to the heat pressed samples is higher than the force applied to the cold pressed samples. In fact, due to their wet nature and high elasticity the cold pressed samples required lower force to be processed/compressed. The cold pressing of the samples, does not interact with the chemical composition of the mycelium membrane cells, therefore it does not interfere with their compression strength but with their density solely. Additionally, the further growth after cold pressing of some samples does not increase their compressive strength but only their density. This can be explained by the fact that the density of mycelium composites, not only depends on the fibre density of the used substrates, but also on the thickness of mycelium growth, therefore the more grown the mycelium, the more dense the composite.

Generally speaking a product is considered more valuable when presenting a lower density together with a high compressive strength. This is because of the easier use that can be applied to lighter materials, in terms of e.g. transport and applications. When taking this into account, the heat pressed samples can be considered as the most relevant, because of their low density but relatively high compressive strength.

COMPARISON TO CONVENTIONALMATERIALS

A comparison with traditional materials is necessary in order to better understand the value of mycelium composites. Table 6 summarizes the densities and compressive strengths of the produced mycelium composites comparing them with conventional materials as EPS and bio foam. Only the heat pressed materials are considered, because of their higher compressive strength and therefore better performance.

TABLE 6 **OVERVIEW COMPRESSIVE STRENGTHS AND DENSITIES**

Sample	Compressive strength (MPa)	Density (g/cm^3)
Hemp	0.21	0.16
Cellulose + Hemp	0.43	0.28
Cellulose + Straw	0.19	0.26
Cellulose + Wood	0.24	0.27
EPS	0.10	0.01
Bio foam	0.04	0.02

As overall, mycelium composites present higher compressive strength when compared to EPS and biofoam. However, their density is more elevated than the considered materials. When looking at these product properties it can be understood that mycelium composites can be a valuable material, even though their higher density decreases their value. It can in fact be noticed that the lowest density of mycelium composite of 0.16 g/cm^3 responds to a compressive strength of 0.21, which is still much higher than those of EPS and bio foam. Lower densities should therefore be achieved in order to increase the market value of mycelium composites.

6.2 BENDING TEST

The bending strength of different fibres and their combination is studied. The analyzed samples present only one process: heat pressing. As mentioned in chapter 8 the studied fibres are the following: cellulose, hemp, straw, and the combinations of cellulose and hemp, cellulose and straw and cellulose and wood chips. These samples are tested in series of triplets.

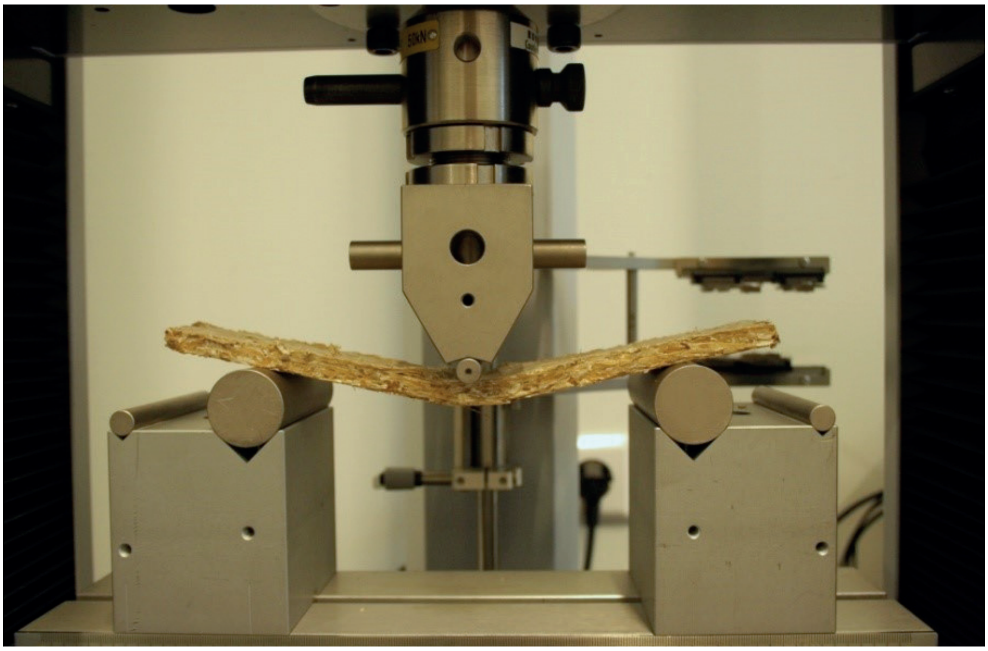
The followed standard to perform the test and to determine the specimens dimensions is NEN-EN-ISO 310. The value obtained from the test itself is the necessary force in Newtons to reach the sample breaking point. The ISO standard provides the formula needed to calculate the bending strength which is as follows:

$$f_m = \frac{3F\,max\,l_1}{2bt^2}$$

Where f_m is the bending strength in Newtons per square millimetres or MPa, F_{max} is the maximum load in Newton, l_1 is the distance between the centres of the supports, in millimetres, b is the width of the test piece and t^2 is the thickness of the test piece in millimetres.

A product is considered more valuable when presenting high bending strength. Nowadays products present relatively high bending strengths, as it is shown in Table 7, where MDF is used as a term of comparison.

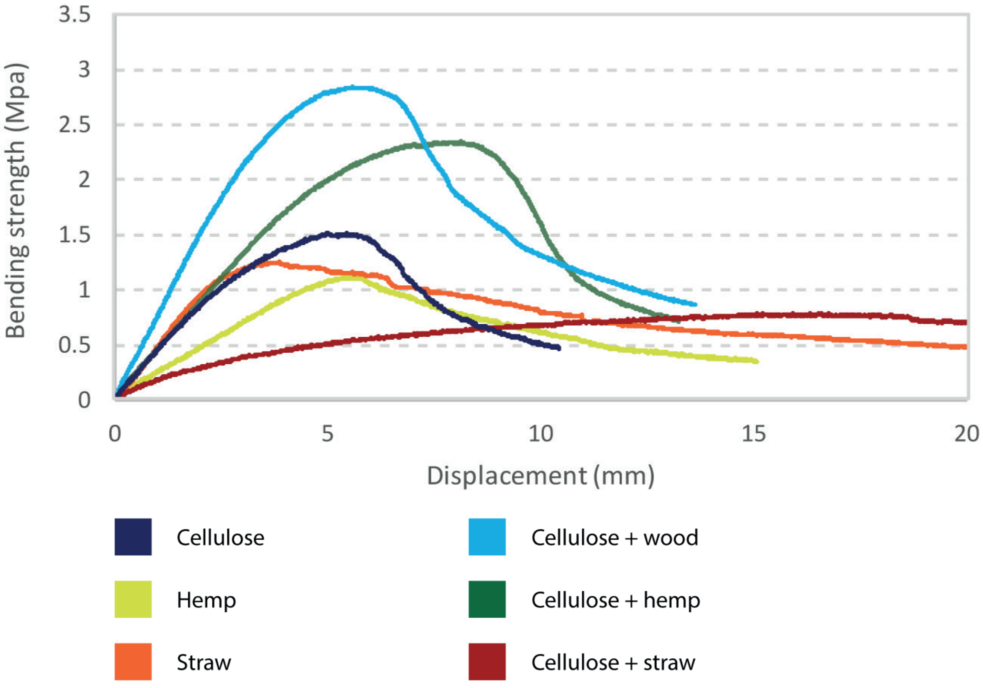
FIGURE 25 BENDING TEST SET-UP



RESULTS

Graph 7 shows a comparison between the bending strength of all the analysed fibres. In the graph the bending strength is represented by the peak of the line. The breaking point can be visualized when the line starts curving.

