Investigation of Mycelium-Miscanthus composites as building insulation material

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Abstract – Good insulation materials have low thermal conductivity which is mainly related with the density of the material. Bio-composite insulation materials contribute to reduce the environmental footprint of buildings. The main goal of this study is to study the effectiveness of a self-growing, bio-composite building insulation material made of Miscanthus x giganteus and the mushroom Mycelium. Different mix proportions of Miscanthus and Mycelium were considered to identify the most suitable mixture to produce a porous composite which has a lower density. Scanning electron microscopy images were used to evaluate the microstructural geometry of the composite material. Thermal conductivity test was conducted on eight composite plates, and the results showed that the thermal conductivity of this new material is between 0.0882 and 0.104 $Wm^{-1}K^{-1}$. Moreover, other experiments were carried out to characterize the density, compressive strength and water absorption. In addition, fire resistant tests on composite plates with and without render were conducted, and it was found that the composite plates belong to the category EI15 according to the EN13501-2:2003. The initial results were found to be satisfactory to make a sustainable insulation material out of Miscanthus and Mycelium.

Keywords – Miscanthus, Mycelium, Thermal insulation, Bio-composite

1 INTRODUCTION

Depletion of natural resources, such as sand and gravel, is occurring at an alarming rate because the current pace of consumption in the construction industry is not sustainable [1]. Besides, the extraction, processing, manufacturing and transportation of building materials have the highest contributions in carbon emissions related to the construction industry. In order to protect the environment and reduce the overall environmental footprint of buildings, natural resources have to be used more efficiently, reducing the carbon emissions related to construction activities. As a result, several action plans have been issued in Europe, such as the European Green Deal**,** a fundamental roadmap to make the EU economy sustainable resulting in zero net carbon emissions in 2050 [2].

Traditional insulation materials come from different sources like animal products (such as sheep wool and feathers), plant-based products (such as cotton and wood fiber) and synthetic compounds (such as polystyrene and polyurethane). Nowadays, synthetic compounds, which are based on plastic-based fibers and foams, are more likely to be used in the building insulations. The creation and development of these materials takes a lot of time and is often very complicated and costly. On the other hand, these materials exhibit high-embodied energy, have high carbon footprint and produce toxic substances. Generally speaking, current insulation materials are not sustainable and environmentally friendly. As of today, new environmental-friendly bio-based insulation materials are introduced which often require less energy to be produced than traditional materials. As a result, this paper focus on the possibility of introducing a self-growing insulation material based on a Mycelium-Miscanthus composite that could replace traditional insulation materials.

With the increasing demands on grappling with the concepts of low-carbon economies by bringing in photosynthesis as the driver, researchers have given their focus on new environmental-friendly, energy efficiency and sustainable alternatives over the last few years. In this respect, it has been found that bioenergy crops have all the right characteristics to substitute many building materials [3, 4, 5].

Miscanthus, which is a C4 grass that originated in Eastern Asia, is one of those crops, and it is very efficient and economical to grow in most states in European climate [6]. Higher water use efficiency, low use of fertilizers and the capability to absorb large amounts of CO_2 from the environment compared to other C4 grass lead Miscanthus to high yield [7, 8, 9]. Due to its versatility and favourable properties, a large amount of Miscanthus plants have been planted for various purposes as well as to make value-added products from it all over Europe in the recent [10].

Miscanthus has already been used in a variety of different ways whereas Miscanthus lightweight concrete is one of these interesting products based on Miscanthus. Investigations on Miscanthus showed that it can be used in passive noise protection and fire protection [11]. It has already been proven that Miscanthus fibers have relatively high insulation capacity with respect to temperature

[6, 12, 13]. Eschenhagen et al. [6] developed low-cost insulation particleboard panels by using Miscanthus and Sunflower stalk in France and showed that they have great potentials because they have low density and good thermal conductivity. El Hage et al. [12] carried out an investigation about new insulating bio-composite made of Miscanthus and recycled textile fibers bunded with chitosan and found that its thermal conductivity varies between 0.069 and 0.09 WmK^{-1}. Miscanthus fibers have thermal conductivity of 0.04 WmK^{-1} which is equivalent to the thermal conductivity of conventional insulation materials available on the market [13].

Used as lightweight aggregates in a concrete mixture, Miscanthus fibers increased the compressive strength of concrete by 4 to 28% [3]. Dias and Waldmann [1] concluded that the best theoretical mixture considering the compressive strength of the Miscanthus concrete would constitute of 150 kg/m^3 of Miscanthus and 592 kg/m^3 of cement with 0.8 of water/cement ratio. Moreover, pore structure of Miscanthus contribute to reduce the thermal conductivity of the Miscanthus concrete [14, 15]. Miscanthus fibers significantly enhanced the acoustic absorption properties of bio-based lightweight concrete containing Miscanthus [16].

Mycelium is the vegetative part of the mushroom and is considered as one of the largest living organisms on earth [17]. It is formaldehyde free and non-toxic. Recently, the use of mycelium has been investigated to replace the already used resin by a fully natural one. Mycelium is a fungus which spreads its branches and acts like a binder within the fibers. It comes from biological and agricultural waste and is therefore very inexpensive on a large scale. In other words producing more of these, prices will decrease because it allows optimized growing procedures. Over the last decade, Mycelium based bio-composites have appeared to be used as a green alternative to several building materials such as building insulation [18, 19]. Elsacker et al. [20] mentioned that these composites have thermal conductivity of 0.08 WmK^{-1} and density of 57-99 kg/m^3. Yang et al. [21] showed that a Mycelium bio-form has higher characteristics than the conventional expanded polystyrene foam except density.

From the above perspectives, it implies that there is a huge potential to develop a Mycelium-Miscanthus bio-composite as a new building insulation material. Therefore, this research offers a novel way of combining Miscanthus and Mycelium for the production of a new bio-based building insulation material. This study investigated the optimal mix proportions of Mycelium and Miscanthus to produce a lightweight bio-composite. Furthermore, the properties of the composite including density, strength, water absorption and thermal conductivity were investigated.

This paper is structured in four sections including an introduction. Section 2 presents the experimental procedure. In section 3, the results are presented with a discussion, followed by the conclusion of study.

2 EXPERIMENTAL STUDY

This section reports the experimental tests carried out by the authors at the laboratory of Solid Structures of the University of Luxembourg. Firstly, the different materials used in this study are discussed. Then, the preparation procedure of the samples are presented. Weight and volume changes of each sample were measured to identify the optimal mix proportion of the materials. Then, on the selected samples, compressive test, water absorption test and thermal test were conducted. The results obtained from the experiments are presented and discussed in Section 3.

2.1 MATERIALS

The two main materials used in this study are Miscanthus and Mycelium. In this study, Miscanthus x giganteus (Figure 1(a)), the giant Miscanthus, which is locally available in Luxembourg was chosen due to its wide availability on the European market because of its high potential, good environmental profile and minimal risk of invasiveness [22]. It is a renewable raw material, that grows up to 4 m, on basically any type of hydromorphic grounds. Miscanthus x giganteus is able to filter up to 30 metric tons of CO_2 per hectare over one year. It has high rigidity with low density due to a high content of parenchyma surrounded by a tough fibrous structure [23]. In this study, dried Miscanthus with average density of 120 kg/m^3 was used. Figure 1(b) shows the dried and chopped Miscanthus fibers used in this study.

