THE POSSIBILTY OF REPLACING STONES WITH MYCLIUME COMPOSITES

Author: Sherif F.F. Ghaly

In-company supervisor: Joost Vette.

HZ first examiner: Vana Tismopoulou.

Middelburg, January 2022

Table of Contents

Chapter 1: Introduction

1.1) Problem statement

Climate change and the depletion of the world's natural materials are widely regarded as major socioeconomic issues. One of the most critical elements will be reducing energy use and the associated usage of fossil fuels and fossil-based products. Building construction and use account for 40% of total European energy consumption and around 45 percent of CO2 emissions (economy, centre of experties biobased, 2018). Almost half of this energy is encapsulated in materials.

According to the United Nation Environment Program (UNEP), which has reported that the building and construction industry is in charge of the consumption of 36% of the global energy consumption, this industry is also responsible for 40% the carbon dioxide emissions, as the process of producing the construction materials consumes a lot of energy and emits a significant amount carbon dioxide. (Abegaz, 2019)

Table 1 presents the amount values of the embodied energy and amount of CO2 emission per Kg of material for several construction materials:

Materials	**Coefficients**	
	Embodied Energy (MJ/Kg)	**CO_2 Emissions (Kg/Kg)**
Cement	3.32	0.730
Sand	0.06	0.004
Coarse aggregate	0.16	0.010
HCB	7.96	1.550
Rebar	15.97	1.06

Table 1: Embodied energy & Co2 emissions coefficient (Abegaz, 2019)

The usage of natural resources is increasing day by day and the increasing demand for raw materials is putting a great strain on the environment. It is quite advantageous to figure out an ecologically friendly technique for building by employing a bio-based material that has a very low influence on our ecosystem. As a result, an alternative bio-based material has to be introduced to the market, during this project the main will be focusing on a bio-based material called Mycelium. Because mycelium is made up of fungus and an organic substance that will act as nutrients for the fungus to feed on, it is necessary to provide an adequate environment for the fungus. This organic substance that the fungus will consume in order to build a network of hyphal micro-filaments that will bind the organic material and form a mycelium composite is referred to as the substrate.

The aim of this project is to investigate whether it is possible in the future to build a bridge with mycelium composites. Since mycelium seems to be a material with high compressive strength, the main focus will be on bridges whose construction elements need a good compressive strength, such as roman bridges. In order to make sure that the design used is reliable, I will be using a bridge design that has been existing for years already, which is Pont Saint Martin in Aosta, Italy. (A.Sinopoli, 1998) During this project, I will be using this bridge as a case study and trying to figure out whether it is possible to replace the stones used in that bridge with mycelium bricks or not.

When the bricks of mycelium are put in groups, the bricks start to get attached together, due to the strong bond that has been formed between them, after a couple of hours. They also absorb Carbon dioxide, that's why it is considered as one of the most sustainable materials for construction. (de Bruin, 2018)

However, there are still some information about this material that need to be figured out. For example, which substrate produces the mycelium composite with the highest compressive strength. The organization that I am working with, Bio Based Economy, gave me access to labs where I made Mycelium composites and performed compression tests on them. The organization also provided all materials needed to produce Mycelium composites. In addition, I Had an in-company supervisor, Mr. Joost Vette who was assisting me throughout the project by having weekly meetings to discuss the progress of the project step by step.

1.2) Objective

Research questions:

- Can mycelium bricks replace stones of the roman bridge of Pont Saint Martin in Aosta, Italy?

1. Which substrates will result in the composites with highest compressive strength?
2. How much compressive force can the mycelium composites resists?
3. How much compressive force can a stone brick in Pont Saint Martin bridge resist?

Chapter 2: Theoretical framework

2.1) Background of bio-based materials in construction

The European standard EN 16575 defines 'bio-based' as 'produced from biomass.' As a result, a bio-based product is one that is entirely or partially generated from biomass. Biomass is defined as material of biological origin that is not buried in geological formations or petrified (EN 16575, 2014). Paper and wood are examples, but so are polymers like PLA, whose building blocks are made from sugars. (Martien van den Oever, Karin Molenveld, Maarten van der Zee, Harriëtte Bos, 2017)

2.2) Background of Mycelium

Mycelium is the vegetative roots part of the fungi and it can also be the bottom part of the mushroom which is the part below the soil as shown in figure 1, the roots. Mycelium is made of hyphae, hyphae is a fiber threads that has the ability to get stretched and prolonged cell, mainly consists of Chitin, glucans and proteins. (Davine Blauwhoff, Ilaria La Bianca, 2019; Davine Blauwhoff, Ilaria La Bianca, 2019; Davine Blauwhoff, Ilaria La Bianca, 2019)

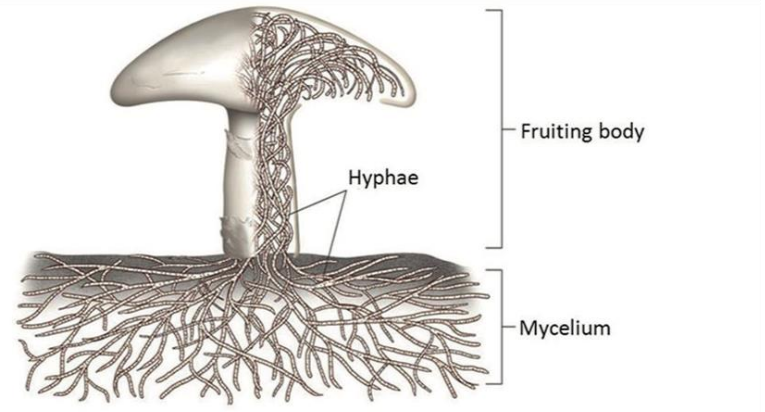


Figure1: Mushroom drawing (Davine Blauwhoff, Ilaria La Bianca, 2019)

Fungi can decompose very stable compounds like plant structural polysaccharides thanks to a complex enzymatic mechanism. The mycelium has the power to consume the substrate, grow through it and keep it together. Resulting in the formation of a natural and light-weight bio-based composite. (Davine Blauwhoff, Ilaria La Bianca, 2019) This procedure creates a high-value composite from a low-value material by connecting the substrate with a network of long and branching filamentous structure of fungus. (Ltd, 2019)

2.3) Chemical process of growing mycelium

Mycelium composites are produced by inoculating an individual strain of fungi in a substrate. The substrate is the organic fiber-based growth medium for mycelium, these fibers make the mycelium composite a more durable material. Mycelium grows on fiber-rich substrates like sawdust, straw and other agricultural waste streams.

