HOME: Wood-Mycelium Composites for CO₂-Neutral, Circular Interior Construction and Fittings

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Abstract. Office and retail interior fittings have a relatively short service life of 5-7 years. In this context, composite materials are often used, hindering possibilities of reuse or recycling. This research explores novel bio-composite materials and subsequently a construction method for CO₂-neutral, circular interior fittings for office spaces. Based on the potential of fungal mycelium as a rapidly renewable, regenerative, affordable, low-carbon building material, bio-composite construction methods are explored in conjunction with timber-based additive manufacturing using continuous fibres. As mycelium has potentially excellent sound-absorbing properties but low load-bearing capacity, composite construction of timber veneer and mycelium allows to increase the structural capabilities of resulting components, while relying entirely on bio-based value chains. We describe the production process as well as the material development, including robotically aided processes for additive manufacturing of veneer reinforcement grids and compatibility studies of different mycelial species and substrates, and their bonding capabilities with veneer. We further present initial results on the mechanical characterization of the composite material, and its comparison to conventional mycelium composites. Minimal structural, acoustic, and functional requirements for different interior fitting elements are studied and compared to the characteristics of the proposed composite, highlighting the range of applications of the presented wood-mycelium composites.

Keywords: construction product, material development, mycelium, biofabrication, additive manufacturing.

1. Introduction

1.1. Motivation

Office and retail interiors have a relatively short service life of 5-7 years, with a variety of conflicting performance requirements for the materials used. The used composites often combine materials from the natural cycle, such as wood fibres, with materials from the technical cycle, such as adhesives, thus hindering possibilities of reuse or recycling. As a result, the environmental footprint of interior finishes is significant, and there are still limited choices of alternative bio-based, high-performance and
affordable materials. This research aims at filling such gap by exploring bio-fabrication approaches through the integration of mycelium and additively manufactured timber reinforcement grids.

1.2. Mycelium-based composites in architecture

Mycelium, the root structure of filamentous fungi, can be used as replacement for synthetic adhesives. Filamentous fungi feed on lignocellulosic waste materials and form mycelium, which acts as a natural binder for the substrate relying exclusively on biological processes. This provides an environmentally-friendly manufacturing process, offering potential replacements for various energy-intensive building materials. At the end-of-life, mycelium-bound materials can be recycled or composted [1]. Thanks to the absence of any toxic substances or synthetic components in such products, they provide an ideal fit for a circular economy model [2].

In general, parameters of the production process can alter the properties of mycelium-bound materials to a certain degree. Elsacker et al. [3] established a comprehensive framework of the primary determining parameters. Previous research has identified a variety of beneficial material properties, such as low heat conductivity, high acoustic absorption, and fire resistance. However, currently the application of mycelium is mostly limited to non-structural or semi-structural uses, as in-depth research knowledge on material behaviour is still lacking [1]. Mycelium-based composites versatility allowed their application in various contexts, including 3D printing [4], packaging [5], household appliances [6], textiles, [7-9] and buildings [2, 10, 11]. It must be noted that, in all cases mentioned, mycelium composites are intended exclusively for indoor use, due to durability concerns.

Investigations are ongoing regarding mechanical properties of mycelium-bound composite materials for structural applications in the form of boards and bricks. However, due to diverse range of substrates, fungal species and process parameters, the direct comparison of mycelium-bound materials to conventional building materials is a challenging process [2]. To realize the full potential of fungal materials for engineering applications, future research is needed on topics including new processing strategies and reproducibility of these materials [12].

1.3. Additive manufacturing with fibre-based biomaterials

Additive manufacturing (AM) technologies have developed extensively in recent years. While most processes are based on inorganic materials, new technologies are emerging that allow for the use of organic materials [13]. In the case of timber, the conventional approach is Fused Deposition Modelling (FDM), where wood is ground and mixed with a thermoplastic [14], thereby losing the structural potential of its fibres’ layout. Similarly, in applications utilizing mycelium-based pastes for AM, long fibres are also absent [15], providing a final product with relatively low structural characteristics.