(a) (b)

Figure 1. (a) Miscanthus x giganteus plant [18] (b) Dried Miscanthus

As mentioned above, Mycelium is the vegetative part of mushroom. In this study, Mycelium was obtained from Ganoderma resinaceum mushroom. The Mycelium from the Ganoderma family develops better than other mushrooms. Only the grains of the Mycelium were used to envelop the Miscanthus (Figure 2). The Mycelium penetrates its nutrients by physical pressure and not enzymic secretion to break the host's polymers in order to transform them into more easily transportable nutrients such as sugars. In this study, the selected nutrient substrates are pure cellulose biopolymers and cellulose-potato dextrose both are composed of potato Infusion solids and Dextrose (sugar). This choice was made because of the abundance and availability of this natural polymer for cellulose and for the latter, it is because this medium is the most common used for the development of mushrooms thanks to its composition based on sugar easily digestible by the Mycelium. Because of their similar chemical form as well as by their surface homogeneity it is expected that these two nutritive bases allow a hydrolysis without gene with the Mycelium to guarantee a growth which will not depend on the nutritive base to provide a homogeneity of the material [18]. It does not need additional energy input to propagate. It only needs the usual fungus propagation conditions to grow (high humidity, the sample should stay in a dark place and stay under room temperature). Sterilization is important for the growing process of mycelium, because other spores could affect it or worse kill it. Thus, the development environment should be sealed to protect it from contamination [18].

Figure 2. Mycelium Ganoderma resinaceum grains

In addition to these two main materials, as mentioned above, potato starch extracted from potatoes (Figure 3) were used as substratum of Mycelium, which is the base material used by the mycelium to grow. Here starch was used for the Mycelium to grow as a web. The potato starch itself contains large oval spherical granules, which size is between 5 and 100 µm.

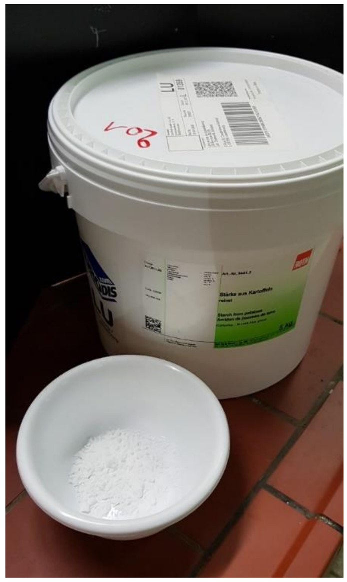


Figure 3. Potato starch

2.2 PREPARATION OF SAMPLES

Twelve different weight percentages of Miscanthus fibers, Ganoderma resinaceum mushroom and potato starch were used to manufacture the test samples. The mix proportions used are given in Table 1. Samples ID are labelled to easily identify the mix proportions of three materials. The letters G, M and P in the sample IDs represent the materials Ganoderma resinaceum mushroom, Miscanthus fibers and Potato starch, respectively. The number associated to each letter defines the ratio of corresponding material to the amount of Miscanthus. In the last four mix proportions, NS stands for non-sterile. In other words, in these samples not constantly disinfected materials were used.

Table 1. Mix proportions used for manufacturing of test samples

Sample ID	Mix proportion (Ganoderma resinaceum mushroom : Miscanthus fibers: Potato starch)		
G0.2_M1_P0.1	0.2	1	0.1
G0.2_M1_P0.2	0.2	1	0.2

G0.2_M1_P0.5	0.2	1	0.5
G0.3_M1_P0.1	0.3	1	0.1
G0.5_M1_P0.1	0.5	1	0.1
G0.7_M1_P0.1	0.7	1	0.1
G0.7_M1_P0.2	0.7	1	0.2
G0.7_M1_P0.5	0.7	1	0.5
G0.2_M1_P0.2_NS	0.2	1	0.2
G0.5_M1_P0.1_NS	0.5	1	0.1
G0.7_M1_P0.1_NS	0.7	1	0.1
G0.7_M1_P0.2_NS	0.7	1	0.2

Three test samples were carefully manufactured from each mix proportions for the testing. The manufacturing procedure of the test samples involves mixing of potato starch and water, adding mixture to the dried Miscanthus, boiling the mixture, cooling down the mixture, mixing the mushroom to the Miscanthus-potato starch mixture and manufacturing of samples using the prism moulds, as shown in Figure 4.

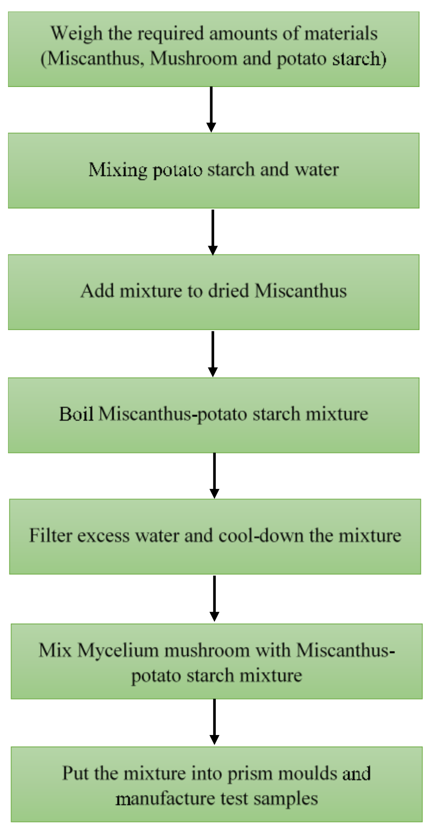


Figure 4. Manufacturing procedure of test samples

The mixing procedure was done as follows: weighted potato starch was mixed with 15l of water, and then the mixture was added into 150g of dried Miscanthus. The mixture was boiled for 30 minutes to kill most of the bacteria on the Miscanthus fibers. After that, the excess water was filtered away by using a sterilized strainer, and the wet Miscanthus-potato starch mixture was then put on a sterilized bowl to cool down itself until 30 to 35 ˚C. This was done to avoid a high difference as this would have killed the Mycelium before its growth. It has to be noted that the Mycelium was kept at 4 ˚C before being mixed to the rest in order to prevent the mushroom from growing already before its application in these specimens. Once the desired temperature was reached, the Miscanthus was mixed with the mushroom Mycelium until a homogeneous mixture was obtained. Finally, the mixture is put inside three prism moulds with the dimensions of 40 mm x 40 mm x 160 mm and covered with a sterilized plastic wrap, as shown in Figure 5(a).

Since a dark environment is helpful to the growth of the mushroom, the samples were kept in a closed cabinet for 7 days at room temperature (around 20 – 22 ˚C). The given condition is ideal for Mycelium to grow in the prisms, so that a good binding between the Mycelium grains and Miscanthus fibres can be achieved. After 7 days, the samples were taken out from the cabinet and demoulded. Figures 5(b) and (c) show the samples after the first growing phase. Mycelium is a fast growing fungus. Thus, in the first growth phase it develops and bind surrounding material, i.e. Miscanthus. In this phase, Mycelium grows the most due to higher amount of starch available. Thus, it can be assumed that the samples will have firm shape after the first growing phase.

The dimensions and weights of the demoulded test samples were measured, and the samples were then put separately in sterilized bags and sealed in order to begin the second growing phase. Although the samples had a stable shape at the end of the first growing phase, it was observed that the part of the sample which was against the mould was not enveloped by the Mycelium ligaments. Thus, the second growth phase is aimed to reinforce the structure of Mycelium which leads to stiffer and stronger final product. Therefore, the samples were put in the same cabinet again as in the first phase to stimulate Mycelium growth towards a denser network and to obtain a better homogeneity on the surfaces. The Mycelium continued to grow in this environment although the growth in this second phase is slower. The second growing phases was limited to 10 days to prevent the initiation of the growing of fruiting bodies as well as the deterioration of the fungus in the mixture. The samples were measured and weighed again at the end of the second growth phase.