Mycelium may be grown using a variety of fungus from the Basidiomycota genus. Mycelium-based materials may be grown in oyster mushrooms (Pleurotus Ostreatus), turkey tail mushrooms (Trametes Versicolor), reishi mushrooms (Ganoderma Lucidum) and Dryad's saddle mushrooms (Cerioporus Squamosus). These species have the ability to form thick mycelium networks that grow quickly and are not easily contaminated by other organisms, making them easy to cultivate. (de Bruin, 2018)

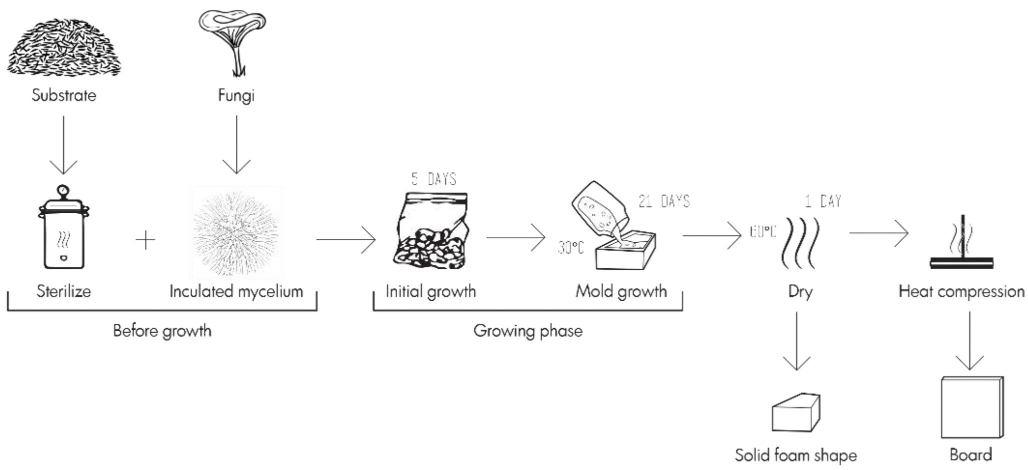


Figure 2: Schematic representation of the mycelium-based composite manufacturing process.

The manufacturing of mycelium composite materials is separated into three stages: the pre-growth stage, the growing phase, and the post-processing stage as shown in figure 2. For each stage there are some parameters need to be considered as they affect the quality and properties of the product.

In the pre-growth stage parameters related to the substrate and fungal specie should be considered, like the amount of substrate added and the amount of fibers in the substrate. While in the growth phase, parameters related to the growing environment like temperature, level of humidity, and the intensity of light and oxygen have an influence on the strength of the mycelium composites. In the post-processing phase, the material has to be dried or heated to end the growth phase.

When mycelium is dried, it remains in a "hibernated" state and will begin to grow again with the correct environmental growth circumstances. Heating the composites at 60 degrees Celsius for 24 hours will permanently halt the growth process of mycelium. With heating, mycelium composites exhibit qualities comparable to polystyrene or other foams, but after heat pressing (putting a weight on top of the sample while heating so its dimensions do not change), the mycelium composite becomes more solid and stronger, similar to natural materials such as wood. (de Bruin, 2018)

2.4) Typical design of roman bridges

2.4.1) Roman Arch bridge

Stone arch bridges are one of the world's most durable structures. More than two thousand years ago, the Romans used lime mortar to construct stone arch bridges and aqueducts. In the middle ages, there are stone arch bridges that have stood the test of time for hundreds if not thousands of years and are still as strong as they were when they were built. (BTC uganda, 2013)

A curved compression member carrying a transverse load is what an arch is. The use of the compression cross section gives arches their remarkable structural efficiency. (Dirk Proske, 2009). The vault is a stone ceiling made up of wedge-shaped stones that impends freely and transfers its own weight and operational stresses to the walls and columns. From a static standpoint, vault bridges may be thought of as arched girders since they create a horizontal pressure resulting from the vertical loads. A vault bridge acts as a support structure that allows bridges to pass over highways and other barriers This structure has a curved surface with either simply parabolic or parabolic and elliptic points protruding from the sides, as well as a clearance of at least 2.0 m. The substance used for making this structure is compressible but has low tensile resistance. (Dirk Proske, 2009) Which is very similar to the properties of mycelium composites, as it also has high compression force and low tensile resistance.

Arch bridges are all built using the same fundamental idea, which is simple but takes some expertise and training to ensure that the constructions are sturdy and long-lasting. Stone arches are constructed atop a temporary wooden formwork that keeps the masonry in place while it is being erected. Because the structure will not be stable until the arch is closed, the interim shape is required. (BTC uganda, 2013) The same technique of building will be used in building the mycelium bridge as well.

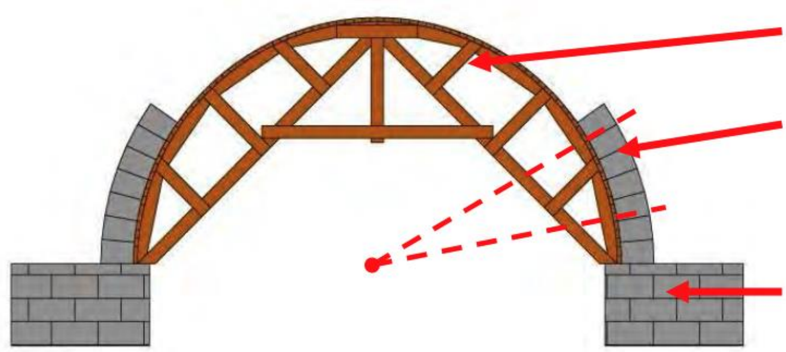


Figure 3: temporary wooden formwork (BTC uganda, 2013)

2.4.2) Limitations of roman bridges

It is critical to analyze the local environment to ensure that a stone arch bridge is the best choice. Where labor costs are high, the building cost of a stone arch bridge may surpass that of a concrete bridge. Another difficulty is increasing the capability of local artisans and contractors. (BTC uganda, 2013)

The rise-to-span ratio of 1/2 already reveals a serious difficulty with Roman arch bridges. Such high-rise bridges require steep ramps that were difficult for carriages to cross. Wide piers were a second issue with Roman bridges. The Romans devised countermeasures here. Either the piers were built with more apertures to allow more water movement in the event of flooding or the bridge's superstructure was simply built very high above the valley. (Dirk Proske, 2009)

The limitations of the roman bridges are the same as the limitations of the mycelium bridge, since the two bridges have the same design. The difference is in the components of each bridge as the stone will be replaced with mycelium composites.

