

Application of Mycelium-Bound Composite Materials in Construction Industry: A Short Review

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Abstract

Mycelium-bound composite materials are a new class of sustainable and affordable biocomposites that have been recently introduced into packaging, fashion, and architecture as alternative to traditional synthetic materials. In recent years extensive investigation and research studies have been dedicated to explore methods of production and processing as well as to find potential applications for mycelium-bound composite materials. However, application of this novel biocomposite within the construction industry has been limited to only small-scale prototypes and exhibition installations. The problems with low mechanical properties, high water absorption and lack of standard methods for production and testing of mycelium-bound composite materials remain as main challenges that need to be addressed when used as non-structural or semi-structural elements. This short review aims to display the potential of mycelium-bound composite materials for their use within the construction sector in the form of thermal and acoustic insulation as well as replacement for drywalls and tiles. This review summarizes the main available information with regards to the properties of mycelium-bound composites that have been used in construction sector while suggesting the direction for the future research and development on these biocomposites for their applications within the construction industry.

Introduction

As populations and aspirations grow, so does the demand for materials and resources to support them. Although such demands were once satisfied by local and regional hinterlands, they are becoming increasingly global in scale and reach. This phenomenon has generated material flows that are trans-continental and planetary in scope, and has profound consequences for the sustainability, functioning, sense of ownership and identity of future cities. However, the global concentration of the construction industry on a selected few material, namely steel and concrete puts high pressure on our natural resources. If we talk about the future city, it is clear that it cannot be built with the same resources as the existing ones. Although the current market is trying to solve some of the mentioned issues by tapping on natural resources such as bamboo and timber in the form of engineered composite products such as Mass Engineered timber (MET) and Engineered Bamboo Composite (EBC), the safety and sustainability of such applications are still under investigations [1-6]. Given the current rate of deforestation across the globe one needs to address the challenges the construction industries will face due to market demand for forest products such as hardwood and softwood. Furthermore, the number of toxic adhesives that are being employed within the construction industry and subsequently are released into nature after the end of the product life cycle is unacceptable. There is thus an

urgent need to look into other alternative building materials that are sustainable and can be completely recycled without having negative impacts on the environment [7].

For instance, deforestation is a major modern-day plague in Southeast Asia. Southeast Asia is home to more than 600 million people. Due to the increasing human population, governments have taken measures to clean more rainforest in order to create urban space. The rainforest trees are known to be suitable for a variety of purposes in forms of lumber products for applications in the construction industry. Southeast Asian countries are now faced with the problem of depletion of their natural forest resources to meet global demands for wood-based products. Although deforestation to create urban space seems an inevitable solution to the growing demand for housing and infrastructure, mitigation of deforestation caused by construction demand alternative materials and technologies needs to be explored and introduced to the building and construction sector. Development of novel and green composite materials from mycelium have been introduced recently and could potentially revolutionize the construction sector. Indeed, in the quest for new materials, mycelium-bound composites would enable a shift towards activating the urban waste resources and binding them to make a sustainable replacement to some of the traditional construction materials. Mycelium-bound composite materials are a new form of advanced biocomposites which are developed

based on fungal growth of at least one species of commercially cultivated edible mushrooms on different organic and inorganic substances. Typically, these substrates are sourced from food and agricultural waste and by-products that are crushed and compacted into a porous block. During the development and growth of the fungus on to the substrate, it develops a mycelium that consists of thread-like hyphae forming a tight interconnected network[8]. Fungal mycelium therefore acts as a binder around the substrate material. Mycelium-bound composites are proved to be affordable, environmentally friendly and recyclable for a wide range of applications within the building and construction sector[9,10].

