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Fungal mycelium as a building material

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Abstract

A result of society's heightened awareness for the scarcity of resources and the immense material and energy consumption of the building industry is the increasing demand for bio-based building materials and components. With its favorable material characteristics and fast growth, fungal mycelium has become a promising object of investigation in recent years. Provided with a sufficiently nutritive substrate, the growth of fungal mycelium is virtually limitless. The material itself is a composite of at least the fungal mycelium and a substrate, e.g. chipped wood, which the fungus digests and perfoliates. With favorable insulating properties and moderate strength, this composite material is an ideal bio-based substitute for conventional insulation elements. In order to expand the range of application beyond insulation panels, however, the stiffness as well as the tensile and compressive strength of the material has to be increased. A current research project at the RWTH Aachen University examines the possibilities of increasing the strength and stiffness of fungal materials with the aim of creating load-bearing mycelium-based building components. First results indicate that the choice and geometry of the substrate, the selection of fungi as well as the type and quantity of the aggregates allow for a targeted setting of the material properties.

Keywords: Natural material, bio-based material, natural design, fungal mycelium, compressive strength

1. Introduction

The building sector is considered a key element in the shift toward a resource efficient future (CRI [1]). In the context of a more sustainable building sector, the concept of resource efficiency encompasses the reduction of resource use throughout the entire lifecycle of a building – from the sensible use of materials and components during construction, through an energy-efficient or even zero-energy occupancy to a demolition phase that holds potential for re-use or recovery of building components.

Building components and materials that emanate from an energy efficient production process combined with an application that creates more energy efficient buildings, e.g. building components with favorable insulating properties, or lightweight structural elements that foster an efficient use of material, are of pivotal importance toward the creation of a more sustainable built environment. Bio-based materials will greatly facilitate this shift since they not only contain less embodied energy, but counteract the depletion of resources through the utilization of renewable sources.

While the utilization of plant-based construction materials, in both load-bearing and non-load-bearing capacity is comparatively common, the application of fungal-based materials in buildings is a novelty. A multidisciplinary team of architects, structural and mechanical engineers and biologists from the

RWTH Aachen University collaborates in order to systematically assess the potential for fungal-based building materials and derive suitable applications for the building sector.

2. Fungi – the invisible builder

For thousands of years mankind made use of parts of multicellular organisms for the construction of dwellings. Oftentimes parts of plants and especially trees were employed for this purpose (Trautz [10]), but in some instances even bones from whales would be used for construction (Savelle *et al.* [9]). These ancient 'building materials' belong to the biological kingdoms 'Plantae' and 'Animalia' respectively. Alongside those two kingdoms, a third kingdom containing multicellular organisms exist, called 'Fungi'. Until today the capacity of this kingdom remains underused and its full potential is not yet comprehensively researched.

The kingdom 'Fungi' comprises of single cellular organisms called yeast as well as multicellular organisms e.g. mold or mushroom. All multicellular fungi grow in the form of filaments, so called hyphae, which constitute the mycelium. Like organisms of the kingdom animalia, fungi are characterized as heterotroph, meaning that they have to acquire food by absorbing dissolved molecules, and are unable to perform photosynthesis. Like plantae, fungi are immobile. As a consequence, fungi have to grow along a gradient of nutrients in order to reach their next carbon source. While the fruiting body of a fungus is restricted in size, its capacity to develop filaments and thereby enlarge the mycelium is virtually unlimited.

Fungi can be found around the world. They are common destruents for other multicellular organisms and a developed mycelium is able to 'hold' a nutritive particle at a given position within its network until it will be digested. The strength of the mycelium is proportional to the content of chitin in the surrounding cell wall (Gow and Gadd [3]). In contrast to plantae, the fungal cell wall is mainly build by beta-1,3- and beta-1,6-glucans, as well as mannans, chitin and proteins. In this context, the chitin in the cell wall stabilizes the structure. Due to the higher capacity to form hydrogen bridges, chitin might be even harder and more stable than cellulose (Gow and Gadd [3]).

A few fungi families grow by breaking down lignin in plants (Knežević *et al.* [6]). Those families are called white-rod fungi as the degradation of lignin leads to a bleach of the decayed wood. During their growth, they form tight junctions with the substrate. Some of those fungi can attack living trees, and live as a parasite, but the majority of white-rod fungi infect only dead wood. Many of them will be cultivated for food production as for example oyster mushroom (*Pleurotus spp.*) and shiitake mushroom (*Lentinula edodes*).