Then, the samples were put in an oven and continuously dried at 80 ˚C for to stop the Mycelium from growing. The samples were measured and weighted repeatedly every 1 hour. The drying process was stopped after 24 hours or when the samples reached at least 35% of the initial weight. Figure 5(d) shows all the final test samples after the drying process.

(a) (b)

(c) (d)

Figure 5. Test samples (a) Miscanthus mixture in the prism moulds covered with plastic wrap (b) Test samples after first growing phase (c) Demoulded test samples after first growing phase (d) Test samples after the drying process

3 RESULTS AND DISCUSSION

The prism test samples were completed in a total time of 18 days. Based on visual analysis, a difference in growth of Mycelium on the test samples was observed. The varied amount of white visible on the samples might be a result of various factors such as a lack of mycelium, the availability of the substrate for Mycelium to grow or the differences in airflow. It was observed that the prism test samples of G0.7_M1_P0.1 was completely white at the end of first growing phase and had enough growth of Mycelium to hold the composite together. The prism test samples of G0.2_M1_P0.1 had built some yellow-brownish liquid after the first growth phase compared to other test samples. The composition of the liquid was not analyzed in this study. However, it was assumed that the brownish color would come from the Miscanthus and the yellow watery part represent the initiation of the growing phase of fruiting bodies or the deterioration of the fungus in the mixture.

The measured average density of all the mixtures after each phase was compared and are presented in Figure 6. It is observed that the weight of the all the samples except G0.2_M1_P0.5, G0.5_M1_P0.1, G0.7_M1_P0.1_NS and G0.7_M1_P0.2_NS has changed at the end of the second growing phase. At this phase, the weight changes depend on how the Mycelium grew and on the humidity lost. In the first hours of the drying process, the weight decreased considerably every hour. This is due to the evaporation of the humidity present in the samples. After 24h the decrease of the weight slowed down.

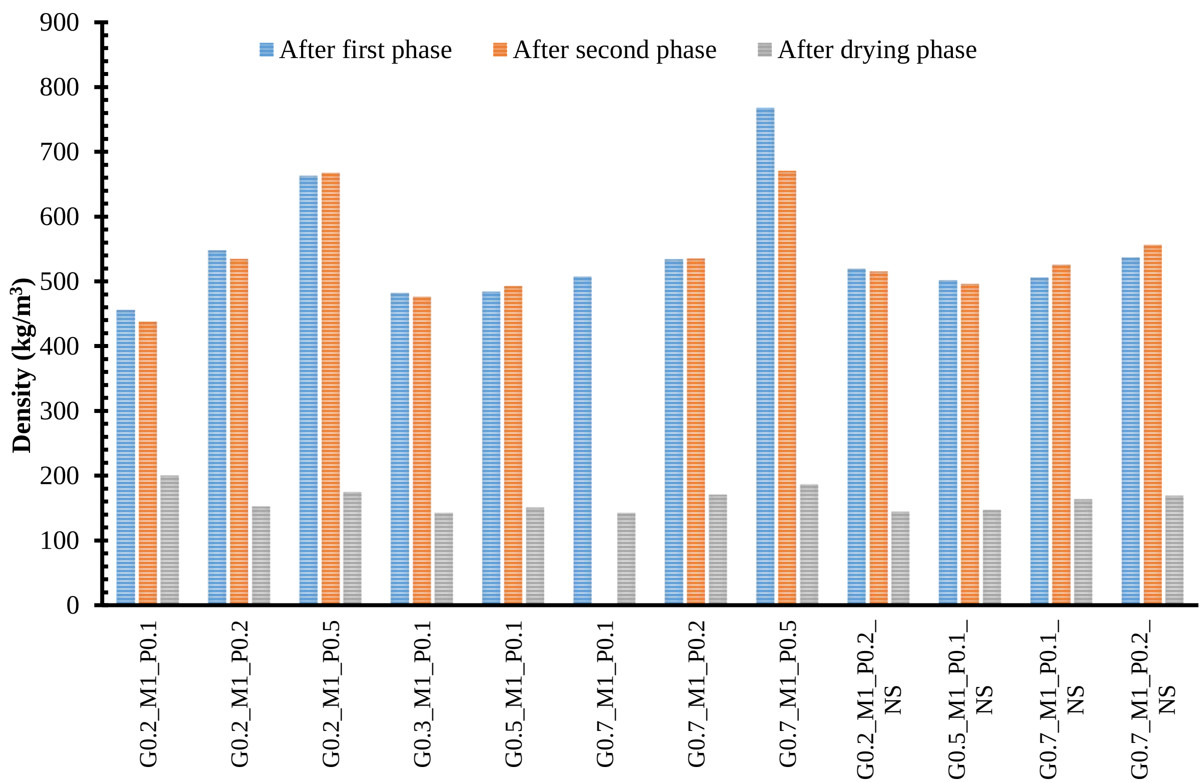


Figure 6. Average density of all the mixtures after each phase

As the mixtures G0.3_M1_P0.1 and G0.7_M1_P0.1 present a low-density, for these mixtures an excellent thermal insulation capacity could be expected. However, since for mixture G0.3_M1_P0.1 sample less Mushroom, that is 45g, is used, it was identified as well-balanced mix proportion for being applied in a lightweight Mycelium-Miscanthus thermal insulation board.

3.1 Feasibility of use coffee as starch

As described in Section 2.1, Mycelium needs a base material to start natural growth. In this subsection, further experiments were carried out by substituting the potato starch by coffee to check the usefulness of the coffee as ecological, renewable and biodegradable material. A mixture of G0.3_M1_C0.1 with a ratio of 0.3 times the weight of Miscanthus for Mycelium and a ratio of 0.1 times for coffee was produced.

Figure 7 compares the observed results on average density of these two test mixtures. It can be seen that the average density was obtained for both samples is almost the same after the first growth phase. In general, the samples made of used ground coffee has slightly lower density than samples made with potato starch, after the drying phase. It was also observed that there is no visible difference between prisms made with potato starch and prisms made with used ground coffee. Apart from the fact that during the development of the mushroom, a strong smell of coffee emanates from the samples.