2.5) compression test

2.5.1) Compressive strength of materials

The maximum compressive load that the floor material can sustain without collapsing or deforming beyond what is permitted is defined as the compressive strength of the floor.
Loads on a material such as stones are represented as the force applied divided by the area required to support the material. **Compression Strength = Force ÷ Area**

The compressive force generated by a cylindrical shaped container is for instance equal to weight of the planter including soil and plants divided by the area of the planter's bottom. (Marble Institute of America, 2016)

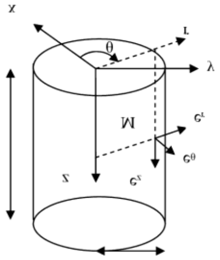


Figure 4: cylindrical shape

To offer a safety factor, permissible loads in real usage are fewer than the maximum loads that a material can resist during testing. To determine the allowed design strengths, the maximum material strengths are lowered by a safety factor in all structural designs. The safety factor accounts for differences in strength of the material, potential increase loads in usage and other factors. (Marble Institute of America, 2016)

2.5.2) compressive strength of granite stones

The endurance to crushing loads is measured by compressive strength. For instance, if one were to construct a stone wall, the stone at the bottom would have to bear the compressive load of the stones above it. A stone floor must be able to withstand the weight of people, furniture and other items on it. The compressive strength of a stone refers to the greatest load per unit area that it can withstand without crushing. A stone with a higher compressive strength can resist a greater crushing load. The required values range from1,800 psi (12.45 MPa) for marble to 19,000 psi (131 MPa) for granite. (Marble Institute of America, 2016)

2.5.3) The process of measuring the compressive strength of stone sample

Multiple specimens of stone are examined to assess compressive strength. They should be a cubed shape with a side length of at least 2" to 3". Every cube face has to be completely flat

Centre of Expertise Biobased Economy

and parallel or perpendicular to the one before it. There should be no tool scratches on the surfaces and no bumps at the edges of each cube. The sides should be refined or polished to remove all blade marks and other tool markings. Any defects in the samples might cause the compressive strength to be lower. That's why in some cases, the testing facility remake the samples in order to provide flat surfaces suitable for compression testing. (Marble Institute of America, 2016) The same procedure of compressive strength testing will be used for measuring the compressive strength of the mycelium composites as well.

It is possible to measure the compressive strength in both dry and wet conditions, with the load parallel or perpendicular to the fissure. The specimens are dried or soaked for 48 hours in both the dry and wet conditions. The specimen is put on the flat plate of the testing equipment for compressive strength testing and increasing stresses are supplied to the top of the specimen through another flat plate. (Marble Institute of America, 2016)

Chapter 3:

3.1) Methodology

This project will be focusing on the suitability of cellulose, hemp shives and hemp fibers as substrates in producing mycelium composites. The project is composed of two main stages, the first stage is the material development focuses on the growth of the substrate and processing the material, while the second stage is testing the compression strength of the material that has developed. Some compression tests need to be performed to have a solid information regarding the compression strength of the mycelium composites that will be produced. (Davine Blauwhoff, Ilaria La Bianca, 2019)

The main objective of this project, is to figure out whether it is possible to replace the stones with mycelium bricks in a roman bridge design or not. The answer of this question will be divided into several sections.

3.1.1) The substrate that will produce mycelium composite with highest compressive strength

Three types of mycelium composites will be made in the lab out of three different substrates, according to the ISO standards, (economy, 2019) the first type is pure hemp shives, the second one is a mix between cellulose and hemp shives and the third type is a mix between cellulose and hemp fiber.

3.1.2) The mycelium type with highest compressive strength

After producing the three types of mycelium, a compression test will be performed on the three types, the compression strength values of the three types will be compared with each other to know which type has the highest compressive strength.

3.1.3) compressive force exerted on the stone bricks of Pont Saint Martin bridge

In order to figure out the possibility of replacing the stone brick with mycelium brick, first the compression force exerted on the stone brick of Pont Saint Martin bridge needs to be calculated and compared with the compressive strength of the mycelium composites that where done in the lab. So a case study will be done on the structure of Pont Saint Martin bridge to know the maximum values of compression forces acting on that bridge.

3.2) Mycelium growing process

In order to make a mycelium composite a type of fungus and a substrate is required. Substrate is the organic material that the fungi will digest to create a network of hyphal micro-filaments that will bind the organic material (substrate) and form a mycelium composite. (Ltd, 2019)

This process consists of several steps (see figure 2), but before starting these steps, there are some factors which have a direct influence on the properties of the composites need to be considered. For example, the composition of the substrates and their structure. The most likely substrate to be chosen is the one that is rich with cellulose fibrous material, as it supports the mycelium with nutrients which make the process of growing the mycelium easier. (Avans University of Applied Science / CoE BBE, HZ University of Applied Sciences / CoE BBE, Utrecht University, 2018)

In Addition, there are some growing conditions that need to be considered as well, like temperature, level of humidity and the intensity of light and oxygen, these conditions have a direct impact on the density of the final product as previous tests shown the more humid and less air, the denser the composite will be. (Avans University of Applied Science / CoE BBE, HZ University of Applied Sciences / CoE BBE, Utrecht University, 2018)

The first step in the growing process is mixing the fungus with the substrate, the mix of the fungus and substrate is called feedstock, then the feedstock is placed in plastic bags with holes in it to allow the passage of oxygen in to the bags as the fungus will need oxygen while feeding on the substrate to start producing the Mycelium. Then the feedstock has to be sterilized by using heat treatments like pressurized steam and autoclaving to make sure that there no bacteria that might ruin the growing process.

Depending on the type of substrates and fungus, it takes from 5 to 7 days after the initial growth for the mixture to be removed from the plastic bags and put into molds where the mycelium is going to grow into the required shape which is the brick shape. The real growth will take place in the incubator where a temperature of 27 degrees Celsius is required, also the incubator need to be totally dark as the light will encourage the growth of fruiting bodies which is not required at all. The time taken from inoculation to the final growth level may differ between 10 to 14 days. During this growing time, the fungal hyphae will start to be formed in the shape of white blanket. After the growing process is finished, a heat press is required in order to dehydrate the final product. (Avans University of Applied Science / CoE BBE, HZ University of Applied Sciences / CoE BBE, Utrecht University, 2018)

Chapter 4: laboratory work execution & results

4.1) Creating mycelium bricks

Mycelium composite materials are manufactured in three stages: pre-growth, growth, and post-processing. The characteristics of the substrate and fungus species in the first phase, the environment in the development phase and the processing in the final phase all have a direct impact on the quality of the products.

First, the ISO standards (economy, 2019) for creating Mycelium samples were checked, this ISO standards were set by the organization bio-based economy. There are numerous standards that we can pick from, the amount of the samples to be done will be determined based on the type of test that will be performed on the samples.