GRAPH 7 BENDING STRENGTH OVERVIEW

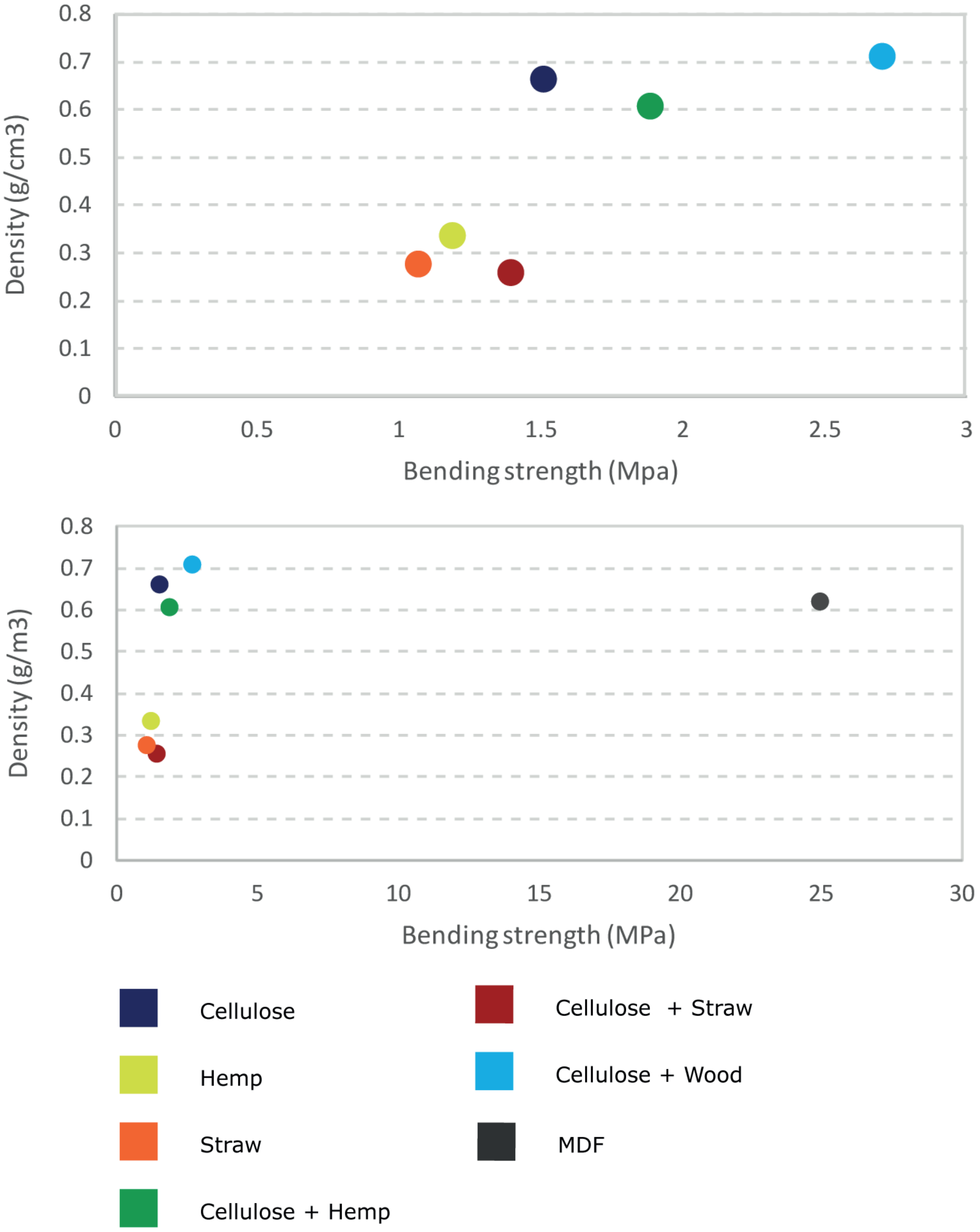


The following consideration can be done from the graph:

- The samples made of a mixture of cellulose and wood present the highest bending strength
- The combination of straw and cellulose presents the least bending strength
- The mixture of hemp and cellulose shows the second high bending strength
- Straw performs better as pure fibre rather than when mixed with cellulose

To get a better view on their performance the bending strength of the samples has been compared to their densities (Graph 8). The shown values are the average values between the triplets. Also the density and bending strength of MDF are added as a reference material.

GRAPH 8 **DENSITIES AND BENDING STRENGTH OVERVIEW**



DISCUSSION

Generally, samples presenting higher density also present higher bending strength. The samples made of pure straw and of a mixture of cellulose and straw present the lowest density, and lowest bending strength, probably due to the longer and more voluminous fibres. Moreover, a lower bending strength can be seen when straw is mixed with cellulose. Higher performance is seen when cellulose is mixed to fibres, such as wood chips and hemp, this can be due to the higher flexibility of the mentioned substrates because of their longer cells. In fact cellulose can be considered as a more fragmentated substrate.

Samples made of mixed substrates present lower density and higher bending strength than the pure ones, excluding the straw. Both hemp and wood chips have high content in lignin, cellulose and hemicellulose (see chapter 4.3), while straw has a quite small quantity of these molecules. This can explain the higher bending strength presented by hemp and wood chips mixtures as lignin gives strength to fibres. Moreover, as aforementioned the straw substrate has longer fibres, which can results in a less dense and less strong composite. In fact, straw composites present the lowest density compared to the other tested samples. Table 7 summarises the bending strengths and densities of the produced mycelium composites, also comparing them with MDF (medium-density fibreboard) material.

TABLE 7 **FIBRES' BENDING STRENGTH AND DENSITIES**

Material	Bending strength (MPa)	Density (g/cm^3)
Cellulose	1.51	0.66
Hemp	1.19	0.33
Straw	1.39	0.26
Cellulose + Hemp	1.89	0.61
Cellulose + Straw	1.07	0.28
Cellulose + Wood	2.70	0.71
MDF	24.93	0.62

As can be seen on the Table, MDF presents a much higher bending strength when compared to mycelium composites. This indicates that the board material is not yet suitable as a construction material. However, adjusting and improving the processing technique regarding the heat pressing could make the mycelium more applicable for structural purposes.

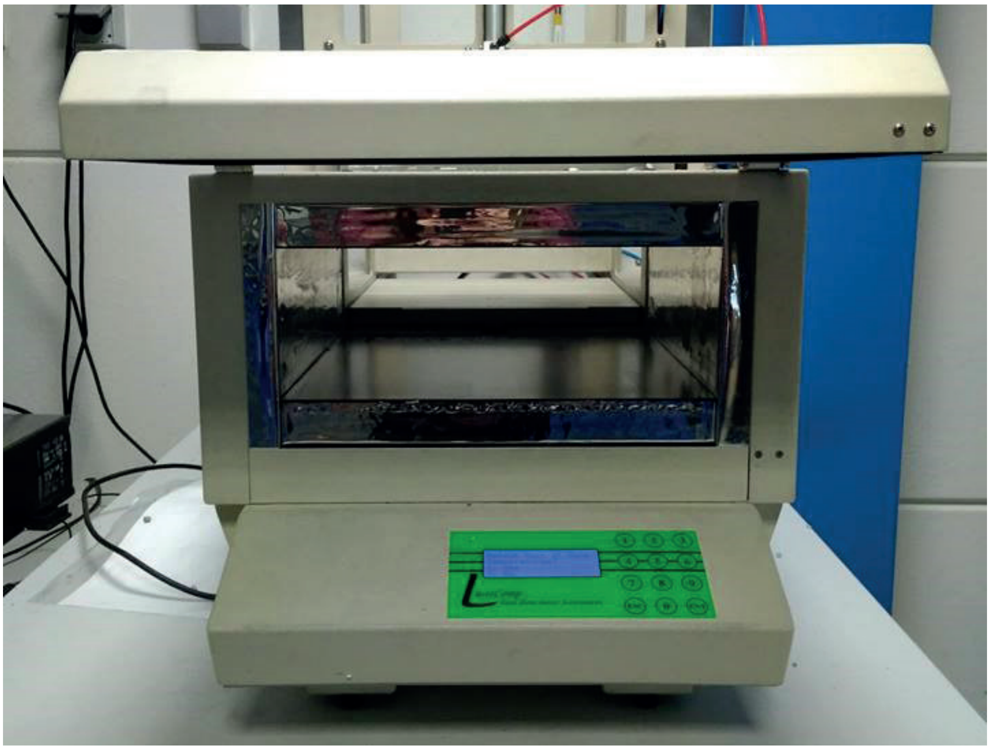
In comparison to the mycelium composites, MDF has a higher density in most cases, which correlates to the higher bending strength of the material. However, a higher density does not immediately mean that the material is stronger.