Approaches towards AM processes using continuous fibres can be found in the aerospace industry, where techniques such as Automated Fibre Placement and Automated Tape Laying are commonly used to manufacture high-performance components using carbon fibres [16][17]. More recently, researchers proposed a fabrication method using continuous timber fibres filaments through robotic placement, combining the advantages of fibres-based manufacturing with bio-based materials [18]. Other approaches towards the use of natural fibres have also been presented and discussed for the creation of fibres composites [19], mostly realized with winding processes rather than AM [20]. However, most processes rely on binders of non-biological nature to achieve structural cohesion of the fibres. Given that the fibre-to-resin ratio used is very low [21] in comparison to the ratio of conventional composite timber products, research for alternative binding methods is needed if timber and other natural fibres are to be used more for fibre-reinforced composites.

1.4. Contribution

To address the described lack of bio-based materials for interior fittings, we propose an innovative wood-mycelium composite to enable CO₂-neutral, circular interior construction for office spaces. We analyse requirements for interior components, describe the material concept and production process, and present initial results regarding its characterization and application scenarios. The objective is to
engineer the build-up and growth process of alternative mycelium-based materials with distinct mechanical and acoustic characteristics, suited for a wide range of applications as interior fittings.

2. Methods

2.1. Application requirements definition

In order to identify the most suitable applications for the proposed composite, a wide range of possible end-uses, including ceiling and wall panels, partition walls, flooring systems, acoustic sails, furniture, and meeting pods were identified and evaluated. For each application the desirability, feasibility and viability for scalable, compliant products that could meet or exceed the performance of standard building materials were assessed. Two applications, the partition wall and the acoustic sail, were pre-selected as potential use cases due to their design flexibility, relatively large contribution to total embodied carbon and high requirements both for structural and acoustic performance.

2.1.1. Structural requirements. As general design requirements, ultimate limit states (ULS) and serviceability limit states (SLS) based on DIN EN1990 and DIN EN1991 were applied. The main actions to be considered for a partition wall include self-weight and horizontal loads typical for office and workspace areas (Cat. B). While deadload leads to generally relatively small in-plane loads for a top and bottom supported partition wall, the governing load cases for failure of structural components (ULS) and deflection limits (SLS) are horizontal loads such as crowd and impact forces. For the serviceability, the performance and appearance of the wall, as well as the comfort of users, vibrations must be addressed in addition to deformations.

For an acoustic sail suspended from the ceiling by a certain form of subframe, the structural requirements are relatively low, assuming the sail will be out of reach of people or other accidental loads. The actions to be considered will mainly be the self-weight of the material, which will be low for the proposed composite. Possible effects on the sail will be out-of-plane bending and shear force caused by self-weight only, and possibly in-plane axial force depending on the overall shape of the sail.

2.1.2. Acoustic requirements. The acoustic evaluation of the use cases focused on potential for direct application into facility design and construction, under consideration of state-of-the-art acoustic standards and performance criteria. While international standards came into general consideration, the evaluation process focused on applicable ISO and DIN standards currently utilized in Germany.

In the case of a partition wall, the fundamental design requirement is that the assembly guarantees a minimum level of “protection from noise”. This criterion is expressed in terms of the airborne sound insulation index Rw, which is quantified in decibels (dB). Minimum criteria are established as a part of building code for different building typologies under the standard DIN 4109-01:2018-01. Recommendations for Rw values which can be optionally applied to partition walls between rooms within a single user’s area are provided in standards such as DIN 4109:1989 and VDI 2569:2019, but are not legally required for building permitting or code compliance. Standard partition walls are generally composed of metal or timber studs for the framing, gypsum boards for the wall finishes and mineral wool for the cavity insulation to improve the sound insulation performance Rw. Under consideration of the given acoustic requirements, the goal is to substitute these materials with the novel bio-based composite material.