Mycelium-bound composites have numerous advantages over other traditional synthetic composites, namely lower cost, lower density and lower energy consumption. Furthermore, they also have shown lower environmental impact and CO₂ footprint compared to apparently environmental-friendly composites such as bioplastics or wood composites [11-13]. Mycelium-bound materials are natural and fully compostable and therefore they can support the transition towards a circular bioeconomy, where the value of the materials is maintained throughout the economy and the generation of waste as by-products is reduced to a minimum. Mycelium-bound materials have only been recently introduced in the construction industry; therefore, the information regarding their applications is very limited. They have been used in a variety of applications ranging from nonstructural to semi-structural applications replacing traditional plastic films and sheets, synthetic foams and plastics, paneling, furniture, and decking thus paving the way for alternative environmentally sustainable construction materials [14-17].

However, there are various limitations in the current applications of mycelium-bound biocomposites in the construction industry. The low mechanical properties combined with highwater absorption and lack of universal standard test methods for evaluating their properties have triggered interest and effort of many academic and commercial entities to push forward the research and development in various fields of applications. Although there have been many existing developments toward the large-scale processing of mycelium-bound composites, many of these processes are under confidential agreements and know-how, thereby not directly accessible to the public who should benefit directly of such an opportunity to participate to a circular bioeconomy. The aim of this short review is thus to summarize extricable paste out of mycelium materials to develop a higher degree of freedom in design using 3D printing technologies [27]. Mycelium-bound materials have been recently introduced for applications in selected industries, such as packaging [28,29], home appliances [30], and construction [27,31-37]. However, its application in the paper and textile industry [38,39] dates back to the mid-1950s [40]. A recent review study on the application of leather-like mycelium materials, includes comprehensive information on the influence of environmentally responsible materials on the fashion industry [41]. While traditional leather and its alternatives are mainly produced from animals or synthetic materials, mycelium based leather alternatives are fabricated

through upcycling agricultural and forestry byproduct in to chitinous biopolymer resembling leather in both the aesthetic texture and its properties. In the majority of these studies, mycelium species of filamentous fungi, such as *Ganoderma lucidum* (*G. lucidum*, a medicinal mushroom commercially known as reishi, and *Pleurotusostreatus* (*P. ostreatus*), a common edible species of pearl oyster mushroom, have been used for the development of mycelium-bound composite materials.

Utilizing biologic growth rather than energy intensive processes to convert low-cost by-products to high-value mycelium-bound material, which is biodegradable, makes it an attractive alternative to synthetic materials. Mycelium-bound composite material production is environmentally sustainable with low costs for production and disposal at the end of the life-cycle [42].

Companies that are currently designing and commercializing mycelium-bound composites are still few. MycoWorks[43], Mycotech[44], and NEFFA [45] are examples of such companies focusing on the fashion industry. Ecovative Design [46] is focusing on the packaging industry, and MOGU [47] is focusing on acoustic panels and flooring for the construction industry.

Mycelium-bound composites in construction industry:

Studies conducted to characterize mycelium-bound composite materials for applications in the construction industry have generally compared the material to petrochemical foams [10]. The applications in the construction industry have been primarily limited to thermal insulators [34,48-50] and acoustic dampers [35,36]. The material has also shown great fire-retardant properties, making it safer for use in construction applications [13,34]. Given all the ecological advantages of mycelium-bound materials, the question remains as to why it has not been widely applied for structural and semi-structural applications. This may have to do with the low structural strength and water-resistant properties of the material. One recent study showed that mechanical properties and water uptake of mycelium-bound materials could be adjusted by varying production methods, fungal species, and substrate type [51]. The use of good structural geometry would be another innovative way to overcome structural limitations [31,32,37].

