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Sustainable material using bamboo-based substrate mycelium composite

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Abstract

In response to the 2050 net-zero carbon movement, this research explores the possibility of using Phyllostachys makinoi bamboo as the mycelium composite substrate in building materials. The study used Phyllostachys makinoi bamboo, one of the native species in Taiwan, blended with the appropriate amount of liquid culture of Pleurotus ostreatus mycelium and bamboo powder. A series of 5:1, 2:1, and 1:1 fiber/powder ratio substrates were studied, growing in a 25~26°C, 65-80% humidity-controlled environment. Each sample has 5% $C_6H_{12}O_6$ and other nutritious additives to foster a proper environment for incubation. The initial finding is that the 1:1 ratio substrate sample has a higher growing rate than another ratio due to the higher bamboo powder content, allowing Pleurotus ostreatus mycelium to access the pentosan inside the substrate easily. In addition, the paper presents the finding of the composite strength with bamboo fiber and mycelium by demonstrating a 1:2 scale module that can interlock horizontally and vertically. The strength of the composite is based on a series of cylinder specimens resulting from the compression test following the ASTM D695 procedure. The experiment also compared the bamboo mycelium composite for different species in Taiwan and whether the pentosan content would impact material performance. Further research aims to establish the optimal composition of the innovative experimental material and its future benefits. We considered replacing the roof structure to harmonize with the surroundings and explored its potential as an architectural element.

Keywords: Biodegradable materials, Bamboo Fiber, Mycelium Bamboo Substrates

1. Introduction

The buildings and construction industries are vital in combating climate change. They account for 30% of global final energy usage and 27% of total CO2 emissions from the energy sector. (IEA et al., 2023). Without focused policy interventions, energy consumption in buildings could surge by up to 70% by 2050. Records from the International Energy Agency (IEA) show that emissions from the construction industry accounted for approximately one-third of total energy system emissions in 2022, including building operations (26%) and embodied emissions related to the production of building materials (7%). If we want to reach the Net Zero Emissions target in 2030, the embodied emissions of steel need to drop by 25%, and the embodied emissions of cement need to drop by 20% (IEA et al., 2023).

The 2020 Energy White Paper released by the Taiwanese Federal Government outlines the country's strategic approach to reducing building energy consumption, focusing primarily on indoor lighting, building mechanical systems, and thermal envelopes (AmCham Taiwan, 2020). While the former two areas benefit from extensive research and commercially available solutions (MOEA Taiwan, 2008), thermal envelope materials for buildings predominantly rely on petroleum-based sources, resulting in non-biodegradable and toxic thermal barrier products (Yang, 2013). These materials pose environmental hazards during production and emit harmful TVOCs when burned (ABRI Taiwan, 2010). Consequently, researchers globally are exploring alternative materials, with mycelium composite emerging as one of the most promising options.

Mycelium composites have gained recognition as promising materials in recent years, often explored as alternatives for insulation (Zhang et al., 2022). Additionally, commercially viable products have emerged, such as indoor acoustic insulation panels and packaging stuffing made from mycelium composite (Huang, et al., 2024). Studies on the mechanical properties of mycelium composites indicate lower thermal conductivity than traditional insulation panels, with superior compressive strength over tensile strength (Alaneme et al., 2023). The remarkable structural strength of mycelium's organic fiber structure is enhanced after high-temperature baking.

Due to its rapid growth, bamboo requires harvesting every three years. However, failure to harvest and renew it regularly can lead to environmental burdens (Lin, 2011). Phyllostachys makinoi, an endemic species to Taiwan, is particularly noteworthy. Compared with ordinary wood forests, which can sequester 7.45 to 14.9 tons of carbon per hectare per year, Phyllostachys makinoi can sequester 47.36 tons of carbon per hectare per year (Yang, 2021, pp. 16-17), making it a valuable ecological green building material. However, the current decline of the bamboo industry is attributed to challenges such as the need for regular logging and related transportation costs.