The acoustic sail was pre-assessed as a use case with high potential, primarily because of the demonstrated capacity of mycelium as a sound-absorbing material. Acoustic absorption within occupied rooms is mandated under a variety of standards and design criteria. For example, the standard DIN 18041:2016-03 establishes specific planning criteria for reverberation times in a range of space types, as a part of “barrier free” design to ensure that the rooms provide sufficient “audibility” for all users. Furthermore, the Regulation for Workplaces (Arbeitsstätten Verordnung) ASR §3.7 outlines minimum criteria for reducing sound levels within workplaces, to ensure that employees are adequately protected against noise exposure. Sound level reduction in environments prone to noise build-up can be achieved
through sound-absorbing materials, which are evaluated in accordance with standards such as DIN EN ISO 11654:1997-07.

2.1.3. Sustainability impact evaluation. A holistic sustainability impact evaluation involves performance rating of the wood-mycelium composite under various sustainability targets, with a particular focus on net-zero CO₂ emissions and circularity. Both these aspects are to be evaluated by conducting a whole life cycle assessment (WLCA). For this, all environmental impacts associated with each individual life cycle stage, defined by CEN 350 standards, DIN EN 15978, and DIN EN 15804, are considered. Specifically, to net-zero emissions, a WLCA requires the assessment of the CO₂-emissions along the Product Stage (Modules A1-A3), the Construction Stage (Modules A4-A5), the Use Stage (Modules B1-B5), and the End-of-Life-Stage (Modules C1-C4). Additionally, a WLCA requires an assessment of the benefits and loads beyond the system boundary (Module D), which considers circularity aspects.

The environmental impacts are accounted as a result of various processes carried out during each stage. Particularly, the total energy use associated to each process, the energy sources/triggers, and the carbon emission factor associated to each trigger. In module A3 (manufacturing) for instance, all energy flows and associated CO₂-emissions resulting of the manufacturing of all components which make up the product, including wood-mycelium composite and other potential elements, need to be taken into account. The same considerations apply to all life cycle stages.

For a product to achieve net-zero or carbon negative performance, circular design strategies play an important role. These are mostly associated to impact reduction during the Use (B1-B5) and End-of-Life (C1-C4) stages. Appropriate strategies are those which ultimately reduce waste generation and maximize the service life of all components. Examples are designing for disassembly, modularity, or recyclability. Disassembly of modular elements, for example, optimizes the resource use during manufacturing and installation stages, increases the potential for repair or replacement of individual units, thus reducing waste generation and demand for additional material extraction.

Implementation of circular design principles and strategies will be assessed following the performance criteria within the Cradle-2-Cradle (C2C) certification. The C2C certification comprises a series of indicators that go beyond whole life cycle carbon emissions. It emphasizes the use of materials contributing to the health and well-being of users, as well as to the shift to circular manufacturing processes. Health requirements focus on aspects such as identification of chemicals, replacement of chemicals, low VOC (volatile organic compounds) content, and overall hazardous materials content. The circularity requirements cover concrete targets and aspects, such as increasing the use of bio-based and renewable contents, use of materials allowing more than one cycling pathway (i.e., recyclable, compostable or biodegradable), or monitoring cycling rates of a product.

The wood-mycelium composite presents great potential to achieve high performance under the C2C certification criteria. Using mostly, if not exclusively, bio-based materials, a low or negative whole life cycle carbon emissions rate is expected. Furthermore, relying on bio-based materials ensures the production of minimal waste at the end-of-life of component, as bio-based composites could be composted or biodegraded with minimal effort, contrary to composites relying on synthetic materials. Attention must be thus paid in the manufacturing process, related energy sources, and circular strategies minimizing future environmental impacts.