6.3 THERMAL INSULATION

The thermal insulation of samples made of hemp and cellulose is tested. Moreover, a mixture of fibres such as cellulose and hemp is also analyzed. For this test, both Ganoderma and Grey Oyster fungi are considered. However, Grey oyster is used to study pure hemp and hemp mixed with cellulose only. In fact the samples made of pure cellulose inoculated with grey oyster did not present enough growth to be valuable for testing.

The standard used is NEN-EN-ISO 9229:2007, which provides the needed samples measures and test apparatus. The searched value is the lambda value λ which is expressed in Watt per meter Kelvin (W/mK). If a determined material presents a high λ value, then it can be considered as a good heat conductor, on the other hand, if a material displays a low λ value, it is a poor heat conductor, also known as an insulator.

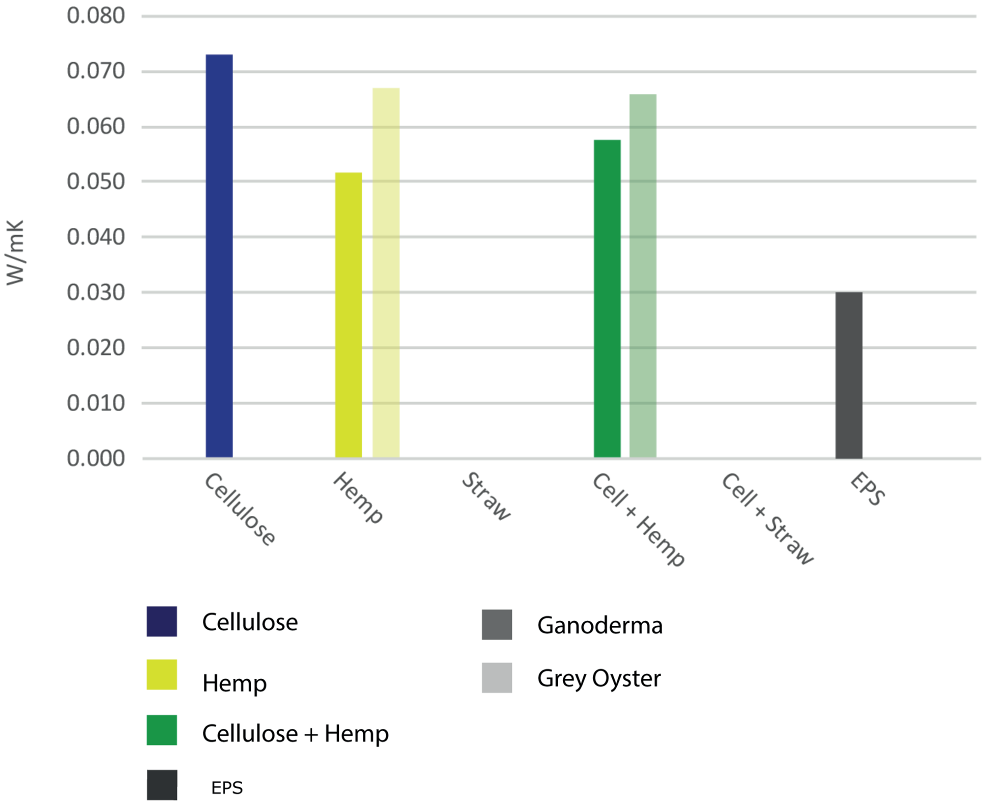
FIGURE 26 HEAT FLOW METER



RESULTS

Graph 9 shows an overview of the λ values of the tested samples. As can be seen only a few combination of substrates have been tested. The straw and cellulose + straw are mentioned in the graph, but were not grown properly enough to be tested.

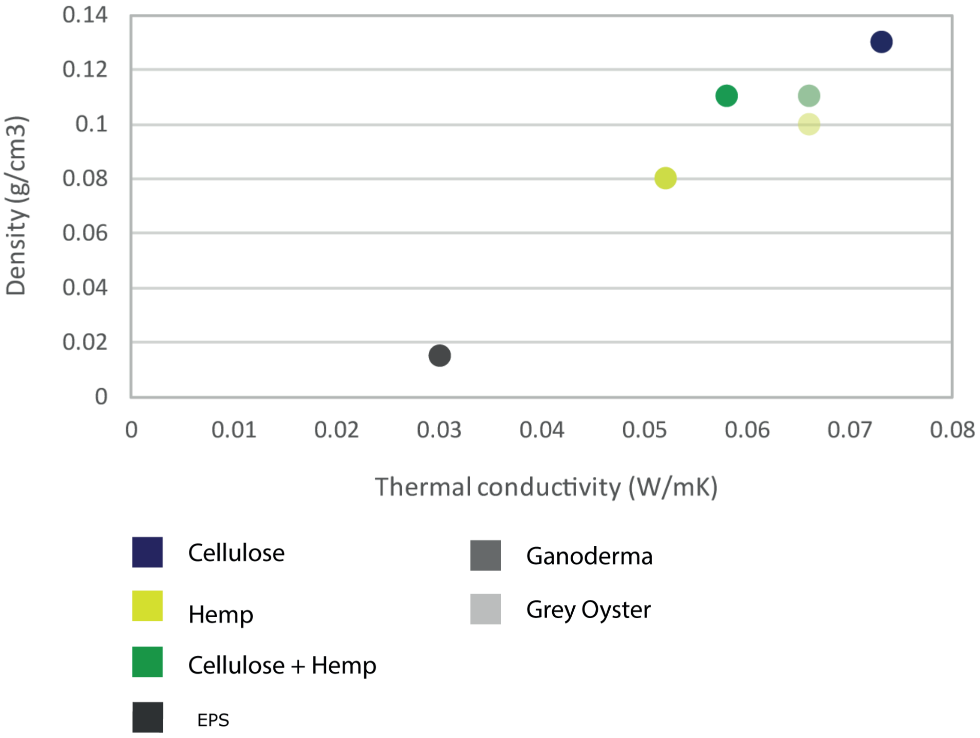
GRAPH 9 DIFFERENT FIBRES THERMAL CONDUCTIVITY



From the graph it is possible to see that pure hemp composites inoculated with Ganoderma presents the lowest thermal conductivity, therefore performing the highest thermal insulation. Pure cellulose samples present the highest λ value, while the mixture of cellulose and hemp presents an intermediate thermal conductivity. The difference between the Ganoderma and Grey oyster mushroom are not very large, however Ganoderma seems to have better insulating properties.

Furthermore, compared to EPS, these mycelium composites would not yet be a suitable replacement, but do show potential as an insulator. In relation to the thermal conductivity, the density is an important factor. Graph 10 shows an overview of the thermal conductivity of the tested samples related to their densities.

GRAPH 10 **OVERVIEW OF THERMAL CONDUCTIVITY AND DENSITIES**



DISCUSSION

The samples presenting the highest densities, such as pure cellulose and cellulose + hemp mixture also show the highest λ values. This can be observed with the samples inoculated with both Ganoderma and Grey Oyster. Table 8 shows the specific values relating to densities and thermal conductivity of the tested samples. A EPS standard foam is also presented, in order to have a term of comparison and to better understand the mycelium composites properties.

TABLE 8 **THERMAL CONDUCTIVITY GANODERMA AND GREY OYSTER**

Fibres	Fungi	Thermal conductivity (W/mK)	Density (g/cm^3)
Cellulose	Ganoderma	0.073	0.13
Hemp	Ganoderma	0.052	0.08
Hemp	Grey oyster	0.066	0.10
Cellulose + Hemp	Ganoderma	0.058	0.11
Cellulose + Hemp	Grey Oyster	0.066	0.11
EPS foam	/	0.03	0.015

Generally, the samples inoculated with Ganoderma present a lower thermal conductivity than the ones inoculated with Grey Oyster. This can be explained by the fact that Ganoderma specimens present a thicker growth of mycelium, which uniformly binds together the fibres, ensuring better thermal properties. This can explain why the mixed hemp and cellulose samples which present the same density but have much higher value when inoculated with Grey Oyster. In fact Grey Oyster samples show a non-homogeneous growth throughout the substrates, also resulting in more brittle and mechanically less stable samples. This can also be the case for the pure hemp specimens which show a much lower thermal conductivity when Ganoderma is used. Looking at the cellulose samples, the ones inoculated with Grey Oyster did not show enough growth to produce a valuable sample, therefore the test could not be performed. When Ganoderma is used however, even though the mycelial growth was well spread throughout the substrate, the denser intrinsic nature of the cellulose fibres, results in too dense of a sample. This characteristic can affect the thermal insulation performance of the specimen, in fact the molecules might be too aggregated to each other to allow the heat to be “trapped” by the material.