Research in the domestic bamboo industry has introduced a series of renovation plans aimed at reassessing bamboo development (Lin, 2011). These plans encompass stable bamboo sourcing, product processing technology, and the reuse of residual materials, all with the goal of reevaluating bamboo's versatility. This particular study focuses on the organic composite of cultivated Pleurotus ostreatus (PO) and locally sourced Phyllostachys makinoi (PM) bamboo fibers as the substrate, aiming to create a lightweight arched structural component that can be sustainably recycled and easily assembled and manufactured.

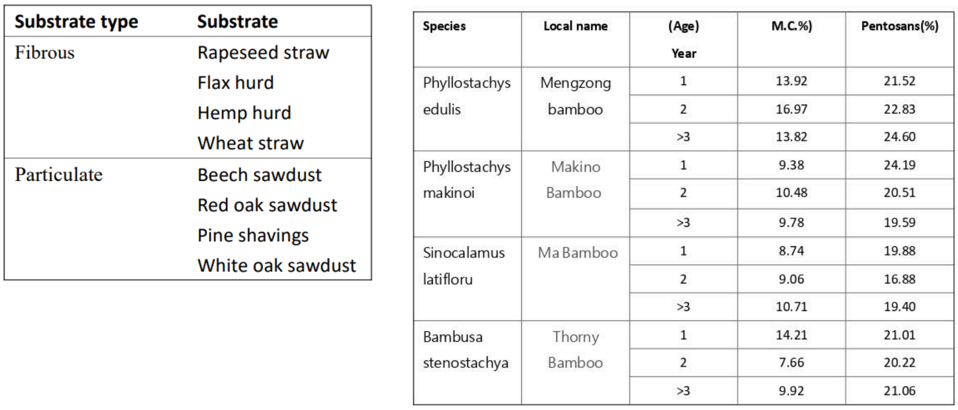
2. Material

2.1. Mechanical Properties

2.1.1. MYCELIUM

Mycelium is the vegetative growth part of a fungus, consisting of a network of thread-like hyphae with a diameter of 1-30 μm (Fricker et al., 2007; Islam et al., 2017). The growth of this network structure requires sufficient water and organic nutrients, typically provided by a substrate and specific growing methods (Soh et al., 2020). Pleurotus ostreatus (PO), one of the most common edible mushrooms, is a ubiquitous species in Taiwan. By utilizing cultivation bag technology, an optimal growth environment has been created through continuous improvement and testing, ensuring efficient production of mycelium that meets quality standards.

From existing research on mycelium, it is evident that mycelium exhibits significant growth tolerance, thriving in environments with drastic temperature changes and when supplemented with various substrate fibers such as rapeseed straw, beech sawdust, hemp hurd, and other agricultural wastes (Fig. 1, Left). The mechanical performance of mycelium-based materials depends on both the substrate's porosity and the mycelium's digestion process (Jones et al., 2020). Additionally, the rate of mycelium growth is influenced by nutrient-rich additives, such as starch or other carbohydrates, incorporated during incubation to create an optimal growth environment. Bamboo comprises various chemical substrates in different ratios, including pentose, lignin, holocellulose, and microcrystalline α-cellulose (Ku & Chiou, 1972)(Fig. 1, Right). Previous research has indicated that when used as additives, starch or other carbohydrates can accelerate mycelium growth(Kuribayashi et al., 2020). Therefore, bamboo with a higher sugar content is more conducive to the experiment.



Substrate type	Substrate
Fibrous	Rapeseed straw
	Flax hurd
	Hemp hurd
	Wheat straw
Particulate	Beech sawdust
	Red oak sawdust
	Pine shavings
	White oak sawdust

Species	Local name	(Age) Year	M.C.%)	Pentosans(%)
Phyllostachys edulis	Mengzong bamboo	1	13.92	21.52
		2	16.97	22.83
		>3	13.82	24.60
Phyllostachys makinoi	Makino Bamboo	1	9.38	24.19
		2	10.48	20.51
		>3	9.78	19.59
Sinocalamus latifloru	Ma Bamboo	1	8.74	19.88
		2	9.06	16.88
		>3	10.71	19.40
Bambusa stenostachya	Thorny Bamboo	1	14.21	21.01
		2	7.66	20.22
		>3	9.92	21.06

Figure 1: (left) The types of substrates. (right) Local references for comparison of carbohydrates in different bamboo species.