Mycelium-bound composite materials properties:

Physical and mechanical properties

Mechanical Properties:

Mycelium-bound materials haven't been widely studied as structural or semi-structural elements mainly due to their low strength. When building with materials that are weak in tension and bending, good geometry is essential for maintaining equilibrium through contact only - that is, through compression. One recent study focused on enhancement of the mycelium-bound material's microstructure mainly to increase its compressive strength and elastic modulus in order to withstand the compressive forces developed within the structure[31,32,37]. In general, information regarding engineering characteristics of

mycelium-bound materials is very limited, this could be due to the fact that mycelium-bound materials have been mainly exhibited in art galleries and museums. Mycelium-bound materials as construction elements come in two different forms, i) light-weight bricks, and ii) dense boards produced by cold or hot pressing the mycelium-bound elements. Table 1 summarizes the available information about the mechanical properties of light-weight Mycelium-bound bricks. Reported numbers in Table 1 are density and compressive strength, because improvements made in compressive properties of mycelium-bound materials would increase the potential of applying these materials in the construction industry to replace bricks [31,32,37]. As reported in Table 1, it was observed that changing the growth substrate could significantly increase the yield compressive strength of the material from 0.05 to 1.1 MPa and from 0.02 to 0.15 MPa in *G. lucidum* and *P. ostreatusstrains* respectively [31,37,52]. Beside changing substrate, one study showed that hybridization of mycelium-bound materials with a natural binding agent such as latex could also potentially improve the compressive strength of the composite from 0.18 to 0.34 MPa [53]. On the other hand, it was observed that densification of the material under stress could increase the ultimate compressive strength of the material to 6.4 MPa and 1.02 MPa in *G. lucidum* and *P. ostreatusstrains* respectively. In the case of *G. lucidum* the ultimate compressive strength reported is close to compressive strength of 8.6-17.2 MPa for clay or shale bricks [31,37,52]. These promising findings shows the potential for further enhancement of the material properties through varying growth parameters and techniques.

Table 2 summarizes engineering properties of dense mycelium-bound boards. Values reported in table 2 are; Density, flexural strength and tensile strength. In the case of dense mycelium-bound materials, information regarding their fabrication process and

Table 1: Mechanical properties of light-weight mycelium-bound materials in brick form, extracted from literature

Growth substrate	Density (kg/m ³)	Elastic Modulus in compression (MPa)	Yield compressive Strength (MPa)	Average Ultimate Compressive Stress (MPa) at (X% deformation) when material fails
Cotton carpel ^a [28,50]	66.5-224	N.A.	N.A.	0.07 ^c (N.A.)
Red-oak sawdust ^a [50]	318	N.A.	0.05	0.5 (>16%)
Woodchip and sawdust of Chinese albizia ^a [31,37]	420	4.00	0.17 ^d	1.2 (31%)
Sugarcane and dried waste of cassava root ^a [31,37]	470	21.10	1.1 ^d	6.4 (50.6%)
Wheat straw ^b [52]	277	N.A.	0.02 ^e	0.07 (N.A.)
White oak sawdust ^b [52]	552	N.A.	0.15 ^e	1.02 (N.A.)
Cotton seed hull ^b [53]	181	N.A.	0.18 ^f	N.A.
Cotton seed hull and 5% latex ^b [53]	225	N.A.	0.34 ^f	N.A.

^aMycelium of *G. lucidum*
^bMycelium of *P. ostreatus*
^cnormalized to polystyrene density of 32 kg/m³
^dfor the design purpose, this value was calculated at 5% deformation of the material
^eCalculated at 20% deformation
^fCalculated at 10% deformation

mechanical properties is not publicly available due to Intellectual Property (IP) restrictions by the researchers and/or the companies who have the know-hows.

In general, cold pressing and hot pressing the mycelium-bound materials to create a dense panel would significantly increase the material mechanical properties due to densification and porosity reduction in the composite. Hot pressing would lead to substantial improvements in mechanical performance compared to cold pressing, this is linked to evaporation of water and flow of steam through cell-membrane and hollow pores which would result in a higher compaction and bound between fibers and mycelium [54].