The thermal conductivity can therefore be influenced by the used fibres, which determine fungal growth, and by the fungal species. The chemical composition of the used substrates can result in stronger and more dense composites, as in the case of respectively hemp and cellulose. Moreover the fungal species, determines the way in which the molecules are bound to each other, as previously explained, influencing the final mechanical properties of the produced products.
When comparing the mycelium composites to conventional EPS foam, it is possible to see that EPS presents a lower density and lower thermal conductivity. It can be understood that a decrease in density and an improvement in mechanical properties is therefore needed in order for the mycelium composites to be competitive with EPS foams.

7

CONCLUSION

The present project focuses on the possible application of biomass residues as cellulose and roadside weeds for the production of mycelium composites. The research is first centered on the mycelium growth capabilities of the mentioned fibres for then analyzing the mechanical properties of the obtained mycelium composites. For the former phase, two species of fungi are used: Ganoderma lucidum and Pleurotus ostreatus. Instead, for the material properties study, for compressive and bending strengths only Ganoderma is considered, however, for thermal insulation tests both Grey oyster and Ganoderma are used.

MYCELIUM GROWTH

Substrates as hay, reeds and raw cellulose are grown as both pure substrates and mixture with hemp. Reeds do not show mycelium growth when used as pure or mixed substrate. On the other hand, both hay and raw cellulose show homogeneous hyphal growth throughout the whole substrates, when used as pure and mixed with hemp. A difference in growth can be noticed between Ganoderma and Grey oyster. The former fungi, when found on substrates as hay and cellulose, is able to homogeneously grow throughout the whole substrate, showing dense and thick hyphal growth. On the other hand, Grey oyster when used on the three mentioned substrates show a more scattered growth, which could result in lower mechanical properties. In conclusion both the processed cellulose as well as raw cellulose have proven to be applicable for mycelium growth. The raw cellulose takes two days extra time to start growing, but could be more interesting from an economic perspective. In this study the combination with Ganoderma *lucidum* proved to grow the best, however, other species could result in even better growth and strength of the materials.

MATERIAL PROPERTIES

The material properties of mycelium composites obtained from pure and mixed substrates of cellulose, hemp, straw and wood chips is studied. The compressive strength, bending strength and thermal insulation is the focus of research.

COMPRESSIVE STRENGTH

Different processes are looked at when considering the compressive strength, such as cold press, cold press with further growth, heat press and non-press. The heat pressed samples show the highest compressive strength and generally lowest densities. The samples presenting the better performance are the mixed hemp and cellulose. This can be derived by the chemical composition of the used fibres, in fact cellulose is an easy source of energy for the mycelium, while hemp, because of its lignin content enhances the mechanical properties of the specimens. When compared to conventional materials both their densities and compressive strengths are higher. Ideally a low density and high strength would be desired as it gives a lot potential for applications. In this case the higher densities decrease the market value of mycelium composites, but it something that could be optimized regarding density – strength ratio.

BENDING STRENGTH

For the board material, the bending strengths of samples made of mixture of cellulose and wood chips present the highest bending strength, followed by the cellulose and hemp mixture. Also in this case, when compared with MDF the mycelium composites present lower bending strength. Despite the lower densities of the mycelium composites compared to MDF, the difference in strength is more significant.

THERMAL CONDUCTIVITY

Mycelium composites made of pure hemp (inoculated with Ganoderma) show the lowest thermal conductivity and density. The values are lower than the samples made of pure cellulose and hemp and cellulose mixture. This indicates that the addition of cellulose would not benefit the insulating performance, although this might mainly be due to the smaller fibres and therefore higher density of the material.

Moreover, the specimens inoculated with Grey oyster present the highest values, determining the preference in using Ganoderma as species. Ganoderma can in fact colonize the substrates thoroughly, resulting in stronger composites.

OVERALL CONCLUSIONS

This study shows the potential of residues as cellulose and hay, also used in the combination with hemp, straw and wood chips. The species Ganoderma has shown to be the easiest to grow, and the one presenting more valuable mechanical properties (when looking at the thermal insulation). As overall, mycelium composites can be considered as valuable when compared to conventional products, especially when looking at the limited needed resources to produce them. However, the higher densities characterizing the mycelium composites can be regarded as a characteristic to work on in order to increase the value of these innovative products.

In conclusion, the research shows the potential of cellulose and certain types of roadside weeds to produce mycelium composites. The material mechanical properties of the mycelium foam can be recognized as valuable, even though more study needs to be performed in order to improve them and make them a biobased alternative for EPS. In relation to bio foam, mycelium composites are more promising as they have a much higher compressive strength and similar density (when non pressed).

Regarding the mycelium board material, it would need significant improvement of strength to be applied as a structural material in comparison the MDF. With more research on heat pressing parameters and chemical reactions during this process, there is definitely potential for the mycelium to be a completely natural alternative without any adhesives.

From economic perspective these mycelium composites are not yet feasible as the conventional materials are in a very low price range. At this moment the mycelium process has not yet been industrialized and optimized. With the focus on circular economy and the need for new biobased materials, mycelium composites are interesting but need further research to achieve their potential.

A more defined final product and application can help in modelling a more specific research question. Currently, the application in the acoustic field can represent a wider and more feasible opportunity in commercializing mycelium composites.

BIBLIOGRAPHY

Al-Khalidi, B. A. (2017). *Sterilization.*

Asmamaw Tesfaw, A. T. (2015). *Optimization of oyster (Pleurotus ostreatus) mushroom cultivation using locally available substrates and materials in Debre Berhan, Ethiopia .*

Cellvation BV. (2018). *Cellvation* . Retrieved from Cellvation .

Charles Alan Rocco, R. E. (2010). *PLASTICIZEDMYCELIUM COMPOSITE AND METHOD.*

G.A. Holt, G. M. (2012). *Fungal mycelium and cotton plant materials in the manufacture of biodegradable molded packaging material: evaluation study select blends of cotton byproducts.*

government, H. A. (2012). *Australian fungi*. Retrieved from An Australian government initiative: https://www.anbg.gov.au/fungi/mycelium.html

ImanTaha, M. S. (2016). *Potential of utilizing tomato stalk as raw material for particleboards.*

J.N. Buah, G. V. (2010). *The Growth and Yield Performance of Oyster Mushroom (Pleurotus ostreatus) on Different Substrates.*

Jing Peng, J. T. (2015). *Thermal Pasteurization of Vegetables: CriticalFactors for Process Design and Effects on Quality.*

José C. del Río, J. R. (2012). *Structural Characterization of Wheat Straw Lignin as Revealed by Analytical Pyrolysis, 2D-NMR, and Reductive Cleavage Methods.*

José Maria Rodrigues da Luz, M. D. (2012). *Lignocellulolytic enzyme production of Pleurotus ostreatus growth in agroindustrial wastes.*

M. L. Lomberh, E. F. (2002). *STUDIES OF MEDICINAL MUSHROOMS IN SUBMERGED CULTURES.*

Mizi Fan, S. H. (2014). *Lignin in straw and its applications as an adhesive.*

Muhammad Haneef, L. C. (2017). *Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties.*

Mustafa Nadhim Owaid, S. S.-S.-A. (2015). *Growth Performance and Cultivation of Four Oyster Mushroom Species on Sawdust and Rice Bran Substrates.*

Phyllis. (2003). *Phyllis*. Retrieved from Phyllis: https://phyllis.nl/Browse/Standard/ECN-Phyllis#hay

Pooja Kapoor, B. S. (2014). *STUDIES ON DIFFERENT GROWTH PARAMETERS OF GANODERMA LUCIDUM.*

Ralph H. Kurtzman, J. (2010). *Pasteurization of mushroom substrate and other solids.*

Raúl Castanera, G. P. (2012). *Transcriptional and Enzymatic Profiling of Pleurotus ostreatus Laccase Genes in Submerged and Solid-State Fermentation Cultures.*