Since compression test will be performed on these samples, the volume of each sample will be 120 x 120 x 30, because this was the size of molds provided be the organization Bio Based Economy. A mold is a plastic frame where the mycelium is put in to be in the shape of a brick, hence the surface area of the sample should be at least 25 cm2. The water content necessary for each sample had been evaluated after determining the volume of each sample. The water content necessary for the sample and is determined by the kind of substrate utilized in the sample and the wieght of the substrate.

Three different types of mycelium were done, each type was done with different substrate, and every type had different water content:

1. In the first type, the substrate used was pure hemp shive.
2. In the second type, a mix of hemp shive 70% + cellulose 30% were used.
3. In the third type, a mix of hemp Fibers 70% + cellulose 30% were used.

After checking the information given by my host organization (Bio based Economy), the following information regarding the water needed for each type substrate that will be used for making the samples was found: (economy, 2019)

1. 41.2 grams of water needed for each 20 grams of Hemp shive
2. 26.7 grams of water needed for each 20 grams of Hemp fiber
3. 50.5 grams of water needed for each 20 grams of raw cellulose

The mass of each substrate used had to be calculated, in order to calculate the amount of water content required for each sample, since the volume each sample was known, which was 120 x 120 x30= 432000 mm3 (for each sample) x 8 (samples) = 3456000 mm3 of substrate for each type is required. After that, the mass was measured by converting the 3456000 mm3 into 3456 ml, however 4000 ml was used instead as some substrates might be lost during the process so always make more than required to be in the safe side. The graduated cylinder had been filled by 4000ml and its mass was measured by using a scale.

Figure 5: Graduated Cylinder

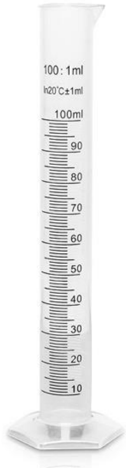


Figure 6: Scale

4.1.1) Mixing substrates with water

First type of samples (Pure Hemp shive)

After filling 1000 ml of hemp shive for four times in the graduated cylinder, the mass was measured, it was 516 grams, since the pure hemp shive requires 41.2 grams of water for every 20 grams of substrates, the 516 grams were divided by 20 and multiplied by 41.2, so 1062.96 grams of water where added to the 4000 ml of pure hemp. Then, the 516 grams of pure hemp and the 1062.96 of water were mixed together in a bucket, before adding them into a plastic bag and sterilizing the substrate and water by using boiling steam for 90 minutes, to make sure that there is no living organism in substrate and that the only ones will be were the fungus that will be added which was the Ganoderma. After that, the bag containing the sub-strate were left to dry up before the fungi was added as the weight of the fungi required is 3% of the dried weight of the substrate.

Figure 7: bag of Hemp shive with 265.74 g of water

Second Type Of samples (Hemp shives + Cellulose)

In this type, 70% hemp shive which is 2800 ml and 30% of cellulose which is 1200 ml were used, after measuring the mass of each substrate, there was 363.44 gram of hemp shives and 236.36 grams of cellulose, these values were divided by 20 grams and multiplied by 41.2 grams for hemp shives and 50.5 grams for cellulose, in order to calculate the required amount of water that was added for each substrate, the required water content was 596.809 grams for the cellulose and 748.68 for the hemp shives.

Figure 8: Cellulose

Figure 9: 90.8 grams hemp shives 1

After that the two substrates were mixed together with the required amount of water for each substrate, then they were put into plastic bag and sterilized by using boiling steam for

90 minutes and it was left for 10 minutes to dry up, in order to measure the dried weight and add the fungi of 3% of that weight to the plastic bag.

Third Type Of samples (hemp Fiber + Cellulose)

In this type, 70% hemp fiber which was 2800 ml and 30% of cellulose that was 1200 ml were used, after measuring the mass for each amount, which was 389.2 grams of hemp fiber and 236.36 grams of cellulose, these values were divided by 20 grams and multiplied by 26.7 grams for hemp fibers and 50.5 grams for cellulose, in order to calculate the required amount of water that was added for each substrate, the required water content was 596.809 grams needed for cellulose and 519.58 needed for hemp fibers.

Figure 10: hemp fibre substrate

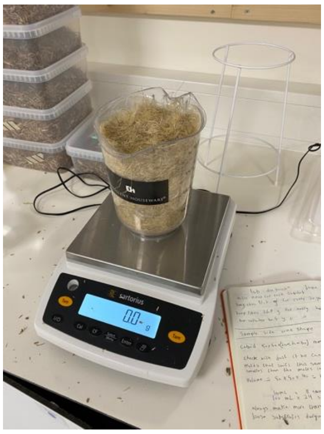


Figure 11: hemp fibre in the graduated cylinder

After that, the two substrates were mixed together with the required amount of water for each substrate until they all became one mixture, then they were put into plastic bag and sterilized by using boiling steam for 90 minutes, after sterilizing the bags they were left for 10 minutes to dry up in order to measure the dried weight and add the Ganoderma, which was 3% of the dried weight of each bag.

4.1.2) Sterilization process of the substrates

The first step after mixing the substrate with the required amount of water and putting them in the plastic bags was the sterilization. There are two methods of sterilization. The first one can be accomplished by high-pressure cooking at 123°C for 20 minutes at a pressure of 100 kPa. However, this method is effective in killing all organisms, reducing the risk of infection of the material, but it also kills beneficial species and is an energy-intensive method.

The second method is the pasteurization, which is the preferred approach and the method that was used in this research, as in this method the majority of dangerous organisms will most likely perish, while the beneficial ones will live. This method is basically heating up the substrate at 60°C for 90 minutes by using steam.

Figure 12: sterilization machine

Figure 13: Mycelium bags inside the machine

4.1.3) Inoculation

Inoculation is when the fungus is given the chance to develop more in the plastic bags, by growing a strong network and start creating the fibrous filaments named hyphae that the mycelium is made of, but there are some conditions required so the inoculation process happens properly. The Light, temperature and moisture have to be regulated and maintained in a controlled environment for ideal growth circumstances for the mycelium.

These conditions differ based on the type of fungus employed. Most species thrive in the dark at temperatures around 30°C and humidity levels of 60-65 percent. Temperatures can range from 15 to 35 degrees Celsius, the lower the temperature the slower but potentially stronger the material will develop. For the Ganoderma, a temperature of 27 degrees Celsius, humidity level of 65 percent and a completely dark medium was the ideal atmosphere. The bags of mycelium were put in an oven that provided the bags with the required growing conditions for seven days. After the seven-days of the inoculation period, it's time to start the molding process.