2.2. Composite material concept
According to the defined requirements for a range of interior fittings, it can be identified how different elements need to withstand a combination of axial, shear and bending forces, while also satisfying varying acoustic requirements. Conventional mycelium composites appear inadequate to satisfy such requirements. For this reason, we propose a novel material concept based on the combination of a mycelium matrix with a reinforcement grid composed of veneer strips. These reinforcement grids are produced using a custom AM method that deposits continuous timber fibres in either 2-dimensional or 3-dimensional layouts. Once the grids are produced, mycelium-inoculated substrate is added. During
growth, the substrate binds to the grid, creating a composite material (figure 1). The resulting composite can be customized by changing the position and layout of the reinforcement grids in relation to the mycelium matrix, similar to how steel reinforcement is added to concrete elements to increase their structural capabilities.

Figure 1. Overview of the production process, combining AM for reinforcement grids (top) with mycelium cultivation (bottom) into a single bio-composite (right).

2.3. Additive manufacturing with continuous timber fibres
For the production of reinforcement grids using continuous timber fibres, we propose a novel AM method to lay veneer strips in custom layouts, and bind them using ultrasonic welding. The goal is to produce tailored reinforcement structures, where the fibres are bound without use of adhesives.

2.3.1. Materials. Timber veneer edge-banding tapes with a thickness of 0.5 mm were provided by H. Heitz Furnierkantenwerk (Melle, Germany). Various timber species (beech - *Fagus sylvatica*, spruce - *Picea abies*, maple - *Acer pseudoplatanus*, Oak - *Quercus robur*) were tested. Additionally, printing tests were performed using a solid filament produced from split willow withies [23].

2.3.2. Additive process for fibres deposition. The veneer strips were placed in custom grid configurations using a robotic process with a custom end-effector (figure 2), adapted from [18]. The tool included a stepper motor for extrusion, a cutting blade actuated by a pneumatic cylinder, and a set of guides able to fit strips with different widths. The tool was mounted on an ABB4600 robot and controlled through an Arduino board and IO signals from the robot controller. The robot program was generated using Robot Components [24], a Grasshopper plugin for robotic programming. Fibres are temporarily held in place by double-sided tape at the edges of the printing area.

2.3.3. Ultrasonic welding of veneer strips. One of the key challenges in developing a fibre-based AM method for biomaterials is the process required for binding the fibres together, as most bio-based adhesives have a long open time, which is not compatible with our AM process. For this reason, a process based on ultrasonic welding (UW) [25], was applied to bind the veneer strips together at intersection points. The process uses a UW horn and generator, provided by Weber Ultrasonics (Karlsbad, DE), which produces high-frequency vibrations while pressing the strips against a surface. The vibrations are converted into thermal energy, which melts the lignin component of the veneer strips, binding them without the application of adhesives (figure 3).
2.4. Mycelium cultivation

Once produced, the reinforcement grids were embedded in mycelium-inoculated substrate, allowing to bind the two into a composite material. We describe the growth process and the testing samples production in the following sections.

2.4.1. Materials. The fungal species of *Ganoderma lucidum* (*G. lucidum*) were purchased from Tyroler Glückspilze (Innsbruck, Austria) in the form of grain spawn and stored at 4 °C for up to four weeks. Loose hemp hurds were obtained from Bafa GmbH (Malsch, Germany). The hemp hurds had an average length of 1 cm and average diameter of 2mm.

2.4.2. Sample preparation. All materials were moistened with tap water. The moisture content of hemp hurds were adjusted to 60-65 wt.% . Moistened hemp hurds were packed in polypropylene (pp) bags and steam sterilized for 20 minutes at 121 °C (Tuttnauer, 2840 EL-D). The bags were cooled to room temperature before further processing. The bags of substrates were inoculated by adding 5-10 wt.% of grain spawn under a laminar flow hood and sealed with cotton wool to allow oxygenation for the growth of mycelium. The bags were then stored in an incubation room at a temperature of approx. 25 °C and relative humidity of 70% for two to three weeks.