2.1.2. BAMBOO FIBER

Incorporating bamboo fiber as a substrate for mycelium growth represents a novel approach, yet the existing research in this area may not be extensive enough to provide comprehensive insights. According to Soh et al. (2020), mycelium has demonstrated the ability to thrive on bamboo fiber. Their study proposes the use of a blend consisting of 500 µm mycelium-enriched bamboo fibers, mixed in ratios of 70:30 or 60:40, along with a 3wt% chitosan content. The observed compression modulus for the bamboo fiber-mycelium composite is recorded at 40 kPa (Soh et al., 2020). While this investigation into compression mechanical properties represents only a segment of those found in non-bamboo-based substrates, it suggests the early feasibility of utilizing bamboo as a substrate material.

2.2. Experiments

2.2.1. PREPARATION OF MATERIAL

There are two methods for obtaining bamboo fiber. The first method involves using a circular saw machine (DeWALT, DCS575, United States) to cut dried Phyllostachys makinoi into one-centimeter-thick segments. These segments are then baked in a constant-temperature oven at 80°C (DENG YNG, D9LD-DH400, Taiwan) for 2-3 days to allow for moisture evaporation, ensuring thorough drying. Subsequently, a grinder (Felsted, 2500A, Germany) is used to break down the bamboo segments into fibers, filtered through a screen to obtain the bamboo fibers.

The second method involves acquiring leftover bamboo materials, such as flakes, powder, blocks, and some Phyllostachys makinoi chips, from the Nantou Bamboo Factory post-bamboo processing. These materials undergo screening and selection to eliminate larger-sized bamboo chips. Subsequently, they are subjected to an 80°C baking process for drying at a constant temperature. Finally, the dried materials are sterilized and preserved in a sterilization kettle (HUNG YI, HY-230, Taiwan), producing bamboo fiber and bamboo powder for use.

To obtain the mycelium strain, we procure a fully grown (approximately 28 days) 9 x 18 cm Pleurotus mycelium bottle from a mushroom farm in Nantou, Taiwan. After demoulding, the bottle is transferred to a controlled environment with a temperature set at 24±2°C and humidity maintained at 65-75% for inoculation.

2.2.2. PREPARATION OF LIQUID CULTURE

Liquid culture is a method for successful mushroom cultivation. This process involves nurturing a blend of water and nutrients and introducing mushroom spores or mycelium into the mixture to foster a potent broth that catalyzes mushroom development. In this paper, we experimented with three distinct liquids as culture broths: peptone, Potato Dextrose Broth (PDB), and RO water. To prepare the culture broth, dissolve 40 g of protein powder and 40 g of PDB powder in 1 L of reverse osmosis (RO) water. Then, add 1 g of glucose powder ($C_6H_{12}O_6$) to the mixture. Sterilize the mixture in an autoclave for one hour. After cooling, inoculate it with PO mycelium (Fig. 2). Observations showed hyphae spreading across the liquid surface within two days, demonstrating rapid growth. However, in later stages, the hyphae darkened, leading to the gradual blackening and turbidity of the liquid (Fig. 3).

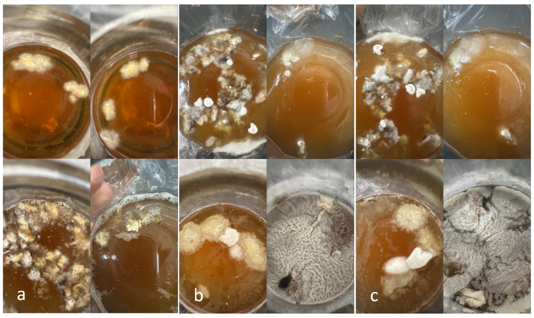


Figure 2: (left) The PDB culture broth.
Figure 3: (right) (a)the second day, (b)the seventh day, (c)the ten day.