Figure 14: Mycelium bags after inoculation for 7 days

4.1.4) Molding substrates

In this stage of the process, after seven days of inoculation, the plastic bags containing mycelium were checked, there was white sponge were formed and connecting the substrates together. This means that the fungus has successfully developed and started forming the fibers filaments. However, there were black spots in some of bags, this means that they got infected, as sterilization process was not sufficient.

Figure 15: Infected parts circled by red

The infected parts of mycelium were then removed by hand from the plastic bags. After that, the mycelium was put in the molds, so it can inoculate in the shape of blocks.

Figure 16: Mycelium in the molds ready for inoculation

After molding the mycelium as shown in figure 16, the molds put back in the oven, so it can inoculate in the shape of blocks for seven days more in the same growing conditions as when they were put in the plastic bags.


Figure 17: Mycelium composites after drying


Figure 18: Mycelium composites after drying

4.2) Compression strength of each substrate

For each substrate three compression tests were done, the first two tests were done with a single sample and the third test was carried out by using two samples combined together in order to figure out whether the compression force of mycelium samples will change when more than one sample is put together or not. For each test the maximum force and displacement were calculated at 50% strain. The maximum force was measured as it is required for the formula of maximum compression strength, since it is dividing the maximum force by the surface area of the sample. The point of measuring the displacement is to compare between the single sample test and the double sample test, to understand the behavior of the mycelium bricks when they are put together in groups, because if the displacement in the double sample test is doubled with a significant increase in the value of the maximum force, this means that the mycelium bricks get stronger when they are put in groups and they have higher compression strength.

Figure 19: Single sample


Figure 20: double sample test

In each substrate the compression strength will be tested and the average value of the three testes will be taken. The formula used to calculate the compression force for each sample is F= P/A, where:

1. F=The compressive strength (MPa)
2. P=Maximum force (or load until failure) to the material (N)

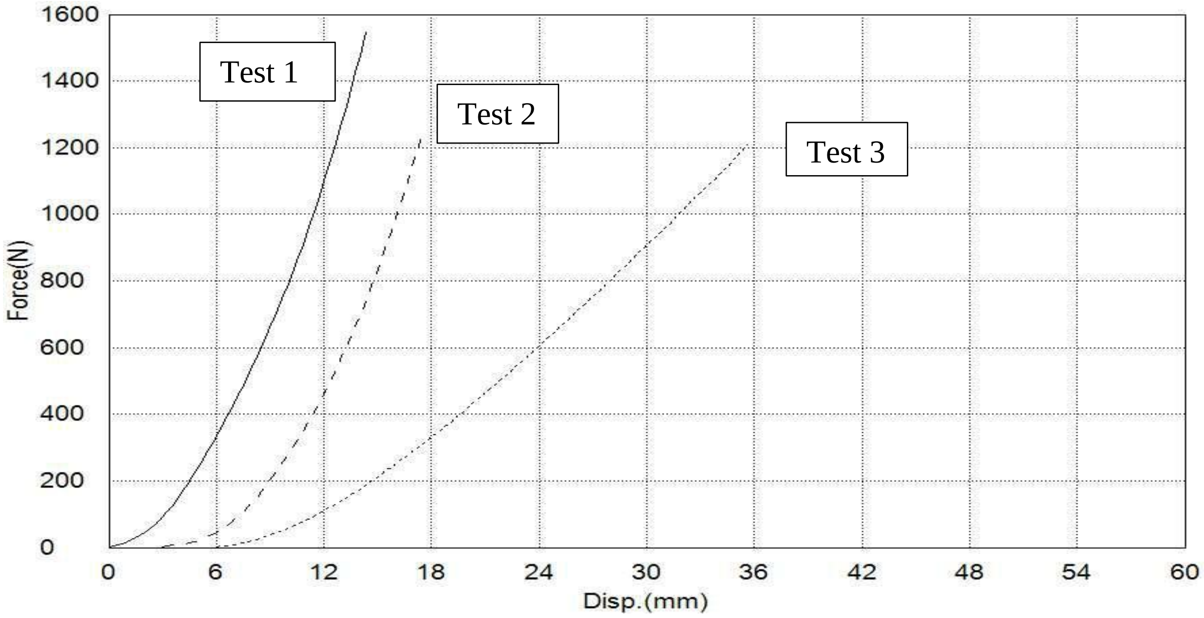
A=A cross section of the area of the material resisting the load (mm2), so the area used in this case, is the area of the circular machine plates, that has a diameter of 100 mm, the area will be **$A = \pi\ 50^2 = 7853.98\ mm^2$**

4.2.1) Parameters of hemp shives

Table 2: Parameters of hemp shives

	Max Force	Max Displacement	Strain
Parameters	Calc. at Entire Areas	Calc. at Entire Areas	Calc. at Entire Areas
Unit	N	mm	%
Hemp shives 1	1547,07	14,3255	50,0114
Hemp shives 2	1237,77	14,4155	50,0105
Hemp shives 3	1211,08	29,6552	50,0025

Graph 1: Relation between the displacement and the maximum force



In the first test the sample of hemp shives had a compression force of 1547,07 N, which was the highest value in the three compression tests of hemp shives, while in the second test the sample had a compression force of 1237,77 N and 14,4155 mm displacement. The third test, which was a double sample test, had a displacement of 29,6552mm, this was double the value of test 1 and test 2, however the samples had a compression force of 1211,08 N, which was almost the same as test 1 and 2, this means that compression strength of this type of mycelium did not change when the samples were combined together. The calculation of the compression strength for each test is shown below:

- **Compression strength of Hemp shives test 1**

F= P/A= 1547,07 N / 7853.98 mm² = 0.196 N/mm²

- **Compression strength of Hemp shives test 2**

F= P/A = 1237,77 N / 7853.98 mm² = 0.157 N/mm²

- **Compression strength of Hemp shives test 3**

F= P/A = 1211,08 N / 7853.98 mm² = 0.154 N/mm²

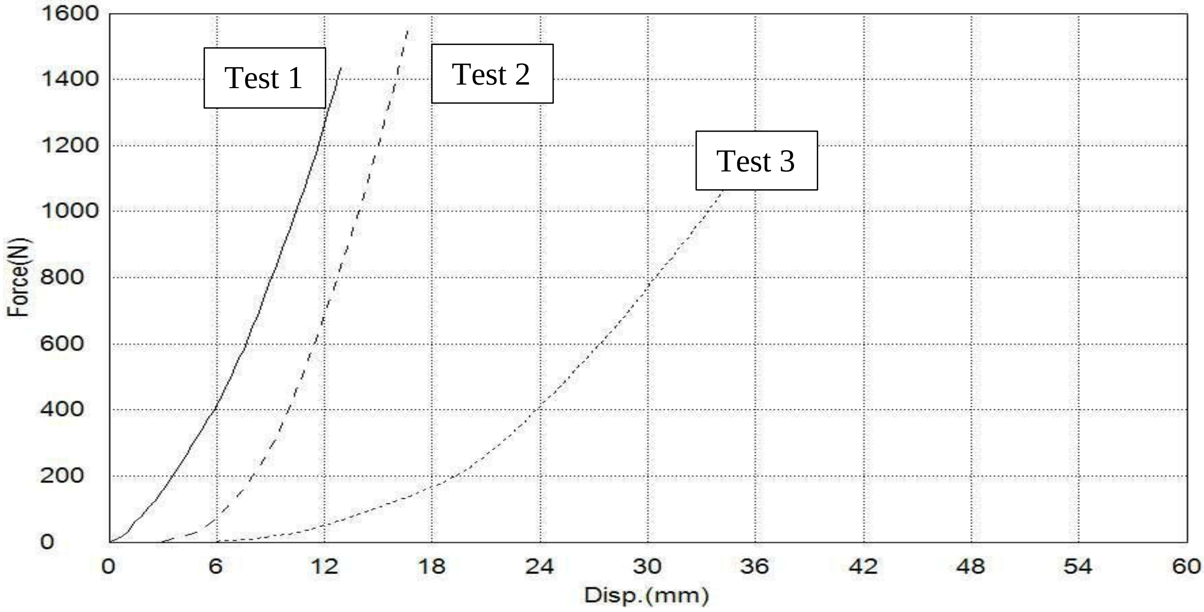
So, the average value of the compression strength is = (0.196 N/mm² + 0.157 N/mm² + 0.154 N/mm²) / 3 = 0.169 N/mm²

4.2.2) Parameters of hemp shives & cellulose

Table 3 Parameters of hemp shives & cellulose

Parameters	Max Fore Calc. at Entire Areas	Ma Displacement Calc. at Entire Areas	Strain Calc. at Entire Areas
Unit	N	mm	%
Hemp shives & Cellulose 1	1435,79	12,8952	50,0063
Hemp shives & Cellulose 2	1548,41	13,6227	50,0107
Hemp shives & Cellulose 3	1087,49	28,5030	50,0036

Graph 2: Relation between the displacement and the maximum force



In the second test the sample of hemp shives & cellulose had a compression force of 1548,41 N, this was the highest value in the three compression tests of hemp shives & cellulose, while in the first test the sample had compression force of 1435,79 N and 12,8952 mm displacement. The third test, was the double sample test, it had a displacement of 28,5030, this was double the displacement value of test 1 and test 2, however the samples had a compression force of 1087,49 N, which was lower than test 1 and 2. The calculation of the compression strength for each test is shown below:

- **Compression strength of Hemp shives & Cellulose of test 1**

F= P/A= 1435,79 N / 7853.98 mm² = 0.182 N/mm²

- **Compression force of Hemp shives & Cellulose test 2**

F= P/A= 1548,41N / 7853.98 mm² = 0.197 N/mm²

- **<u>Compression force of Hemp shives & Cellulose test 3</u>**

F= P/A= 1087,49 N / 7853.98 mm² = 0.138 N/mm²

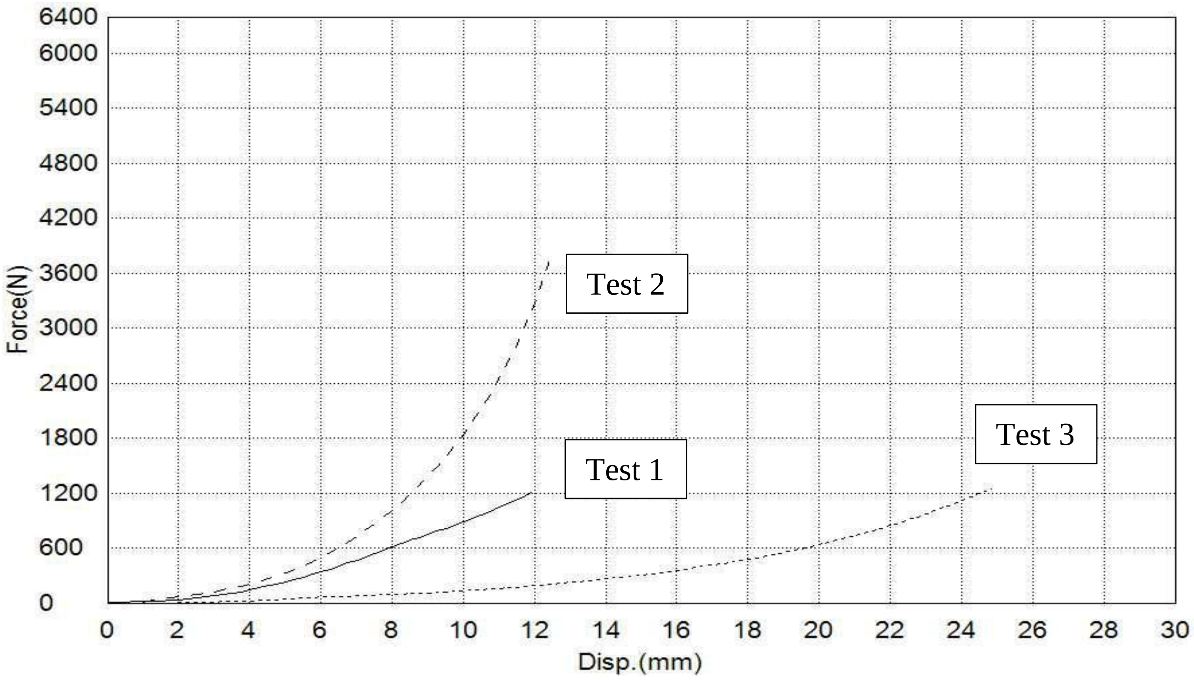
So, the average value of the compression strength is = (0.182 N/mm² + 0.197 N/mm² + 0.138 N/mm²) / 3 = 0.172 N/mm

4.2.3) Parameters of hemp fibers & cellulose

Table 4: Relation between the displacement and the maximum force

Name	Max Force	Max Displacement	Strain
Parameters	Calc. at Entire Areas	Calc. at Entire Areas	Calc. at Entire Areas
Unit	N	mm	%
Hemp Fibers & Cellulose	1202,32	11,9127	50,0066
Hemp Fibers & Cellulose	3784,65	11,4831	50,0092
Hemp Fibers & Cellulose	1254,98	22,8580	50,0069

graph 3: Displacement-force graph



Centre of Expertise Biobased Economy

In the second test the sample of hemp fibers & cellulose had a compression force of 1202,32 N, this was the highest value in the three compression tests of hemp fibers & cellulose, in the first test the sample had compression force of 1202,32 N and 11,4831 mm displacement. The third test, was the double sample test, it had a displacement of 22,8580, this was double the value of test 1 and test 2, however the samples had a compression force of 1254,98 N, which was almost the same as test 1 and lower than test 2. Now it is clear that the mycelium bricks will not get any stronger when they are put together in groups, as the only thing that increased in the double sample test was the displacement with no significant increase in the compression force. The calculation of the compression strength for each test is shown below:

- **Compression strength of Hemp Fibers & Cellulose test 1**

F= P/A= 1202,32 N / 7853.98 mm² = 0.153 N/mm²

- **Compression strength Hemp Fibers & Cellulose test 2**

F= P/A= 3784,65 N / 7853.98 mm² = 0.481 N/mm²

- **Compression strength Hemp Fibers & Cellulose test 3**

F= P/A= 1254,98 N / 7853.98 mm² = 0.159 N/mm²

So, the average value the compression strength is = (0.153 N/mm² + 0.481 N/mm² + 0.159 N/mm²) / 3 = 0.264 N/mm²

4.3) Mycelium type that can replace stones.

In order to be more accurate, the main focus will be on the average value of the compression strength for each type. The type of Mycelium which will be used in this project is the one made out of hemp fibers and cellulose, since it is the one that has shown the highest average value of compression force 0.264 N/mm². In the chapter 5, there will be a case study done on point St. Martin bridge to know the maximum values of compression force acting on each part of the bridge structure and compare them with the hemp fibers and cellulose. Based on this case study, it will be decided whether it is possible to replace stones with mycelium bricks or not. The bridge parts that have compression force acting on it lower than the compression strength of the hemp shives and cellulose, will be possible to replace.

Chapter 5: bridge design

5.1) Case study: Roman arch bridge of Pont St. Martin

This case study will be focusing on the roman arch bridge of Point St. Martin, which is located in Lys valley in Aosta, Italy. This bridge is made of a half circular arch with a radius of 16.5 m and a span of 31.4 m. This bridge has been chosen for the case due to its simple geometry as it only has single span, this will help to understand the theory behind the structure of Romain bridge. (Giorgio frunzio, 2001)

Figure 21: Point St. Martin roman arch bridge

In order to be able to accurately determine the stress and deformation state of the bridge, some knowledge on how the bridge has been built is required. As a result, a detailed analysis has been performed on the structure of the bridge and the materials used. (Giorgio frunzio, 2001)

The foundation structure of this bridge consists of a stone masonry vault that has a width of 6 meters, on top of the stone masonry there are two stone masonry spandrel walls each of one-meter width, between these two walls there is a concrete filling of 4 meters width with a pavement of 0.30 meters on top. On top of the two spandrel walls, there are two lateral parapets the one on the left side has a width of 0.70 meters and height of one meter, while the one on the right side has a width of 0.50 meters and height of 1 meter. The arch then will be placed on top of the two parapets. (Giorgio frunzio, 2001)

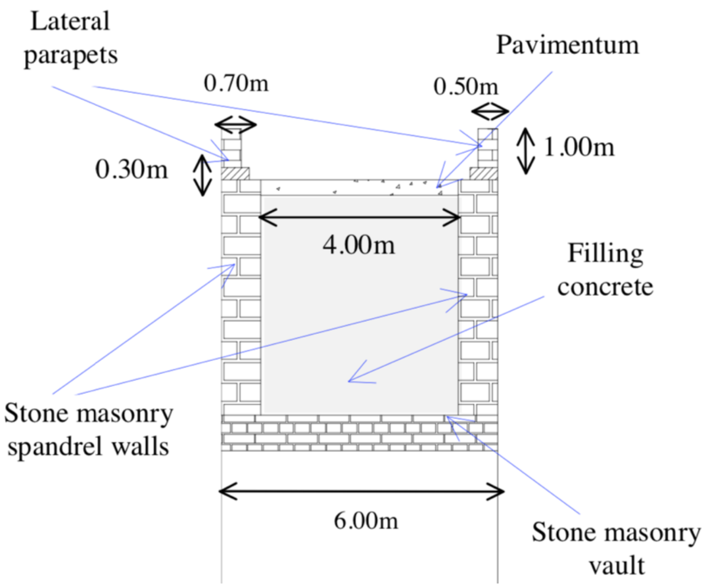


Figure 22. Cross section of the bridge foundation

The parts shown in the cross section (figure 22) are the parts that the compression force is mainly acting on together with the arch part, the main focus will be on the maximum compressive stress acting on each part shown in this cross section and the arch part.

A research was done previously by Mahdi Mahdikhani, Melika Naderi and Mehdi Zekavati on the strucutre of Point St. Martin bridge, the main objective of their research was to develop a method of preservation of the historical stone bridges against possible earthquakes using FRP techniques. FRP is a composite material that is used to protect masonry constructions against catastrophic breakdowns. (Mahdi Mahdikhani, Melika Naderi and Mehdi Zekavati, 2016) The reaserch included a structural analysis of each part shown in the cross section (figure 22) and the arch part. The structural analysis data is shown in table 5, the main focus will be on the value of compressive yield stress of each part and comparing it with the compressive strength of the type of myclium that had been choosen, which was the hemp shives and cellulose.

Material	Modulus of elasticity (N/mm^2)	Poisson ratio	Cohesion (N/mm^2)	Friction Angle (°)	Density (kg/m^3)	Compressive yield stress (N/mm^2)	Dilation Angle (°)
Arch	3000	0.2	1.2	50	1600	6.6	35
Spandrel walls	2500	0.2	1	48	1400	5.2	32
Filling	1500	0.05	0.5	32	1300	1.8	17
Foundation	7000	0.25	1.8	58	1300	12.55	40

Table 5 structural analysis data (Mahdi Mahdikhani, Melika Naderi and Mehdi Zekavati, 2016)

The arch, spandrel wall and Vault are all made of stones of the same size, while the filling is made of concrete. table 5 shows the compressive stress acting on each part of the bridge, the foundation part has the highest compressive stress 12.55 N/mm^2, the arch part has 6.6 N/mm^2, the spandrel walls has 5.2 N/mm^2 while the filling concrete has 1.8 N/mm^2 of compressive stress which is the lowest part in the entire bridge.

5.2) The possibility of replacing stones with mycelium

After comparing the compressive stresses mentioned in table 5 of each part of the bridge with the compressive stress of the mycelium composite that has been produced in the lab, it will be impossible to replace the stones in any of the bridge parts with mycelium bricks.