Nowadays, *Pleurotus ostreatus* is one of the most commonly cultivated edible mushroom worldwide and its cultivation can be performed on a variety of substrates (cereal straw, sawdust, bagasse, waste cotton, hardwood). It needs moderate temperature and humidity to inoculate the substrate. The production of fruiting bodies depends on environmental factors such as light and temperature. Due to this knowledge, the use as a construction material builder is easy to handle.

A non-edible fungus with a comparatively high content of chitin is the tinder mushroom (*Fomes fomentarius*) (Rühle [8]). Due to the high chitin content, it develops a strong mycelium. *F. fomentarius* lives on dead (hard-) wood and can form perennial stable fruiting bodies. After preparation of the hyphae (e. g. boiling, soaking, embedding in nitric acid, or drying) one spark is sufficient to ignite them. Furthermore, the hyphae also serve as a leather substitute and are used to produce caps or bags (Pegler [7]).

3. State of the art

In search of new materials that satisfy future requirements for resource efficiency, researchers and entrepreneurs take advantage of the ample biomass production of fungi in order to develop mycelium-based substitutes for conventional materials. Fungal mycelium cultivated on a substrate is a lightweight material with a low density, favorable insulating properties, moderate strength and a porous surface. The compostable material can be cultivated with little effort and grows into any given shape.

San Francisco based artist, inventor, and founder of MycoWorks Phil Ross was among the first to discover the potential of fungal mycelium for the development of organic materials in the 1980s. His company mainly employs mycelium of the reishi (*Ganoderma lucidum*) to produce furniture, small architectural elements like bricks and substitutes for materials such as leather. Another American biomaterials company, Ecovative, makes use of the favorable insulating properties of fungal mycelium by developing acoustic tiles, insulation panels and compostable packaging material while using fungi. Professor Dirk Hebel of the Federal Institute of Technology in Zurich (ETH) researches the material in terms of its potential for the application in buildings and has created mycelium bricks for the construction of non-load-bearing walls (Hebel *et al.* [4]).

These examples are a selection of current research and commercial activities concerning the utilization of fungal mycelium and demonstrate that there is no shortage of ideas for the application of the material. They also demonstrate, however, that due to the natural material properties of fungal mycelium - with its favorable insulating properties but only moderate stiffness - applications are limited to non-structural components. Especially for applications in the building industry, comprehensive analyses on the material characteristics of fungal mycelium with a particular emphasis on the enhancement of its structural properties are key to broaden the application range. This systematic analysis of influencing factors on the properties of mycelium-based building materials is at the center of a multidisciplinary research project conducted at the RWTH Aachen University.

4. Project description

Since 2016, the project ‘LIMy-Brick’ (Lightweight Insulating Mycelium Brick) seeks to provide a basis for a broad application of mycelium-based components in the built environment by establishing a more holistic understanding of the different influencing factors on the structural material properties of fungal mycelium. The findings of this analysis are then translated into the design and development of a lightweight mycelium-based brick prototype with favorable insulating properties and a usable compression strength for the application in load-bearing interior walls.

Initially, the research project aims at analyzing the different constituent parts of a mycelium-based building component, namely the fungal mycelium, the wooden substrate as well as additional aggregates, and their influence on the structural properties of compression test specimen. Test specimen were then tested for their compression strength in small sample test series.

Based on these preliminary findings, brick prototypes with the most promising combinations of mycelium, substrate, and aggregates were generated to demonstrate the mycelium growth at a larger scale and provide a proof of concept for rigid mycelium-based building components.

4.1. Cultivation of the fungal mycelium

The mycelium initially grows for six to seven days at 26 °C in darkness on malt extract peptone agar plates (3% malt extract, 0.3% soya peptone, 1.5% agar, pH 5.6). The plate is then cut into 10 mm x 10 mm pieces and added to the substrate, the growth basis for the mycelium. 1000 ml autoclaved wood chips imbued with autoclaved sucrose-malt extract-yeast extract medium (1% sucrose, 1% malt extract, 0.2% yeast extract, pH 5.6), which provides nutrients to the mycelium, constitute the substrate. Autoclaving all substrate components reduces the possibilities of pre-contamination with other fungi strains or bacteria.

Subsequently, the mycelium grows for an additional seven days at 28 °C until the hyphae have developed a visible network that perfoliates the substrate. The inoculated substrate is then transferred to a final container in the shape of the finished product. Containers are stored for 14 to 28 days (depending on their size) in a controlled environment at a temperature of 25 °C. During the final growth period, the mycelium perfoliates the molded substrate completely and thus stabilizes the shape. After removal from the container, the wood-based mycelium is baked at 95 °C until it weighs $\leq 50\%$ of its original weight which terminates the growth process by denaturation of the DNA and proteins, and dehydration of the fungal and substrate cells.