Recell BV. (2018). *Recell* . Retrieved from Recell: www.knncellulose.nl

Rózsa, S., M niu iu, D.-N., Gocan, T.-M., Sima, R., Andreica, I., & Rózsa., M. (2017). *AGARICUS BLAZEI MURRILL MUSHROOM COMPOST STUDY ANAEROBIC AND AEROBIC PHASES.*

Shaojun, X., Carlos, M., Lill, E., Maogui, W., Olena, M., Larsson, S. H., . . . Jönsson, L. J. (2018). *Energy-efficient substrate pasteurisation for combined production of shiitake mushroom (Lentinula edodes) and bioethanol.*

Silva, C. F., Azevedo, R. S., Braga, C., Silva, R. d., Dias, E. S., & Schwan, R. F. (2009). *Microbial diversity in a bagasse-based compost prepared for the production of Agaricus brasiliensis.*

Suk-Jun Jung, S.-H. K.-M. (2015). *Comparison of lignin, cellulose, and hemicellulose contents for biofuels utilization among 4 types of lignocellulosic crops.*

Suldbold Jargalmaa, J. A.-Y. (2017). *Taxonomic evaluation of selected Ganoderma species and database sequence validation.*

Tisdale, T. E. (2004). *Cultivation of the oyster mushroom (pleurotus sp.) on wood substrates in Hawaii.*

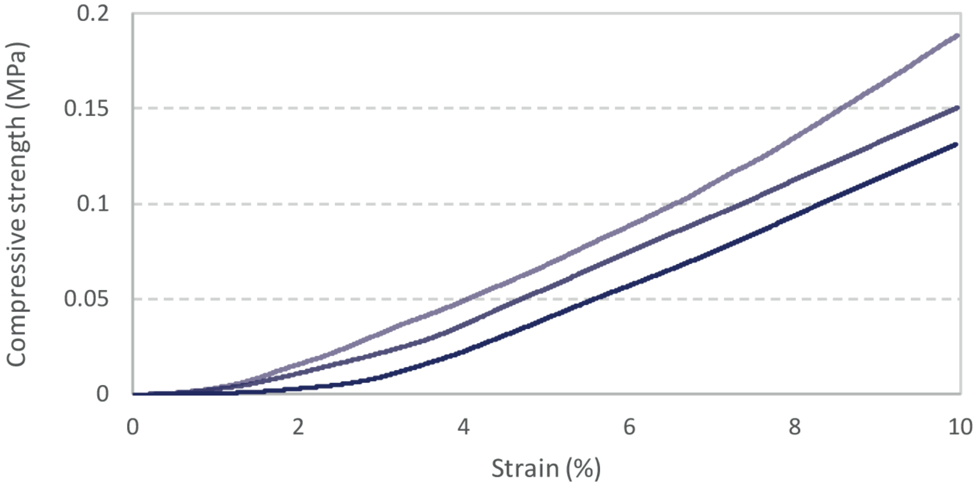
Tommi Räisänen, D. A. (2013). *BASIC CHEMICAL COMPOSITION OF THE BIOMASS COMPONENTS OF PINE, SPRUCE AND BIRCH.*

Turkovi , S. (2015). *Mycelial growth rate and yield of oyster mushroom - Pleurotus ostreatus fruitful part (Jacquin: Fr.) Kumm at different temperatures.*