2.4.3. Reinforced panel fabrication for flexural test. The colonized hemp hurds with *G. lucidum* were shredded and placed in the plexiglass moulds layered with wood veneers of selected tree species. Prior to layering, the veneers were moistened with 35%-40% of tap water and sterilized as explained in the
previous section to avoid contamination. The moulds were then placed in the incubation room with similar conditions, as explained, for an additional week of growing. The mycelium density, the number of veneer layers and orientations could be adjusted according to the required physical and mechanical properties of the desired panel. The moulds were then removed, and grown panels were dried in a conventional oven with a temperature of 60 °C for up to 2 days for terminating the mycelium growth and stabilizing the panel (figure 4a). If a higher density panel is required, the dried panels can be pressed down using a heat press.

2.4.4. Reinforced cubes fabrication for pull-out test. Due to the important role that the interface between the veneer and mycelium matrix plays in the overall performance of the composite panels, it is vital to determine the bond strength between the two. For this purpose, interfacial shear strength can be measured by direct or indirect testing methods. Direct techniques include fibre pull-out, push-out, microbond or fragmentation techniques, commonly used for fibre-reinforced polymer composites [26-27]. Fibre pull-out tests have been chosen for this study, given their wider recognition for determining the bond strength of fibres in natural fibre reinforced polymer composites. However, given the lack of extensive prior research on bond mechanism of fibres in a mycelium-based composite matrix, a pull-out test was designed with modifications to suit the materials used. Therefore, similar to the process explained in the previous section, the shredded colonized substrates were placed into cube moulds and, once the cubes were filled to 10% of their final height, one veneer strip was placed into the cube, perpendicular to the top surface and then covered with the crushed material until the full height was reached. The cube moulds were then incubated with similar conditions as described above for an additional week of growing. After this, as explained in Section 2.4.3, the moulds were removed and grown cubes were dried (figure 4b). Finally, they were tested for pull-out strength.

![Figure 4. Mycelium samples production: a) reinforced panels, b) reinforced cubes.](image)

3. Results

3.1. Materials compatibility

3.1.1. Ultrasonic welding. Initial welding tests were performed with the mentioned veneer species, to assess the feasibility of the process. It was observed that only maple and beech samples were able to provide sufficient bonding strength, while spruce and oak failed to bind, or showed inconsistent performance. Given that maple showed the best results in terms of bonding strength and weld consistency, it was chosen to perform a series of tensile strength tests with 20 samples. While the consistency of the weld strength is still an issue and further studies are needed, most samples showed
failure of the veneer material before the failure of the connection (figure 5), demonstrating that UW can be adopted as the binding method within the proposed AM technique.

3.1.2. Veneer-mycelium growth and bonding. A series of veneer growth compatibility tests with the selected wood veneers and fungal species were carried out to identify the suitable type of veneer for the composite panels’ fabrication. Beech and maple showed better compatibility with the selected mycelium species; however, the final veneer species selection was maple due to its better welding performance. In order to assess the Interfacial shear strength (IFSS), a 5kN HBM load cell attached to a Universal Testing Machine (UTM) was used. The veneer was pulled out on the fixed end with the grip of the tensile test setup while the cube was held in place using custom made clamps. The resulting IFSS was determined using the following formula:

\[ \tau = \frac{F_p}{2l(t + w)} \]

where \( F_p \) is the pull-out force, \( t \) and \( w \) are the veneer thickness and width respectively, and \( l \) is the embedded veneer length in the mycelium matrix [28]. The embedded length was fixed to 75% of the cube height. A minimum of 5 specimens were tested. The sample details and the test results are summarized in Table 1. All tests resulted in a pull-out failure rather than a tensile failure, which indicates that the IFSS of veneers in the mycelium matrix is much lower than the tensile strength of the veneer itself. Further research is currently being carried out to determine factors affecting the IFSS and to improve the bonding mechanism between the veneer and the mycelium matrix [28].