According to the compression tests that was done in the lab, the type of mycelium that had the highest compressive strength is the type that was made of hemp fiber & cellulose, it had a compressive strength of 0.264 N/mm^2. The spandrel wall is the part made of stones and has lowest compressive strength in the bridge, this part has a 5.2 N/mm^2 of compressive stress, this value is 20 times bigger than the compressive strength of the mycelium composite that have been created in the lab. As a result, substituting stones with mycelium is impossible, since there is big risk of the entire bridge collapsing.

Chapter 6:

6.1) Conclusions

The aim of this research was to find out if Mycelium has the ability to replace stones in a roman arch bridge structure, by setting up the appropriate laboratory tests and by conducting a desk research to help identifying the best substrate out of the three substrates picked that will produce mycelium bricks with the highest compression strength.

A study of the qualities of arch design, materials used in arch bridges and the history of arch bridges was undertaken in order for this thesis to be effective. Three types of mycelium were proposed for this and it was critical to assess their workability so that I could have a better knowledge of their behavior as stone replacements. This was accomplished through a literature research and several compression experiments conducted in the lab, as well as a case study conducted on the Point St. Martin Bridge.

Hemp fibers and cellulose was chosen as the best type out of the three types suggested, since it had higher compressive strength than the other two types. However, it was not possible for this mycelium composite to replace stones in any part of Pont saint Martin bridge, as the spandrel wall which was the part made of stones with the lowest compressive stress in the bridge, it had a maximum compressive stress of 5.2 N/mm² acting on it and the mycelium samples that was made in the lab, had maximum compressive strength of 0.264 N/mm², this value was 20 times smaller the maximum compressive stress acting on the spandrel wall. so substituting stones with mycelium is too risky, as this will result in collapsing the entire structure of the bridge.

In a nutshell, along the course of researching Mycelium composites, this substance was examined, analyzed, and tested to the best of our ability, but numerous variables must be investigated further before recommending it to the market. Due to the limited laboratory facilities, the main limitation in this research that could not be addressed and require further research is studying how to increase the compressive strength of mycelium, this is something that will undoubtedly require further research in the future.

6.2) Limitations

In the Production process of mycelium, after the inoculation phase there were some infections in the bags of mycelium, as the sterilizing machine provided by the organization where I was doing the internship was not sufficient enough. The presences of infection mean that not all of the bacteria were removed from the mycelium bags during the sterilization process, these infections had influenced the quality of mycelium, as it affects the developing process of Ganoderma (the type of fungus used) during the inoculation process.

6.3) Recommendations

The mycelium samples that were produced during this research had a rectangular shape, while the compression testing machine provided by my host organization had circular plates with a surface area smaller than the surface area of the mycelium samples, which made the compression test not accurate enough, so during the compression test make sure that the plates of the testing machine is covering the entire surface area of the sample, as the equation used to calculate the compression force is F= P/A, where: F=The compressive strength (MPa), P=Maximum load (or load until failure) to the material (N) and A is the surface area of the sample, so you need to make sure that force produced by the plates is acting on the entire surface area.

The mycelium samples that were produced in the lab had a very small value of compression strength and were not able to replace the stones in any part of the bridge, so further research can be carried out on how to increase the compression strength of mycelium, to be able to replace the stones with mycelium in any of the bridge parts.

Additional research is required to find out more advanced techniques of sterilization to prevent any infection in the production process, as there were some infections spotted in the mycelium bags after the inoculation phase, during the production process of the mycelium samples.

During the desk research, there were no solid information on what kind of environmental conditions the mycelium can withstand, so additional laboratory studies have to be conducted to address weather attacks and durability of this material to understand how a bio-based material like mycelium will behave in case of heavy rain, snow or bacterial attack happened.

Bibliography

A.Sinopoli. (1998). *Arch bridges.* Venice, Italy: Tyalor & Francis.

Abegaz, W. Z. (2019). *Embodied Energy and CO2 Emissions of Widely Used Building Materials: The Ethiopian Context.* Aalto University , Department of Civil Engineering.

Alessio Ageno * , Andrea Bernabò, Federico Foce * and Anna Sinopoli †. (1998). *THEORY AND HISTORY OF THE THRUST LINE FOR MASONRY ARCHES. A BRIEF ACCOUNT (ARCH '04).* Università degli Studi di Genova, Dipartimento di Scienze per l'Architettura (DSA), Genova.

Avans University of Applied Science / CoE BBE, HZ University of Applied Sciences / CoE BBE, Utrecht University. (2018). *building on mycelium.* Avans university.

BTC uganda, t. B. (2013). *Stone arches bridges.* Kasese District Local Government.

Cumming, M. (2017, february 21). *The Machinary Marketplace* . Retrieved from https://www.machines4u.com.au: https://www.machines4u.com.au/mag/bridge-construction-methods-why-are-roman-bridges-so-stable/

Davine Blauwhoff, Ilaria La Bianca. (2019). *From biomass to mycelium composite.* Amersfoort : Stowa.

de Bruin, s. (2018, 06 28). *MYCELIUM; A BUILDING BLOCK FOR PARKSTAD LIMBURG.* Delft: Faculty of Architecture & the Built Environment, Delft University of Technology. Retrieved from https://wasterush.info/: https://wasterush.info/mycelium-construction/

Dirk Proske, P. v. (2009). *safety of historical stone arch bridges.* Springer Science+Business Media.

economy, b. b. (2019). *Iso standards* . bio based economy .

economy, centre of experties biobased. (2018). *Buildiing on Myclium.* Avans university of aplied science. .

G. Vasconcelos, P.B. Lourenço, C.A.S. Alves, J. Pamplona & T. Miranda. (2012). *Relation between tensile and compressive engineering properties of granites.* London: Taylor & Francis Group.

Giorgio frunzio, A. G. (2001). *3D FEM analysis of a roman arch bridge.* historical consturctions . Retrieved from www.researchgate.net.

Lelivelt, R. J. J., Lindner, G., Teuffel, P., & Lamers, H. (2015). *The production process and compressive strength of Mycelium-based materials.* Eidhoven: Eindhoven university of technology.

Ltd, E. (2019, october 25). *www.elsevier.com/locate/matdes.* Retrieved from https://doi.org/10.1016/j.matdes.2019.108397

Mahdi Mahdikhani*1 , Melika Naderi 2b and Mehdi Zekavati. (2016). *Finite element modeling of the influence of FRP techniques on the seismic behavior of historical arch stone bridge.*

Marble Institute of America. (2016). *Natural stone Institute.* Marble Institute of America . ohio: Marble Institute of America.

Martien van den Oever, Karin Molenveld, Maarten van der Zee, Harriëtte Bos. (2017). *Bio-based and biodegradable plastics - Facts and Figures.* Wageningen: Wageningen Food & Biobased Research.