As can be observed in Table 2, hot-pressing the *P. osteratus* composite grown on rapeseed straw and cotton seed hull would significantly increase the tensile, flexural and elastic modulus of the materials compared to the cold pressed (20) composites. In the case of *P. osteratus* composite grown on cotton seed hull, an increase of 0.03 to 0.13 MPa in tensile strength and 6 to 35 MPa in elastic modulus in tensile was observed. Flexural strength and elastic modulus in flexural were also increased from 0.24 to 0.64 MPa and from 12 to 34 MPa respectively. In the event of *P. osteratus* composite grown on rapeseed straw, an increase of 0.03 to 0.24 MPa in tensile strength and 9 to 97 MPa in elastic modulus in tensile were observed. Flexural strength and elastic modulus in flexural were also increased from 0.21 to 0.87 MPa

Table 2: Mechanical properties of dense mycelium-bound materials extracted from literature

Material ^a	Density (kg/m ³)	Tensile strength (MPa)	Elastic modulus in Tensile (MPa)	Flexural strength (MPa)	Elastic modulus in Flexural (MPa)
Mycoboard™ reported by Jones et. al. as evocative design product [22]	801	N.A.	N.A.	15	2640
Hot-pressed Mycelium-bound wood particles [15]	600	N.A.	N.A.	1.5	220
Hot-pressed Hybrid Mycelium-bound wood particles with 2.5% wt cellulose Nanofibrils ^b [15]	600	N.A.	N.A.	3.5	575
Cold-pressed Mycelium-bound cotton ^c [51]	240	0.03	6	0.24	12
Hot-pressed Mycelium-bound cotton ^c [51]	350	0.13	35	0.64	34
Cold-pressed Mycelium-bound rapeseed straw ^c [51]	240	0.03	9	0.21	15
Hot-pressed Mycelium-bound rapeseed straw ^c [51]	390	0.24	97	0.87	72
^a information about the type of fungi is not available ^b Mixture of spruce, pine and pir (SPF) particles ^c Mycelium of <i>P. ostreatus</i>					

and from 15 to 72 MPa respectively [51]. These results showed that changing the production method and substrate within the same species of mycelium has a significant impact on mechanical performance of the final product. Beside varying substrates, production methods and mycelium species, one study showed that hybridization of the mycelium-bound wood particles with 2.5% of nanocellulose can increase the flexural strength and elastic modulus of the product from 1.5 to 3.5 MPa and from 220 to 575 MPa respectively [15]. These promising findings opens up research opportunities for further improvement of the material for applications in construction industry.

Till now, MycoBoard™ produced by Ecovative Design has the highest properties close to standard particle board, however not much of information regarding the production process is available due to IP restriction.

Physical Properties:

Mycelium-bound composite materials either in the form of light-weight foams or dense boards have shown different physical properties when exposed to water and moisture, fire as well as sound and heat [13,15,17,51]. Mycelium-bound materials are developed through a biological process, where moisture plays an important function within the substrate as this is necessary for fungal mycelium to grow and function. After the substrate colonization takes place, most of the moisture should be reduced when the mycelium structure takes its shape and form. The required moisture for this biological process to take place is largely dependent on the type of the substrate and the fungal mycelium species used for the process [9,11,14-16,37,55]. However, exposure to moisture can decrease the performance of mycelium-bound composites. As mentioned in different studies moisture can reduce the mechanical performance of the

mycelium-bound composite materials specially their tensile and compressive strength. Therefore, water uptake of final mycelium-based composite material remains a challenge when it comes to long-term durability and performance when used as construction material [9,27,51,56]

With regards to fire performance and thermal degradation of mycelium-bound composite materials, only a few studies have investigated their behavior when exposed to fire. Some studies have shown that mycelium-bound foams and lightweight mycelium-bound composites display similar ignition time in comparison to polystyrene foam commonly used in buildings [13,57]. Some studies have also shown that the ignition time of mycelium-bound composite material is shorter than particleboard [13,17]. Several other studies have shown that mycelium-bound composite materials do not display any inherent fire-retardant characteristics. Even though the main components of mycelium are chitosan and hydrophobins (a type of proteins that can create a hydrophobic coating on the surface of mycelium) have shown to have fire retardancy characteristics but their effect on fire retardancy within the mycelium-bound composite materials have proven to be insufficient [58,59]. One way to enhance the fire retardancy of mycelium-bound composite materials is through incorporating substrates with high content of natural phenolic polymers and naturally occurring silica (SiO₂) which are found largely in many agricultural by-products or forest residues such as rice hulls or bamboo fibers and leaves. These types of substrates have shown to enhance the performance of mycelium-bound composite materials in fire [57].