![Figure 5. Tensile test specimens for UW. Most samples show a veneer failure before the failure of the welded connection.](image)

3.2. Effect of veneer reinforcement on mechanical behaviour

A series of reinforced and non-reinforced panels produced as per procedure described in section 2.4.3 and were tested under 3-point flexural test using a UTM testing setup. The results are summarized in table 1. It was observed that the application of the wood veneer layers in the mycelium matrix has slightly helped with the increase in flexural strength. Almost all the reinforced samples displayed a clear
flexural failure rather than any shear or veneer delamination failure. Furthermore, it was observed that the use of veneer reinforcement improved the failure mechanism where no sudden rupture of the panels was observed. Further research on investigating the impact of veneer species, their layouts and locations on the load bearing capacity, rigidity, ductility, and stability of the newly developed wood-mycelium composite panels are currently under way, and initial results have been recently published in [28].

| Specimen                | Size (width × length× height) (cm) | Density (g/cm³) | Average strength (MPa) |
|-------------------------|------------------------------------|-----------------|------------------------|
| Pull-out cubes Interfacial shear strength | 5 × 5 × 6 | 140         | 0.34 ± 0.04            |
| Reinforced panel Flexural strength          | 9 × 19 × 6 | 140         | 0.19 ± 0.04            |
| Non-reinforced panel Flexural strength       | 9 × 19 × 6 | 140         | 0.17 ± 0.04            |

### Table 1. Results of the pull-out (IFSS) and flexural tests

3.3. **Wood-mycelium composite panels**

In order to test initial application scenarios, a series of small-scale 20x20cm prototypes were produced using the proposed fabrication process, exploring the possibility of introducing reinforcement at various locations in the mycelium matrix, as well as testing the possibilities of both 2-dimensional and 3-dimensional reinforcement grids (figure 6). Further studies are under way to upscale the fabrication processes to allow larger samples in the 50-100cm range.

![Grid layouts for reinforcement, from left; 2D grid, 2D grid with solid sides, 3D lattice.](image_url)

**Figure 6.** Grid layouts for reinforcement, from left; 2D grid, 2D grid with solid sides, 3D lattice.

4. **Discussion**

The presented bio-composite is considered as a two-phase composite material with mycelium as the continuous matrix phase, and veneer as the strengthening element. Since wood veneer is weak in compression, mycelium can help to stabilize it especially at areas of compression to prevent buckling, and at the veneer-to-veneer joint to prevent out-of-plane pull-out failure. The veneer contributes to tension and compression in parallel to its grain direction, improving the overall performance of the composite. The layout, orientation, and density of the veneer as reinforcement could be optimized following the loading conditions and the flow of forces of the specific end uses. Furthermore, when the veneer is designed as a continuous system, such as a 3D spatial lattice system, it can efficiently provide additional stiffness and strength via its geometry, without redundant material accumulation.

This novel bio-composite differs from the previous studies on the sound-absorbing characteristics of mycelium composites, as it contains sound-reflecting veneer at various depths within the matrix. By utilizing lightweight and thin veneer strips, the sound-reflecting influence of these materials can be minimized, maintaining overall sound-absorbing characteristics of the composite. Initial assessments have suggested that the reduction in sound-absorption may be controllable and limited in scale. An acoustic sail constructed using the proposed composite material would allow for great design flexibility.
through adjusting the thickness, shape and density, customizing the components to the needs of the specific room which is being treated.

With regards to partitions walls, the proposed composite material could simultaneously achieve structural stability and sound absorption through a layered construction using uncompressed material in the interior of the wall elements, combined with compressed panels as the exterior face. The potential for replacing all the elements of a standard partition wall with mycelium composite components led to the prioritization of this design option for further research.

5. Conclusions
This paper described the production process, initial characterization and application evaluation for a novel wood-mycelium composite material. The developed production process has been presented, including additive manufacturing of timber reinforcement grids without adhesives, and mycelium cultivation. Initial tests demonstrate promising results of the integration of mycelium materials with veneer reinforcement, while the evaluation of application parameters for various interior fittings highlights the potential use range of such composite material. Further testing for a more complete characterization of the material properties and their production process are currently ongoing, and will further help to identify the most suitable applications. Overall, the proposed composite offers the potential of extending the range of application of mycelium-based composites to a variety of interior fittings, offering a sustainable alternative to currently used composite materials.

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