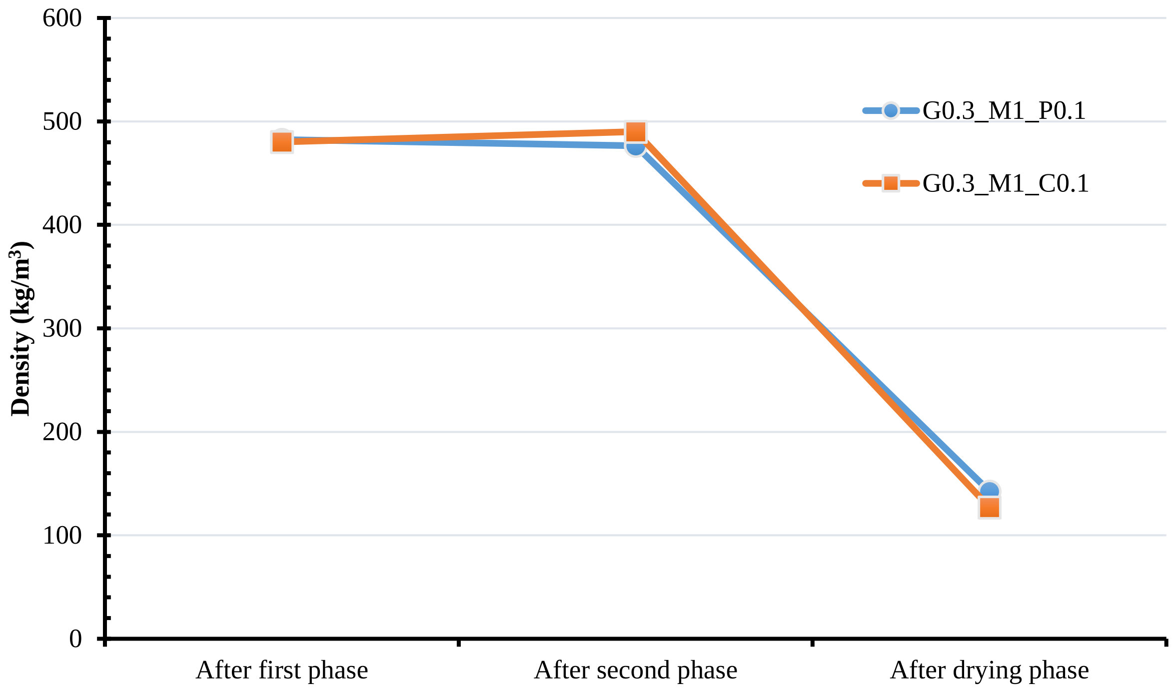
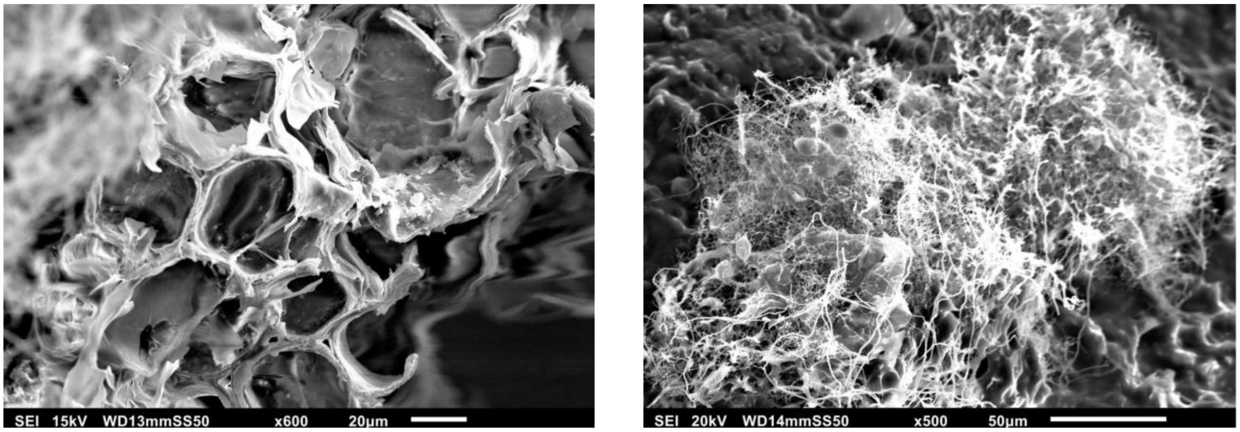


Figure 7. Comparison of average density for the mixtures of G0.3_M1_P0.1 and G0.3_M1_C0.1

3.2 SCANNING ELECTRON MICROSCOPY (SEM) ANALYSIS

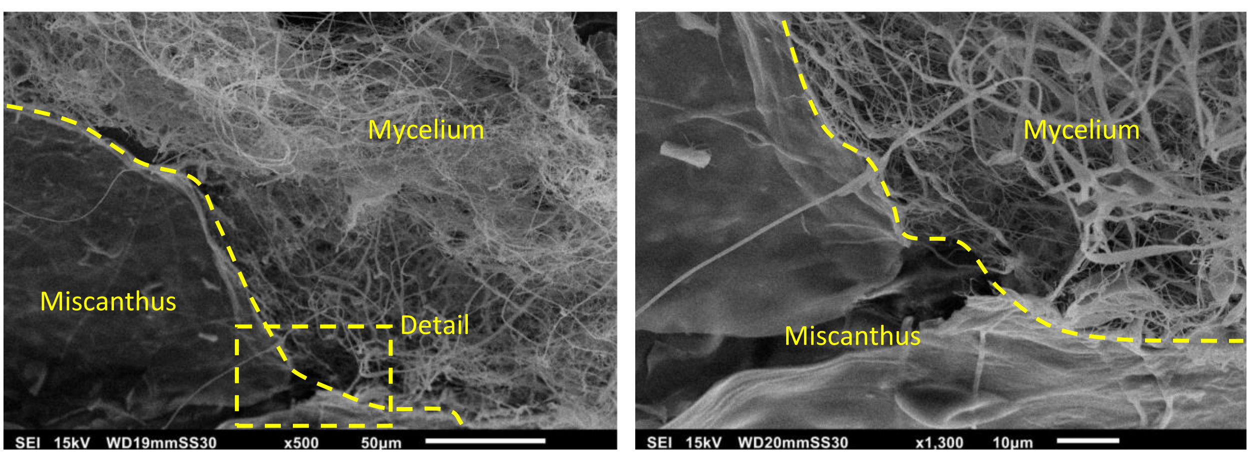
SEM analysis was carried out to evaluate the microstructural formation of the Mycelium in the composites, using a JSM-6010LA scanning electron microscope. The SEM images of the formation of Mycelium around the Miscanthus fibers were analysed on the test samples of G0.7_M1_P0.5. Figures 8(a) and 8(b) show the fibrous network of Miscanthus and Mycelium matrix from Ganoderma resinaceum mushroom, respectively. These images indicate that the microstructure of Miscanthus is not isotropic and it is formed by numerous hollow tubes that all points oriented in the same direction. Moreover, the Mycelium in the mushroom exhibits an interconnected network like microstructure, formed from randomly arranged filaments.



(a) (b)

Figure 8. SEM image of (a) Miscanthus fiber structure (b) Mycelium matrix in Ganoderma resinaceum mushroom

The morphology of the Mycelium-Miscanthus composite is shown in Figure 9(a). It shows that there is Mycelium growth between and around the Miscanthus fibers, successfully embedding the Miscanthus into the composite. Figure 9(b) depicts a closer view of the Mycelium growing into the Miscanthus fibers. Although it is not clear how deep the Mycelium hypha penetrates into the fibers, it is clear that the Mycelium grew within the composite and bonded with the Miscanthus fibers. The abundance of the Mycelium in the center of the composite may be due to the insufficient airflow through the materials. The presence of voids in the center of the composite is expected to affect the mechanical and thermal properties of the composite.



(a) (b)

Figure 9. SEM image of (a) Mycelium bonded with Miscanthus (b) closer view of the Mycelium growth within the composite

3.3 COMPRESSIVE TEST

The experimental study was further extended in order to analyze the mechanical characteristics of Mycelium-Miscanthus samples. Compressive tests on prisms were carried out to determine their compressive strength. Compressive strength of a prism depends on its porosity, pore size and material characteristics including the bonding of the Miscanthus fibers to the Mycelium used. Figure 10 shows a test prism made of G0.3_M1_P0.1 after subjected to compression test. The load on the compression tip was applied at a constant rate and the load vs displacement data were recorded. The compression test was continued until the specimen reaches 10% relative displacement, and the compressive strength was defined according to [24] as the stress at 10% relative deformation displayed if the test specimen does not yield or rupture before it reaches the required deformation. The results for strain versus stress through the compression test are represented in Figure 11. It can be seen that the compressive strength of the prisms varies between 1.2 N/mm^2 to 1.8 N/mm^2. It was also observed that the composite stick together even after it reached to the non-reversible deformation.