Mycelium-bound composite materials have shown relatively good performance as thermal and acoustic insulation products. Mycelium-bound composite materials depending on the type of substrates can have low densities and thus lower thermal

conductivities which makes them great thermal insulation materials. Studies have shown that mycelium-bound materials containing straw and hemp fibers can have low densities (in the range of 60–100 kg/m³) and thermal conductivities (in the range of 0.04–0.09 W/m·K) [55,60,61]. Therefore, they can be a great substitute for conventional thermal insulation products, such as glass wool polystyrene foams. Furthermore various studies have demonstrated the direct correlation between density and thermal conductivity [62,63]. The lower density of lightweight mycelium-bound materials is the result of large dry air particles with low thermal conductivity within the matrix of the composite which results in better thermal insulation properties. In terms of acoustic performance, mycelium-bound composites in the lightweight forms have shown excellent properties. Studies have shown that mycelium-bound lightweight materials outperform cork and some other traditional materials used commonly as noise barriers [35,64]. Mycelium-bound composite materials produced on agricultural waste and by-products such as rice hulls, straws and hemp can provide great acoustic absorption with 70–75% noise absorption [64]. These studies have shown that the type of substrate has a significant impact on the acoustic absorption of mycelium-bound composite materials. For instance, among various agricultural by-products rice straw, hemp, flax, and sorghum fiber have proven to be very effective in enhancing the noise absorption properties of the mycelium-bound materials. The great acoustic performance of mycelium-bound composite materials can be associated to the porous and fibrous texture. This makes mycelium-bound composite material an affordable and sustainable alternative to conventional sound insulation materials currently used within the building and construction sectors.

From exhibition to commercialization:

Only a few pioneer research centers and companies around the world have the know-hows and the capability to produce mycelium-bound materials for applications in the construction and building industry. The research on applying mycelium-bound composites for applications as elements of a structure dates back to 2009 when *Ganoderma lucidum* and sawdust were employed to create the 'Mycotectural Alpha' teahouse by San Francisco-based artist and mycologist Phil Ross from the company MycoWorks commissioned by Düsseldorf Kunsthalle for their 25th anniversary [65]. To show the biocompatibility of the mycelium bricks, the Mycotectural Alpha was boiled and then served to museum guests as herbal tea. The second most prominent application of mycelium-based bricks goes back to 2014 when the mycelium based brick structure known as 'Hy-Fi' opened at the courtyard of the Museum of Modern Art (MoMA) space in New York [66]. The tower was designed by David Benjamin from New York based architects; The Living in collaboration with Ecovative Design. 'Hy-Fi' exceeded 12m in height and was made with more than 10,000 mycelium-based bricks. Ecovative Design is currently specialized in developing mycelium-based packaging and Mushroom Leather only.

A recent collaboration between Karlsruhe Institute of Technology (KIT), Swiss Federal Institute of Technology (ETH)

Zürich, Future Cities Laboratory in Singapore and Mycotech from Indonesia have resulted in 'MycoTree' exhibition which was showcased at the 'Beyond Mining – Urban Growth' exhibition at the Seoul Biennale of Architecture and Urbanism in 2017 in Seoul [37]. 'MycoTree' resembled a tree which had pillars consisting of triangular shaped mycelium-bound composite blocks, which were grown in digitally fabricated molds. The top of the tree was covered with novel bamboo-based composite slates developed by the research team. The blocks and the slates were attached by dowels and the mycelium-bound blocks were bearing the load (Figure 2a). The team has also showcase a second version of MycoTree named 'MycoTree 2.0', a load-bearing structure out of mycelium-bound composite blocks and bamboo slates as part of the exhibition 'Human beings, Nature, Technology' which was opened in FUTURIUM in Berlin in 2019 [32]. In the second version of 'MycoTree' the researchers have improved the mycelium-bound composite blocks by using a new technology to transform the lightweight mycelium-bound materials into dense composite boards with improved mechanical properties (Figure 2b).