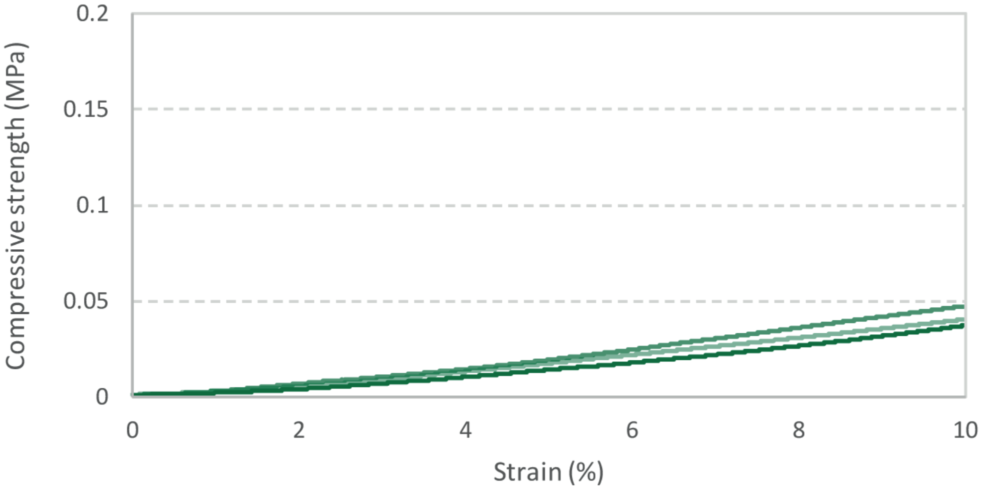
APPENDIX 1

NON PRESSED SAMPLES

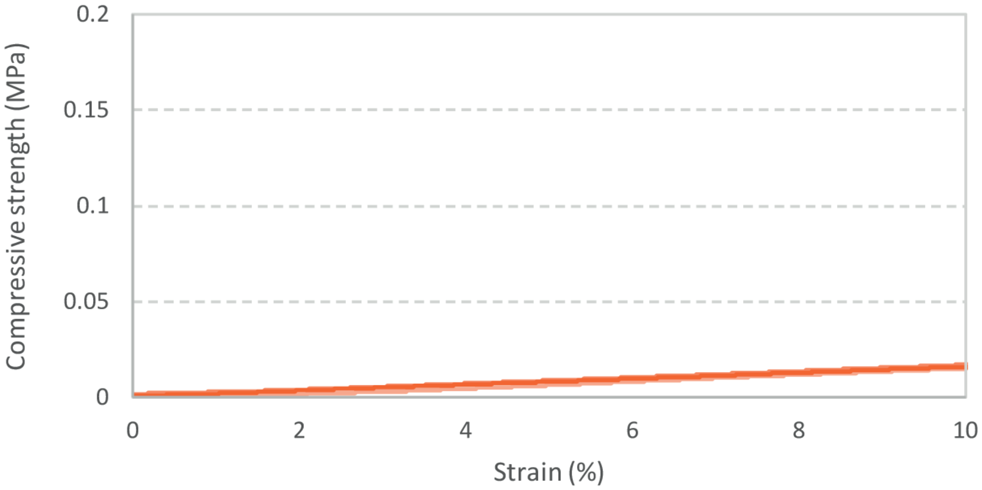
CELLULOSE



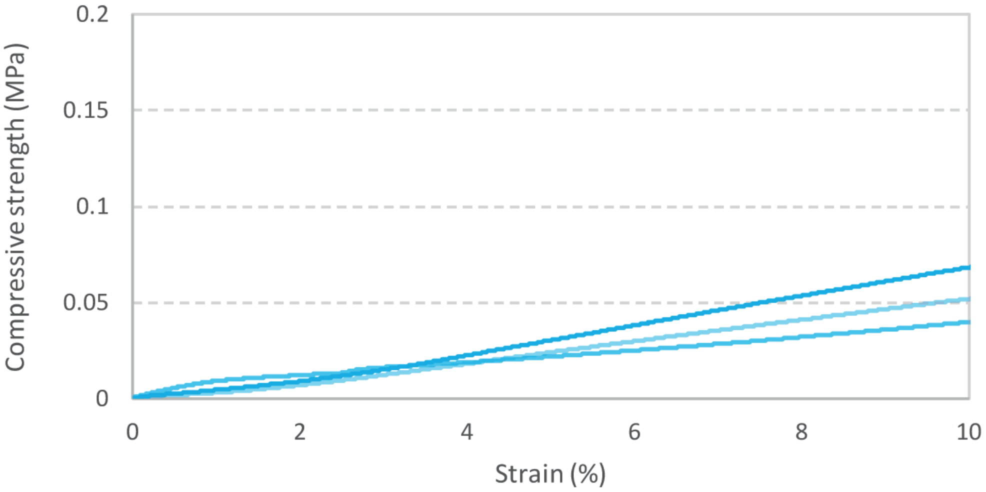
CELLULOSE + HEMP



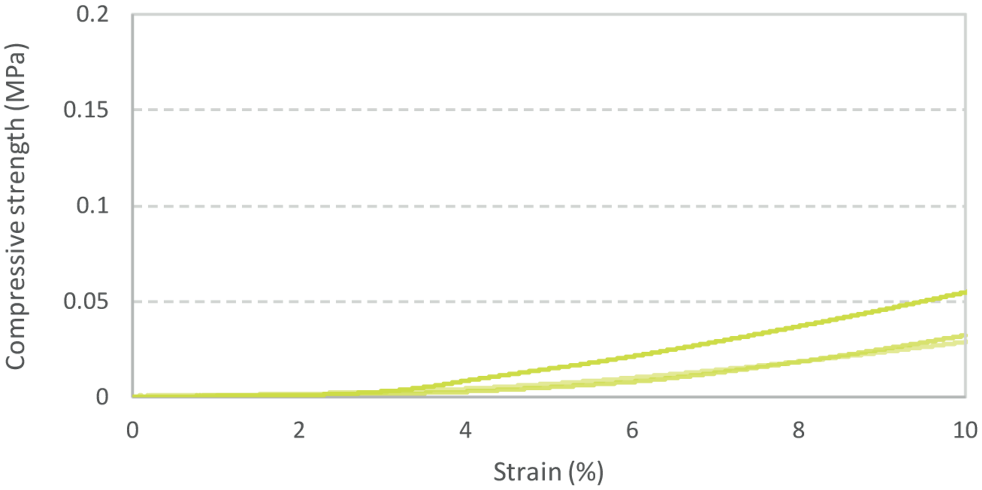
STRAW



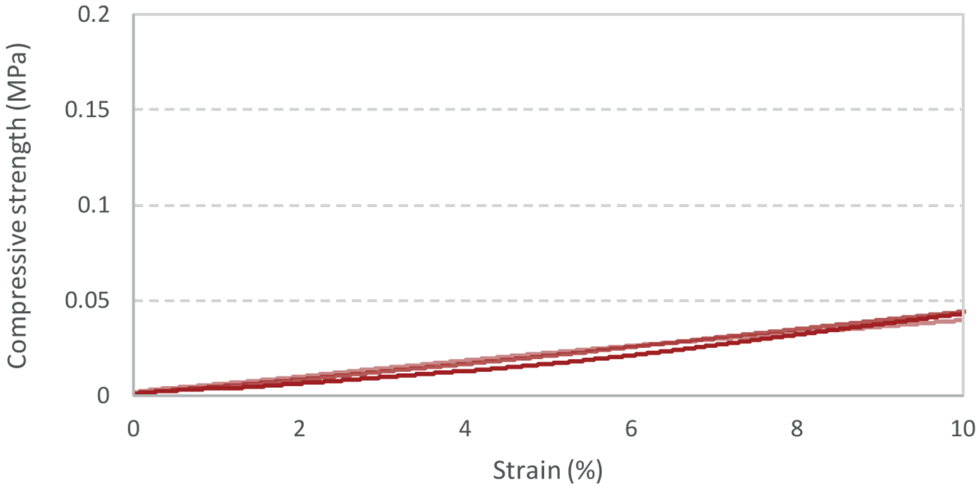
CELLULOSE + WOOD



HEMP



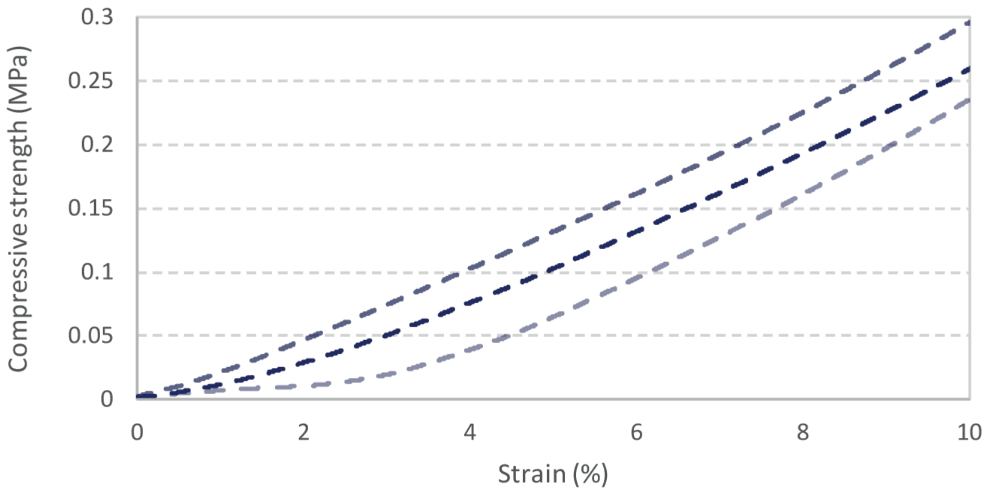
CELLULOSE + STRAW



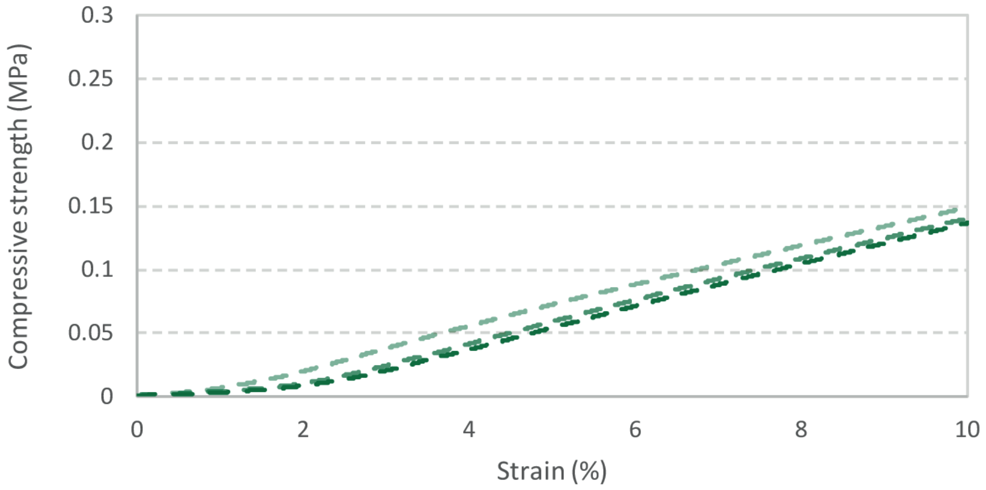