Figure 10. The compressed test sample G0.3_M1_P0.1

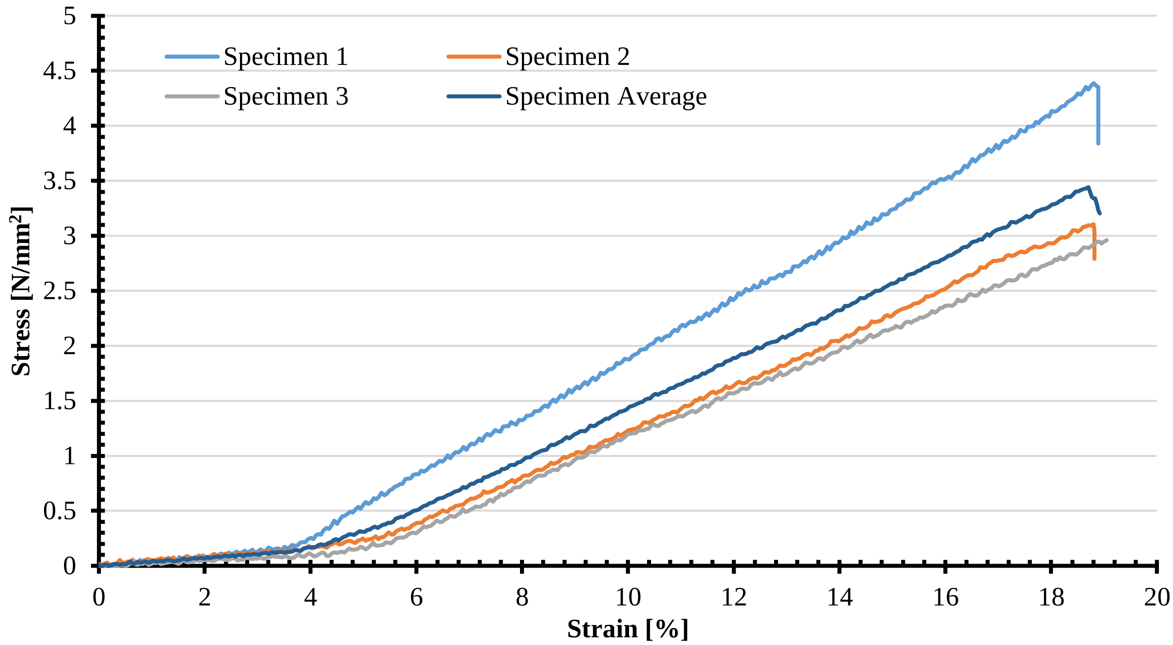


Figure 11. Stress-strain relationship

3.4 Water absorption

Since the composites are hydrophilic, the durability of the material could be affected when the studied Mycelium-Miscanthus composites is used as insulation material. Therefore, the water absorption was measured by immersing the selected test sample made of G0.3_M1_P0.1 in water until the increase in water absorption is negligible. The water absorption capability in percentage was calculated as,

$$Water\ absorption = \frac{M_2 - M_1}{M_1}\ x\ 100\%$$

where M_1 is the initial dry mass and M_2 is the water-soaked mass.

The initial dry mass of the sample was 0.0555 kg. Figure 12 shows the observed results on the water absorption of test sample. It is reported that the water absorption of Mycelium-based materials is very fast and it increases in weight by 40-580 wt% in contact with water for 48-192 hours [25]. The rate of absorption is dependent on the characteristic of the pores with their size, distribution and continuity. It was found that the sample absorbs more water around the first 30 seconds and it has then been reduced with time. This is due to Mycelium-Miscanthus composite, which has a high porosity and a complicated internal structure. Since the thermal insulations are usually used in internally dry conditions, the weight increase occurred within first few seconds is not a significant problem [26], as for other insulation materials too, a render will protect the composite from environmental impacts.

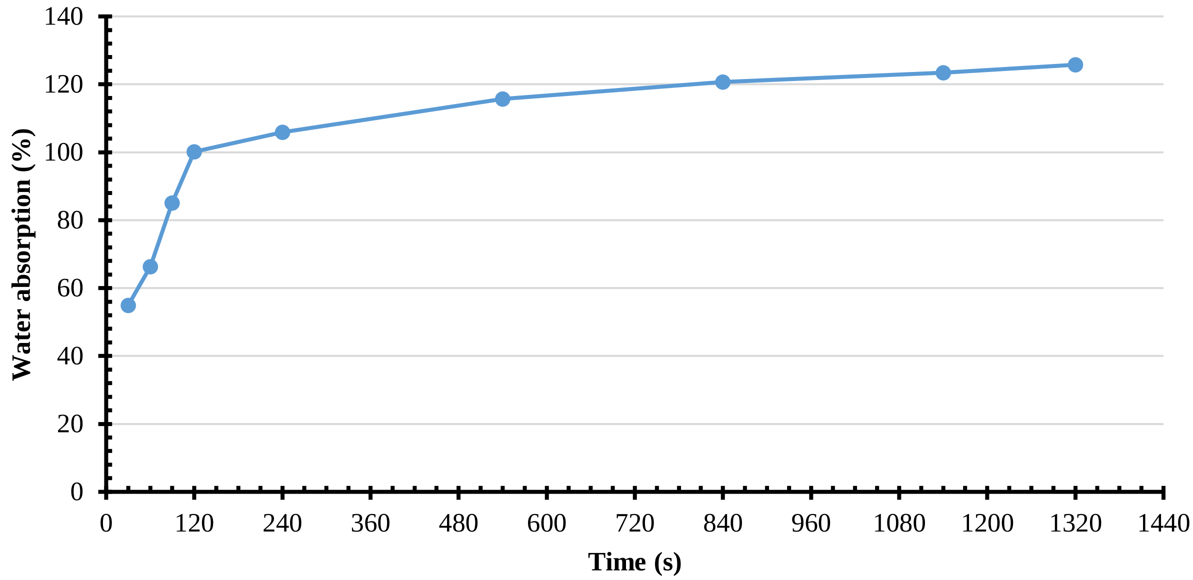


Figure 12. Water absorption in relation of time

Once the absorption test was completed, the test sample was kept in the water for a certain period to observe the possible changes and developments on the sample. Although the composite was observed during 1 month, no development of Ganoderma was observed. After 1 month, a sample was cut in half to inspect inside, and it was observed that Ganoderma had not developed inside the composite as well, as shown in Figure 13. It is apparent that despite the water is partially raised in the sample, the development of the mold stops at the outer space (Figure 13). This, it can be concluded that drying the mixture at 80 ˚C effectively kills the fungus.

Figure 13. Test sample G0.3_M1_P0.1 after 28 days (cut in half); Red circle has drawn around the developed mold on the sample

3.5 THERMAL INSULATION TEST

After having studied the mixture properties with prism samples, Mycelium-Miscanthus plates were produced using the same procedure and the same ratios as for the prisms, described in Section 2.2. The only differences were related to the volumes and the formworks used. The plate dimensions were 500 mm x 500 mm x 70 mm. G0.3_M1_P0.1 mixture was used to manufacture the bio-composite plates. The aim of this experiment was to study the insulation capacity of the Miscanthus and Mycelium composite, and its interaction with plaster. The final plates are shown in Figure 14.

Figure 14. Test sample of Mycelium-Miscanthus plate used to assess the thermal performance

In total, six plates were manufactured. Plates 1 to 4 were made produced without a render, while Plates 5 and 6 were covered with a render. Two layers of render were applied on those two plates according to ETAG-004 [27]. A 15 mm thick layer of Weber DUR 137 was used as a base coat layer and 10 mm thick of Weber TOP 200 was put on the first render layer as a finishing coat. After the application of base layer, a 5mm x 5mm grid was placed on the top of the base layer as reinforcement. Before application of Weber TOP 200, it was ensured that the first layer is completely dry and dust free. Figure 15 shows the manufactured plates with two layers of render.