In 2019, Italian architect Carlo Ratti in collaboration with mycology researchers at the 'Grown.bio' lab in the Netherlands, unveiled arched architectural structures made of mycelium-bound materials, which was showcased at Milan design week [67]. The structure, consisting of 60 4-meter-high arches called 'the circular garden,' was grown on-site over six weeks and was returned to nature as a fully biodegradable structure at the end of the exhibition.

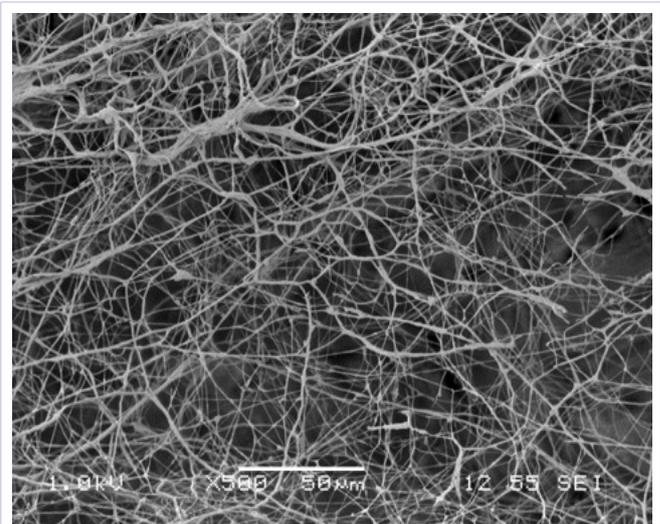


Figure 1: Mycelium hyphae network of *G. Lucidum* grown on sawdust as the main substrate

Conclusion and Outlook for future Research Direction

In recent years many investigation and research studies have been carried out on mycelium-bound composite materials for applications in packaging and fashion industries. The use of mycelium-bound composite materials in the construction industry has been mainly limited to small-scale prototypes and exhibition installations. Mycelium-bound composite materials



Figure 2: Mycotree structure, a) The MycoTree at the Seoul Biennale of Architecture and Urbanism, Sep 2017 © CarliTeteris, b) MycoTree 2.0 at Berlin Futurium, Sep 2019 ©Volker Kreidler

have great potential to be used within the construction sector in the form of thermal insulation and acoustic insulation as well as replacement for drywalls when used in the dense form. Moreover, few studies have demonstrated the ability of the mycelium-bound composite materials in the dense form to be used as load-bearing elements within a low-rise structure.

Research and development into Mycelium-bound composite materials can provide the construction industry with a novel yet low energy material as an environmentally friendly alternative to synthetic construction materials for applications as acoustic and thermal insulation, paneling, drywalls as well as in door panels and window frames. Further research is necessary to enhance the mechanical properties of mycelium-bound composite materials to make them suitable for semi-structural or load-bearing applications. Furthermore, it is shown that the relatively low mechanical properties, high water absorption and lack of standard methods for production, evaluation and investigation of properties have restricted the extensive application of mycelium-bound composite materials specially in the building and construction sector. However, in recent years the extensive research and development on mycelium-bound composite materials and characterization of their physical and mechanical properties have proven that it is possible to reuse agricultural by-products and wastes and turn them into environmentally sustainable alternatives to synthetic construction materials. Mycelium-bound composite materials have the potential to transform the future of construction industry by introducing a paradigm shift on the way we produce our future construction materials based on the concept of circular bioeconomy.

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