2.2.3. PREPARATION OF INCUBATION

In contrast to the previous experiment, where self-produced bamboo fiber was utilized, a significant quantity of bamboo fiber remnants and bamboo powder sourced from the bamboo factory served as the blending foundation in the subsequent stage. After sterilization, the researchers combined them with mycelium at a ratio of 1:1:1 and thoroughly mixed them. The earlier liquid culture solution served as the water source. It was divided into three control groups (peptone powder culture solution, PDB culture solution, and RO water) to investigate potential variations in mycelium growth induced by different liquid nutrient solutions.

After a week of observation, it is evident that RO water and PDB nutrient solution exhibit a robust growth rate within approximately two days. In contrast, the peptone powder nutrient solution shows less mycelium growth (Fig. 4). However, a noteworthy phenomenon arises around the 3rd or 4th day of the growth cycle: the upper layer of mycelium starts to develop tiny black spots, likely Trichoderma or Penicillium spores. The researchers will continue monitoring the subsequent growth.

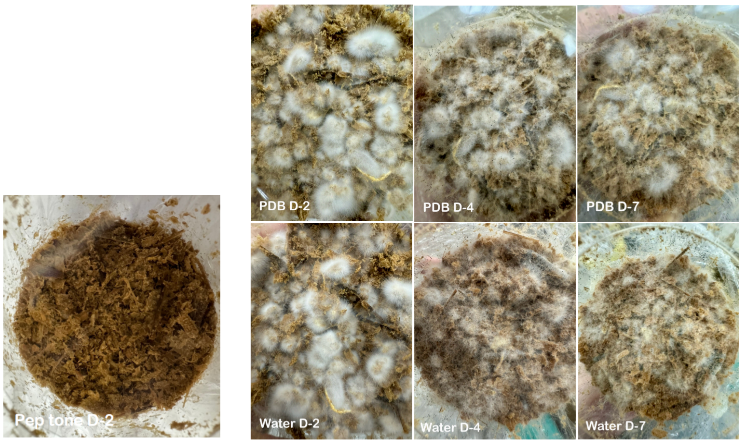


Figure 4 : (left)the second day of Poptone culture broth, (right) a week growth of PDB and water culture broth.

Considering the specified design requirements and verifying material tolerance, performing structural mechanical tests on this material is imperative. A 5x10 cm hollow cylinder will be produced as a growth module to explore shaping possibilities during growth. Subsequently, pressure tests will be conducted, and inoculation will be extended to various modules to test additional material types (Fig.5).

Figure 5: The process of cultivation and molding.

3. Form

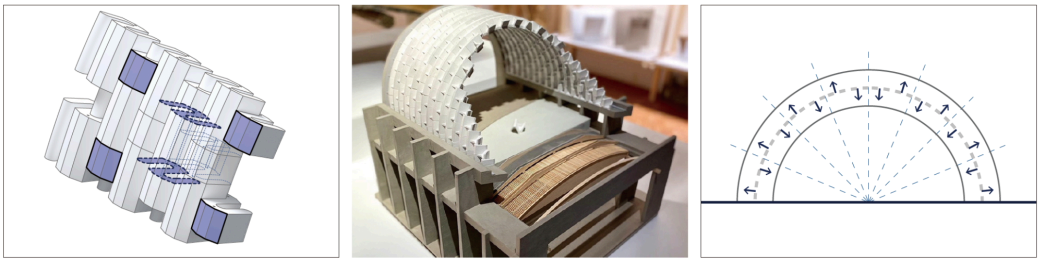
3.1. Arch

An arch has a compression form and characteristics. It can span a large area while resolving forces into compression (Chilton, J.,& Isler, H., et al., p.32), which aligns with the characteristics of mycelium composite material. The Roman's Pont du Gard arch was constructed using a series of identical bricks, providing a concept to build larger structures from smaller units. This approach allows for better control of mycelium growth within a suitable module.To create an alternative to the roof structure and attempt to form an independent structure, this design proposes a feasible architectural method using bamboo mycelium material and the final design form and are influenced by both the architectural aesthetic and the function of the roof.