4.2. Material composition and testing

The influencing factors mycelium, substrate, and aggregates, are analyzed for their effect on the structural characteristics on the mycelium-based material. Within these three categories of influencing factors, variables were defined and combinations of mycelium with different variables of each category were cultivated. Environmental factors during the cultivation and growth period, which can influence the material properties of the mycelium as well, were not modified throughout the duration of the project in order to maintain a manageable amount of variables.

4.2.1 Mycelium

Different fungi have vastly different characteristics in terms of growth rate, appearance and host selection which also translate to their mycelium. Throughout the research project, two fungi and their mycelium were employed as variables: the oyster mushroom (*Pleurotus ostreatus*), and the tinder fungus (*Fomes fomentarius*).

4.2.2. Substrate

Even though fungi can grow on almost any carbon source and substrates of straw, hemp, and other agricultural waste have proven to be effective for white-rod fungi [4], solely wood chips were used as a substrate in this project. Regarding the substrate, two different sets of variables were introduced: tree species and wood chip geometry.

Wood from deciduous trees (beech, European oak, and pear) as well as wood from coniferous trees (spruce) was processed into wood chips and utilized as substrate for the fungi. Two different geometries of wood chips were tested: longitudinal shavings with a thickness of 0.2 – 5.0 mm derived from a smoothing plane, and square chips with sizes of 0.75 – 3.5 mm. The wooden substrate always consists of only one tree species and one chip geometry; however, different sizes of wood chips are utilized for the substrate.

4.2.3 Aggregates

The capability of fungal mycelium to incorporate particles into its network is of great research interest, especially with regard to the structural enhancement of mycelium material. Similar to aggregates in concrete, small particles of organic or mineral origin can be added to the substrate in order to influence its properties. Due to the research focus on the enhancement of the structural properties, mineral aggregates to increase the compression strength of the material were utilized. Different ratios of sand or gravel aggregates to wood chips were tested.

4.2.4 Compression tests

Compression tests on a hydraulic testing machine with small sample series were conducted to determine the most promising combinations of mycelium, substrate and aggregate. Since there is no standardized procedure for the material testing of fungal materials, a modification of the upsetting test – a variant of the compression test with cylindrical specimen – was conducted (Dahl *et al.* [2]). For this, cylindrical test specimen with a diameter of 45 mm and a height of 45 mm with different material compositions were produced. To account for the plasticity of the mycelium-based material, the compression stamp lowers onto the test specimen with a constant speed of 0.25 mm/s until a defined upsetting deformation $\mathcal{E}_{dt}$ = 33 % (equaling a strain of 15 mm) is reached. Thus, the press capacity F at a given specimen height of 30 mm can be determined and is used for the comparison of different material combinations.