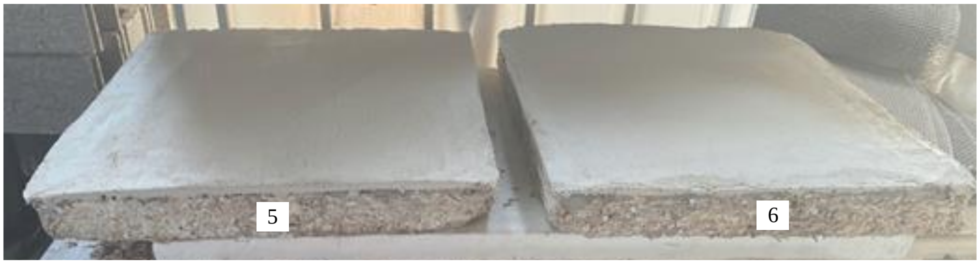


Figure 15. Plates 5 and 6 with two layers of render

Figure 16 compares the final density of each plate. The first four plates are very light having a density between 122.5 and 167.3 kg/m^3. Low density of the composite is desirable for reducing the packaging and transportation costs as well as thermal properties of the composite. The larger thermal conductivity can be attributed to the higher density of the material [20, 28, 29]. Yang et al. [21] showed that Mycelium-based bio-composite has a thermal conductivity between 0.05 and 0.07 Wm^{-1}K^{-1} with a density between 160 and 280 kg/m^3. Cadena and Bula [30] developed bio-composite insulation boards based on rice husks and yucca starch which has a thermal conductivity of 0.065 Wm^{-1}K^{-1} and density of 195 kg/m^3.

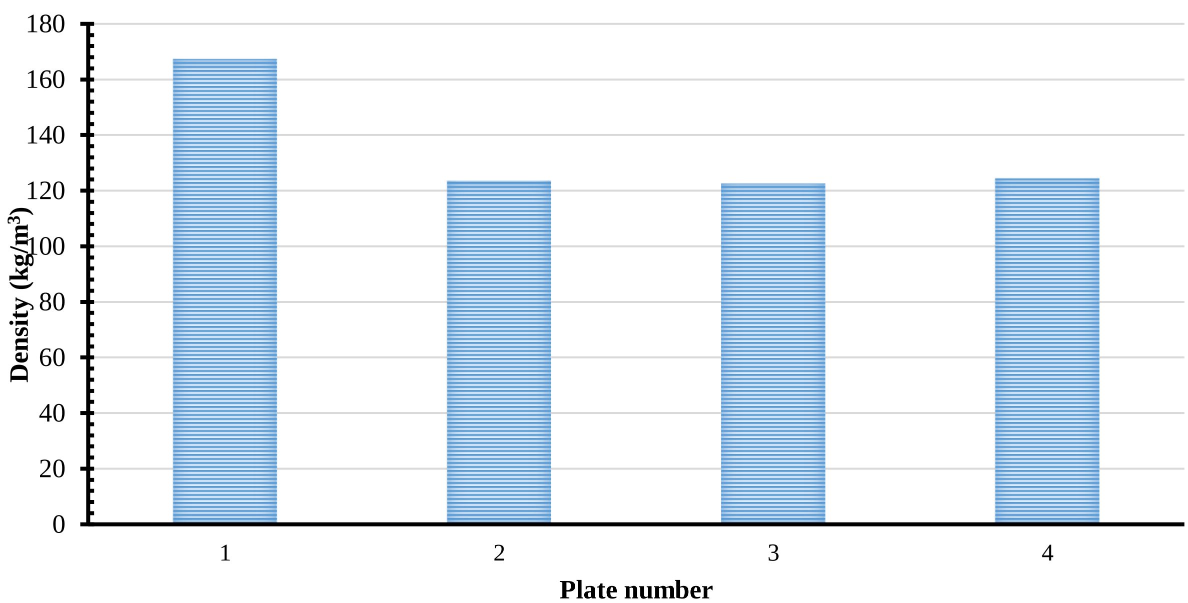


Figure 16. Comparison of density of plates

They were first left for 76 days outdoor in order to study the impact of humidity and temperature changes as well as and UV radiation on them. It was observed that the renders on the plates were unaltered. There were neither cracks nor curvatures visible. However, after six weeks, a bump appeared on the Plate 6. Figure 17 shows the variation of weight of the Plates 5 and 6 during the experiment. In general, it was observed that the plates did not change a lot, which shows that the Mycelium-Miscanthus plates are resistant on the environmental conditions.

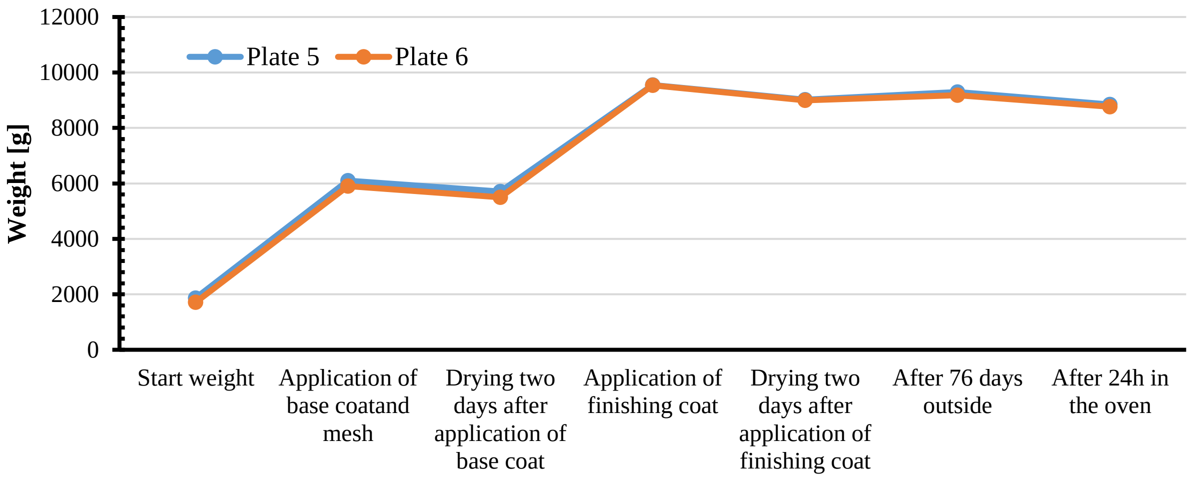
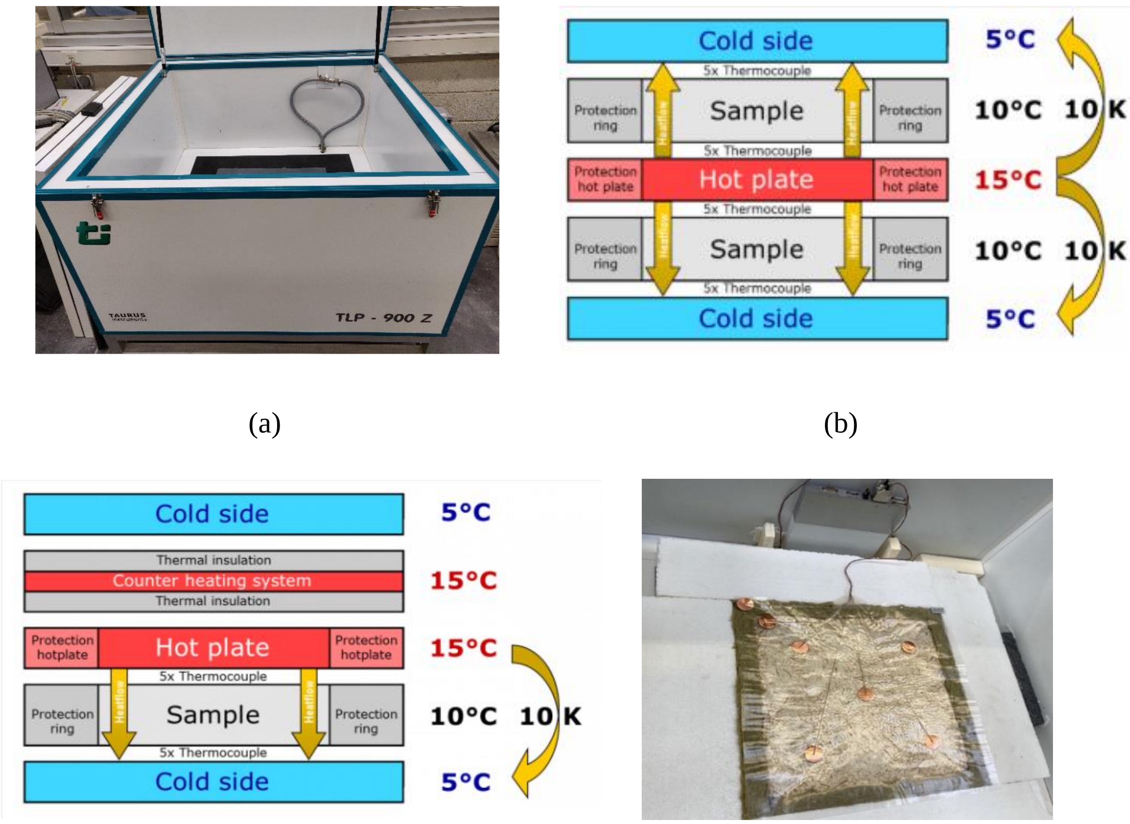