APPENDIX 2

COLD PRESSED SAMPLES

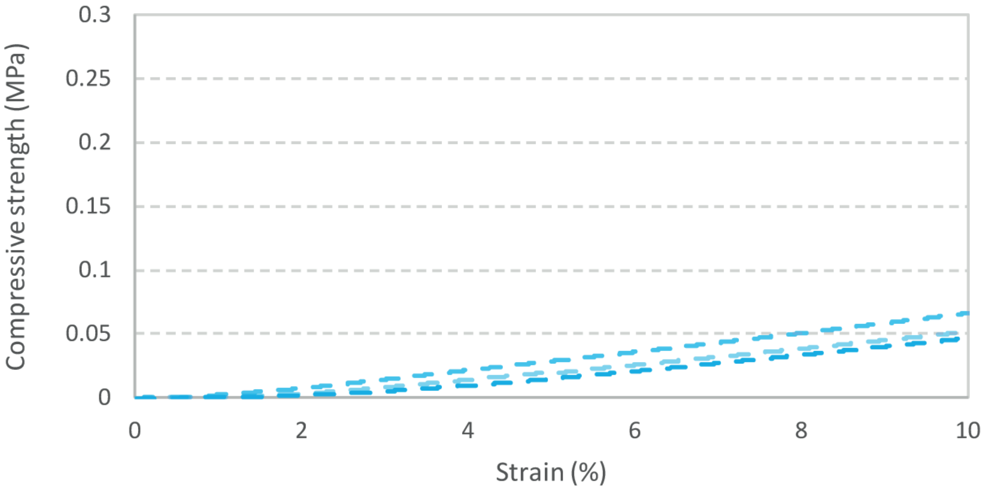
CELLULOSE



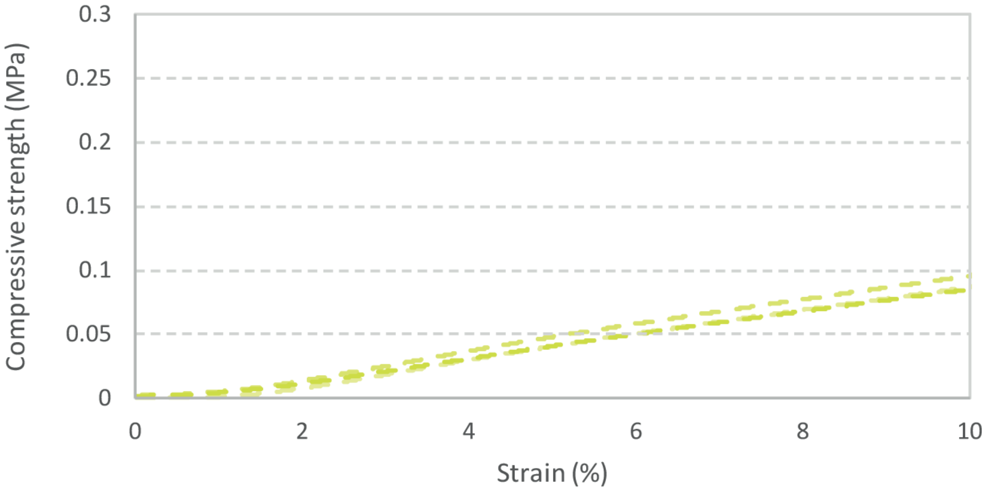
CELLULOSE + HEMP



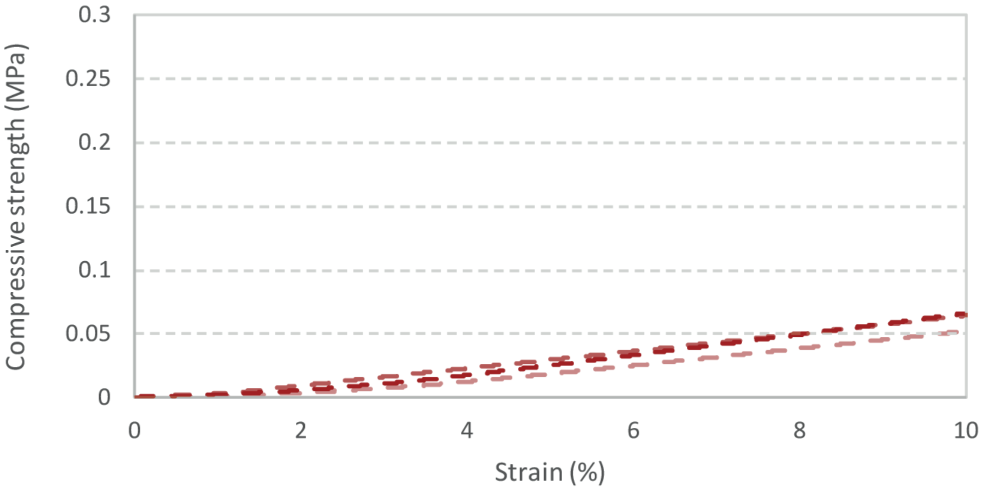
CELLULOSE + WOOD



HEMP



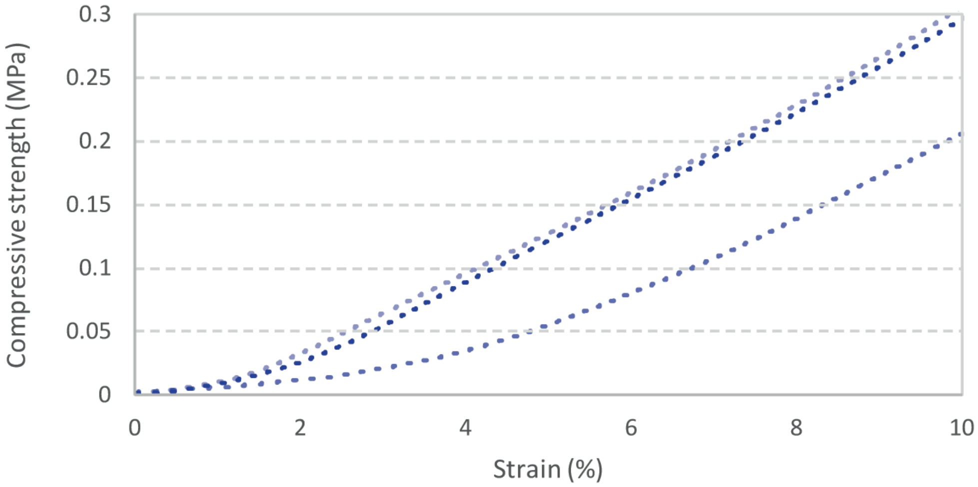
CELLULOSE + STRAW



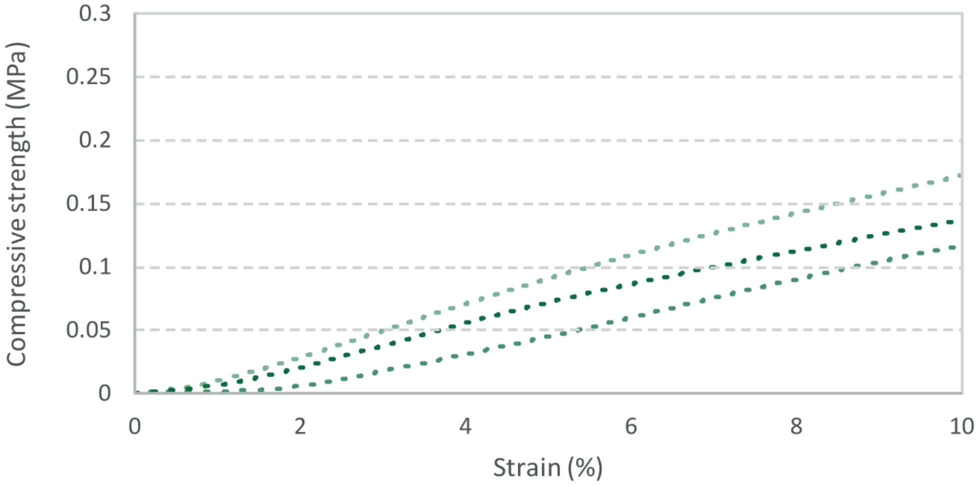
APPENDIX 3

COLD PRESSED + GROWTH SAMPLES

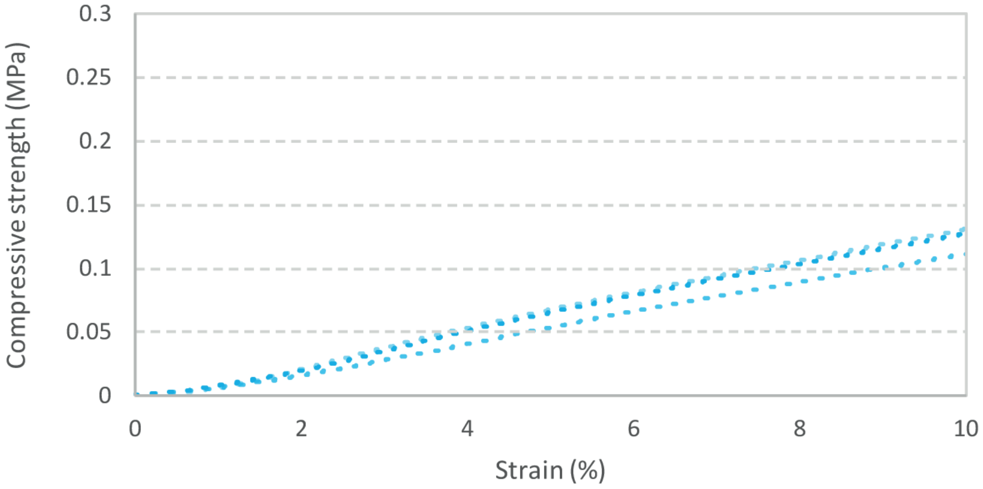