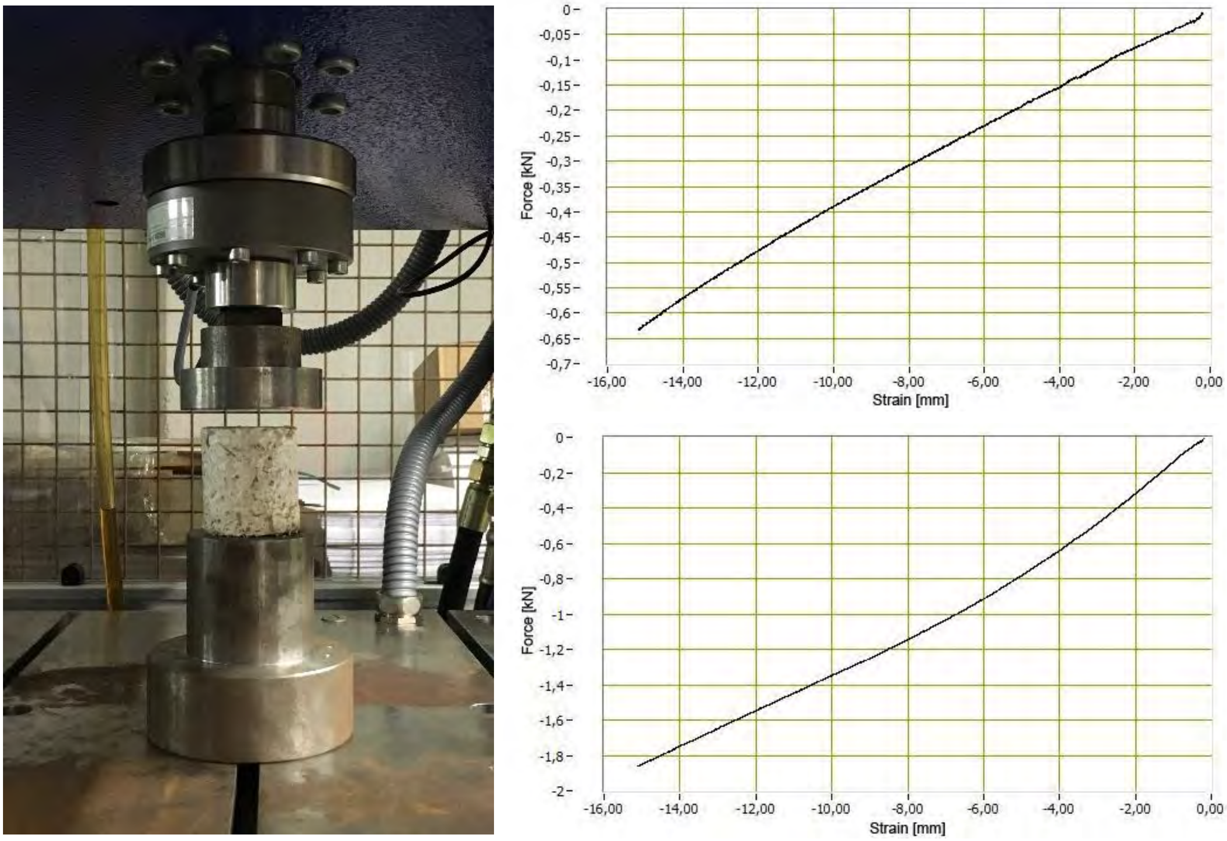

Figure 1: Compression test set-up (left) and diagrams of two test specimen: specimen without aggregates (top right) and specimen with gravel aggregates (bottom right)

4.2.5 Findings

By comparing the different sets of test specimen, an assessment of the effects of the parameters and the intensity of their influence on the structural properties of the mycelium material is possible. The small sample compression test series indicates that both tested fungi are suitable for cultivating a mycelium in a pre-defined shape in a reasonable time-frame. The stronger growth and most dense hyphae network is produced by the tinder fungus, which was then chosen for the remainder of the project and the prototype brick.

The load-deflection curves for a cylindrical specimen are quite linear for pure mycelium-substrate compositions (see Figure 1, top right). Material compositions with silicate aggregates show a progressive load-deflection behavior (see Figure 1, bottom right) While the tree species itself has negligible effect on the compression strength of the test specimen, the influence of the geometry of the wood chips is significant; with square, compact wood chips exceeding wood shavings in terms of compression strength. Aggregates, both sand and gravel, are able to significantly enhance the compression strength of the test specimen. During the initial small sample test series, specimen with gravel aggregates demonstrate an increase in press capacity of up to 300 % compared to specimen comprised of just substrate and mycelium. An even distribution of the aggregate within the substrate, however, is important to avoid a local concentration of mineral components.

4.3. Prototype Design

The brick prototype is modeled after a commercially available sand-lime brick for the application in load-bearing and non-load-bearing interior walls with dimensions of 113 x 175 x 240 mm. Its design features a grip hole that is not only beneficial when assembling walls, but reduces the growth duration of the mycelium brick. The decision to model the prototype after an existing building component supports the argument that bio-based building materials can be used as adequate substitutes for conventional building materials. Throughout the project duration, the requirements for the growth containers were specified; most of the requirements are a direct consequence of the growth process of fungal mycelium and have an immediate effect on the design of the containers. Since fungal mycelium absorbs organic molecules in order to grow, inorganic materials were used to create the containers for they would not be decomposed by the mycelium. Synthetic containers are advantageous since they look in the moisture, thus facilitating a constant moisture content of the substrate which is crucial to a strong mycelium growth. Custom-made Styrofoam molds were deployed for the brick prototypes. In order to facilitate the removal of the mycelium and permit the re-usability of the molds, the Styrofoam containers are designed as an interlocking system. Evenly spread perforation holes in all container elements allow for respiration and foster a steady mycelium growth. Furthermore, the insulating qualities of Styrofoam can compensate against short-term temperature differences which helps maintaining the growth temperature at a steady 25 °C.

Figure 2: Mycelium-based brick prototype with sand-lime brick model (left) and close-up of the surface (right)

5. Conclusion and Outlook

First results on the interdependency between substrate, mycelium, and aggregates and their influence on the structural properties of mycelium material derived from this research indicate a great potential regarding the structural enhancement of mycelium material which will broaden its application range in the building industry. Furthermore, the findings demonstrate that a customization of natural building

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