Figure 17. Weight of the plates during the experiment

In the next step, the insulation capabilities of composite plates were studied by measuring their thermal conductivity. The device Taurus TLP800/900 was used to determine the thermal conductivity of Mycelium-Miscanthus composite plates. Figure 18(a) shows the thermal conductivity test carried out by the Taurus TLP800/900 device on the composite plate according to ISO 8302/EN 1946-3. In total, three tests were carried out. For the first test, two composite plates (Plates 2 and 4) were used at the same time, as illustrated in Figure 18(b), while the second test was carried out for a single composite plate (Plate 1), as illustrated in Figure 18(c). The third test was carried out using the two composite plates with render (i.e. Plates 5 and 6) after their exposition to outside environmental conditions for 2 months. In Figure 18(b), the test setup for the measurement of the heat conductivity using two composite plates is illustrated. The bottom of the measuring device consists a cooling plate following by a levelling mat and thermocouples. At the middle of the machine, a heating plate is positioned. On the top of the machine, another cooling plate is positioned. During the thermal insulation test, each composite plate (test sample) was put between a cooling and a heating plate in order to install a temperature difference of 10 K within each composite plate. This is needed to calculate the thermal conductivity (i.e. λ-value). In addition, a thin layer of temperature sensors was introduced between each heating/cooling plate and these sensors measure the temperature at 5 points on the composite plate (test sample), as shown in Figure 18(d). Moreover, the composite plates were insulated on the four sides so that they are positioned in the middle by use of Styrofoam are placed around the composite plate, as shown in Figure 18(d).



(a) (b)

(c) (d)

Figure 18. Thermal conductivity test (a) Taurus TLP800/900 (b) Principle illustration of measuring with two plate method [31] (c) Principle illustration of measuring with single plate method [31] (d) Thermocouples attached on the test sample

The thermal conductivity of each plate was measured at three different mean temperatures because of the temperature difference between the heating plate and the cooling plate. The λ-value is calculated from the power which is put into the heating plate, the thickness of the sample and the temperature difference. It gives the thermal conductivity of a material in the unit of $Wm^{-1}K^{-1}$. The obtained results are plotted in Figure 19. From these results, it can be seen that the λ-values for plates 2&4, 1, and 5&6 are 0.0882, 0.104 and 0.121 $Wm^{-1}K^{-1}$, respectively. Thus, it is clear that the associated λ-value of new insulation material of Mycelium-Miscanthus composite is between 0.0882 and 0.104 $Wm^{-1}K^{-1}$. These result can be compared to λ-values of straw, hemp concrete, softwoods and gypsum about 0.08 [32], 0.1 [33], 0.12 [34]and 0.17 [34] $Wm^{-1}K^{-1}$, respectively. However, when comparing production costs and environmental impacts, the new Mycelium-Miscanthus composite is cheaper to manufacture and has a significantly lower carbon footprint.

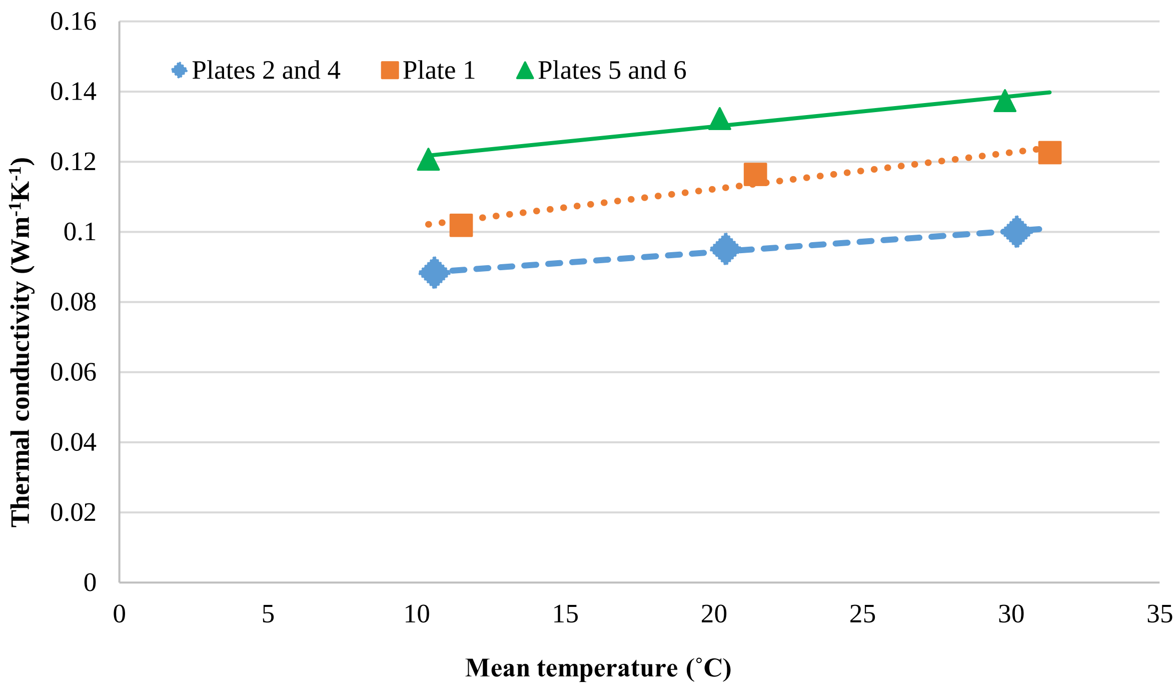


Figure 19. Average results for thermal conductivity

3.6 FIRE RESISTANCE TEST

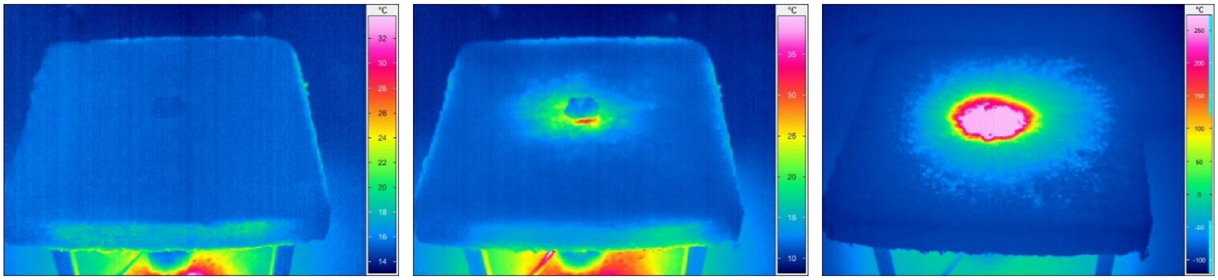
Even though Mycelium and Miscanthus have no notable fire-resistant properties, fire resistance tests focused primarily on the Mycelium-Miscanthus composite in order to analyze the fire resistance so that it can be classified according to the standard EN 13501-2:2003 [35]. The test samples (plates with and without render) were manufactured in a similar way as described above. The fire resistance test involved placing a sample approximately 5 cm above a Bunsen burner which was attached to the gas consisting of 60% Methane, 34.5% CO_2 and 0.5% Oxygen. The experiment was captured with a thermal camera to determine the temperature evolution.