CELLULOSE



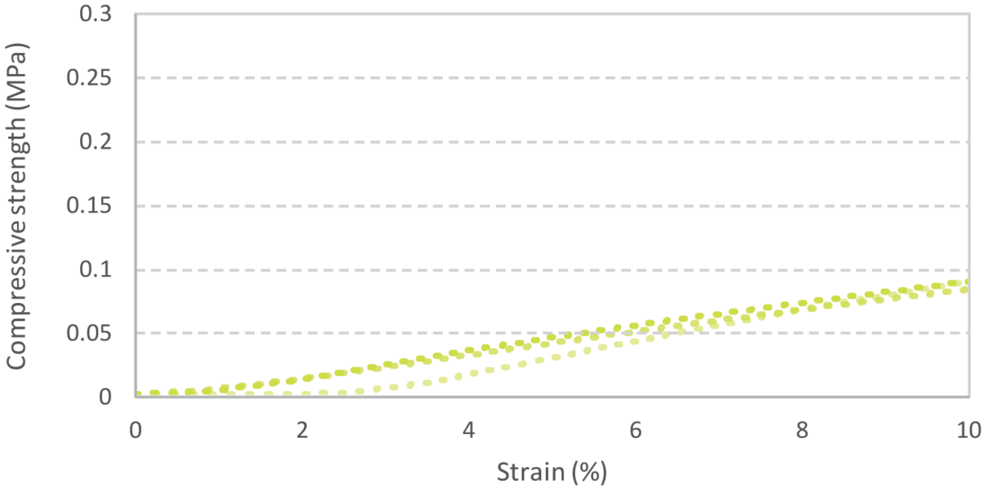
CELLULOSE + HEMP



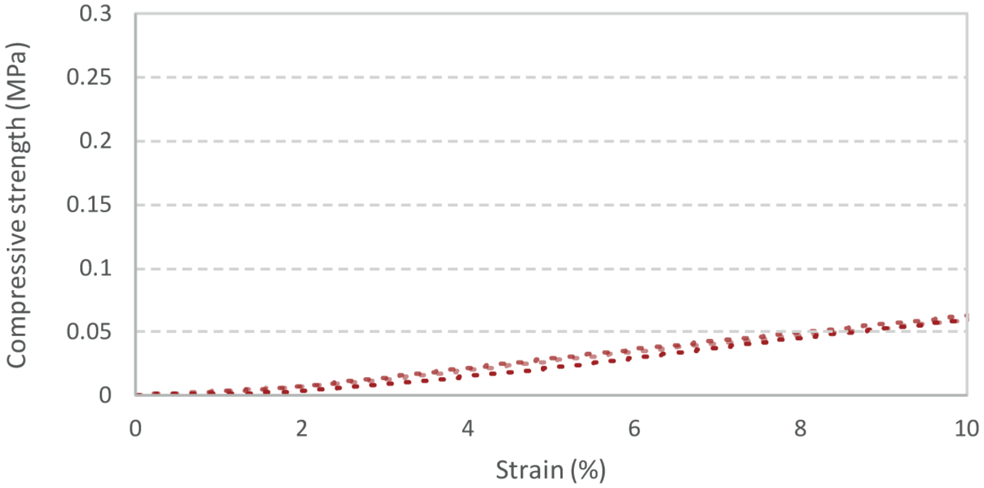
CELLULOSE + WOOD



HEMP



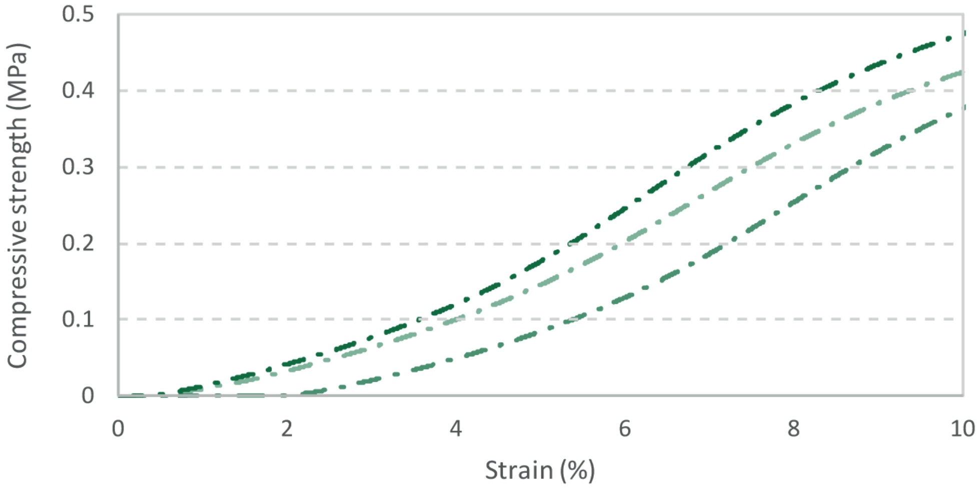
CELLULOSE + STRAW



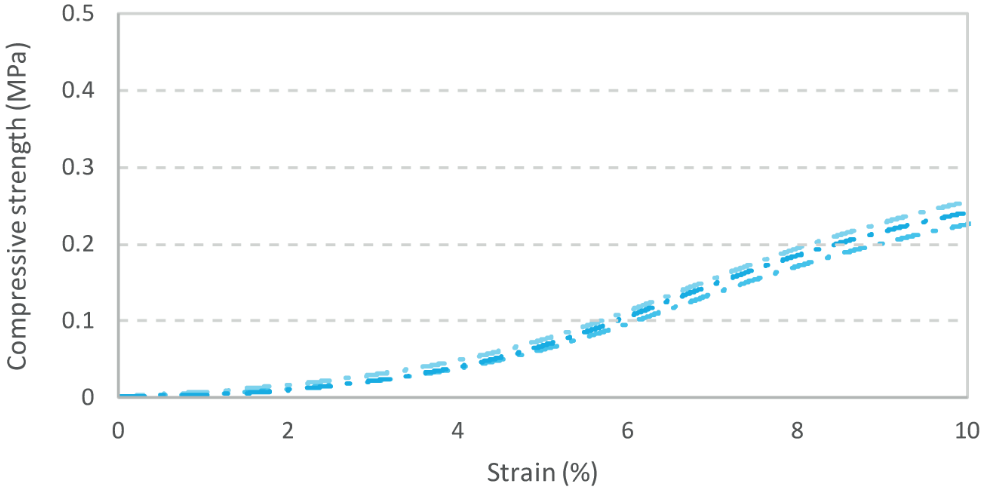
APPENDIX 4

HEAT PRESSED SAMPLES

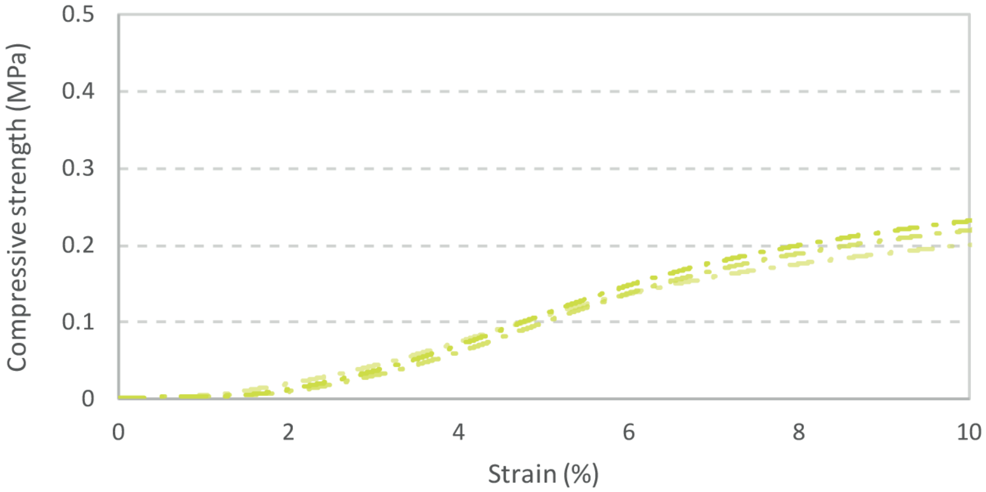
CELLULOSE + HEMP



CELLULOSE + WOOD



HEMP



CELLULOSE + STRAW