First, a plate without render was tested. According to the standard EN 13501-2:2003 [35], a piece of cotton wool was put on the top of the plate, and the test has to be considered to be over when the cotton begins to burn, a gap or opening is visible or the presence of a persistent flame on the side facing away from the fire is appearing. It was observed that a gap was visible and the cotton wool started to burn after 40 minutes. Figure 20 shows the plate before and after it was burned for 40 minutes.

(a) (b) (c)

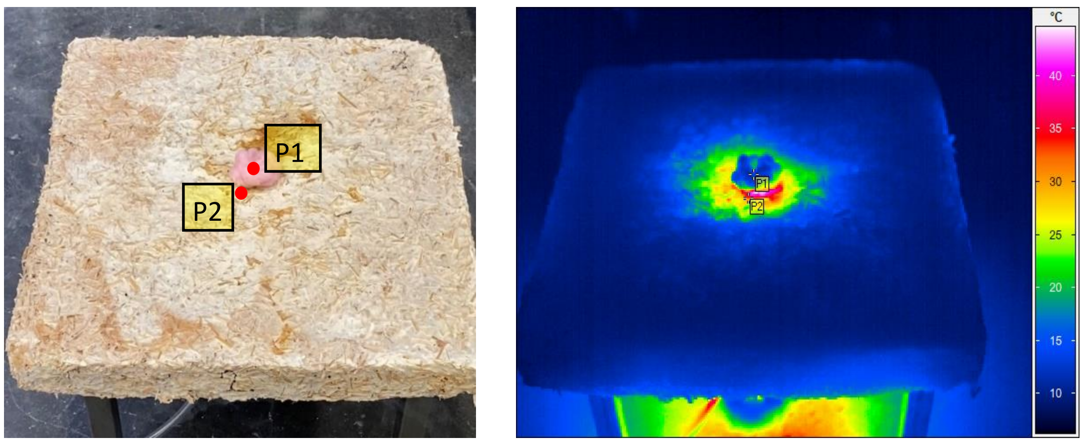
Figure 20. Plate without render subjected to fire test (a) before start to burn (b) after 40 minutes (c) bottom of the plate after 40 minutes

Figure 21 shows the captured temperature progression by the thermal camera during the fire test. It can be seen that the heat from the flame took about 7 minutes to get to the top of the plate and another 33 minutes to burn the cotton wool and create an opening on the top of the plate. Moreover, Figure 22 depicts the variation of temperature at two points, one is on the cotton wool (P1) and another is on top of the plate just close to the cotton wool (P2), during the fire test. It was observed that the temperature at point P1 slightly decreased until 22 minutes. This is due to the high amount of fume, which was created during the test.

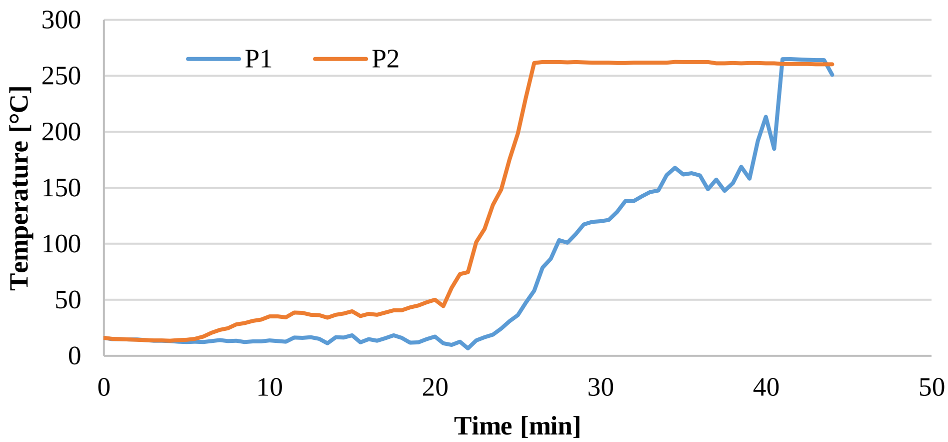


(a) (b) (c)

Figure 21. Temperature progression during the fire test (a) before start to burn (b) after 7 minutes (c) after 40 minutes



(a) (b)



(c)

Figure 22. (a) Measurement points P1 and P2 (b) Captured temperature at P1 and P2 (c) Variation of temperature at P1 and P2

Then, the same procedure was conducted on a plate with render. The side which has no render was placed over the flame, as shown in Figure 23(a). It was burned for 1 hour and 10 minutes. Since the sample did not show any combustion over this period, the test was then stopped. It was observed that the cotton wool did not burn like in the first test, as shown in Figure 23(b), because the fire did not go through the plate. However, it can be seen that the bottom of the plate has burned, as shown in Figure 23(c).

(a) (b) (c)

Figure 23. Plate with render subjected to fire test (a) before start to burn (b) after 1 hour and 10 minutes (c) bottom of the plate after 1 hour and 10 minutes

Based on the results from fire test and according to the EN13501-2:2003 [35], it can be concluded that the fire resistance of the Mycelium-Miscanthus composite is EI15. The classification of *EI* was chosen because of the consideration both parameters *E* and *I*. *E* is attributed if the integrity of the component is maintained and no breakthrough of flames is generated, while *I* is attributed if the temperature of the non-exposed side of the element does not rise over 140 ˚C [35].

4 CONCLUSION

Research on bioenergy crops based products are one of the key strategies to reduce the use of non-renewable resources. The current market is established for mainly non-biobased building insulation materials. However, developing and promoting bio-based building insulation materials have great benefits on the environment. This paper focused on the Mycelium-Miscanthus composites as an economical and sustainable alternative material to traditional building insulation materials. Since the thermal conductivity depends on the density, different proportions of Mycelium to Miscanthus were considered to produce lightweight porous composite. The best mix proportion was identified as G0.3_M1_P0.1 which has the mix proportions of 0.3:1:0.1 of Ganoderma resinaceum mushroom, Miscanthus x giganteus fibers and potato starch. Compressive strength and water absorption of the composite were also investigated. The microstructural geometry of the composite was evaluated using the SEM images, and it was observed that the Mycelium grew around the Miscanthus fibers. Insulation capability of the composite was measured by measuring their thermal conductivity. The thermal conductivity between 0.0882 and 0.104 $Wm^{-1}K^{-1}$ observed for new insulation material Mycelium-Miscanthus composite with average density of 122 kg/m^3. Furthermore, fire tests on composite plates were proving that they have considerable fire resistance and belong to the category EI15 according to the EN13501-2:2003. It was found that the prepared new composite has comparatively better properties than the conventional insulation materials and meet most of required for the indoor building applications.

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Research data for this article

The raw/processed data required to produce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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