This research proposes utilizing bamboo mycelium composite material interlocking modules to construct a barrel vault based on the circular arch design principle. The module design considers the minimum thickness of mycelium growth at 3cm (Olivero, et al., 2023). It references Le Corbusier’s modular golden ratio, setting the interior height of the barrel vault at 226 cm. This height enables the mycelium barrel vault to serve as a roofing structure or as the construction of an independent pavilion. The actual data needs to be calculated after the actual-scale bricks are manufactured to determine the loads supported by foundations.

3.2. Interlocking Mechanism

The proposed interlocking mechanism can assemble both the vertical and horizontal units (Fig. 6-A), inspired by The “Click Brick” designed by BRG ETH (Fig. 6-B). One benefit of employing the barrel vault form is that when the arch is evenly divided, each segment becomes precisely identical, making it ideal for creating a modular unit. The primary load is mainly concentrated in the center zone; thus, it remains consistent with the principle of circular arch design (Fig. 6-C)



(A) (B) (C)

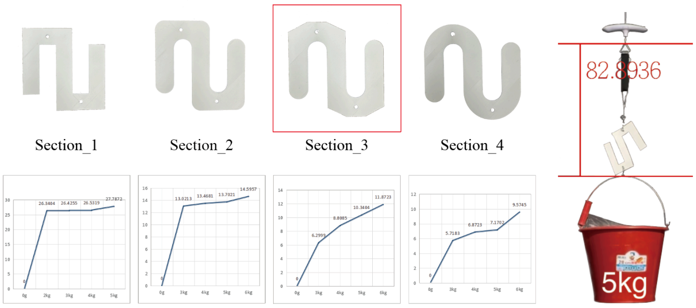
Figure 6: (A) Proposed interlocking mechanism, (B) The Click Brick, (C) Principle circular stress line [images credits: https://noncrete.com/project/clickbrick/]

4. Applications & Manufacture

4.1. Prototype Detail

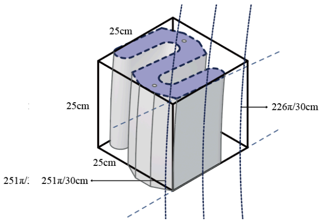
The prototype brick design begins with a 25cm×25cm square. The double U tenon has been divided into five parts to ensure uniform thickness in each direction. Investigations have explored four different section types, considering both ease of assembly and the growth characteristics of mycelium composite material. The four different types were fabricated from 3D-printed PLA with a thickness of 1mm for tensile testing (Fig. 7). Section 1 exhibited the highest z displacement and permanent deformation under a 5kg load (Fig. 7). Vertical tenon assembly proved the most challenging, and controlling mycelium composite density at right angles was difficult. Section 3 was chosen for its lesser z displacement, architectural aesthetics, and potential function as a roof structure.

Based on the selected section, the 226 + 25 / (2π) arch length was divided into approximately 25 cm segments (238.5π / 30 = 24.975) to form the height, creating a cubic bounding box (Fig. 7). The prototype will follow this arch to form the final model (Fig. 8). Considering the average density of mycelium composite (0.10~0.39 g/cm³, Appels et al., 2019) and the module volume (13053 cm³), the weight is estimated at approximately 3197 g. The module will be comfortable for an adult to carry and assemble (Fig. 9).



27.7872 mm 14.5957 mm 11.8723 mm 9.5745 mm

Figure 7: 3D-printed PLA section (1mm) tensile test z displacement graph and the deformation of section1 .



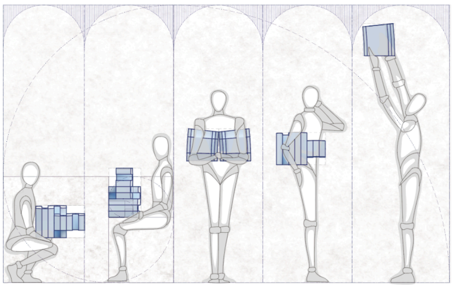
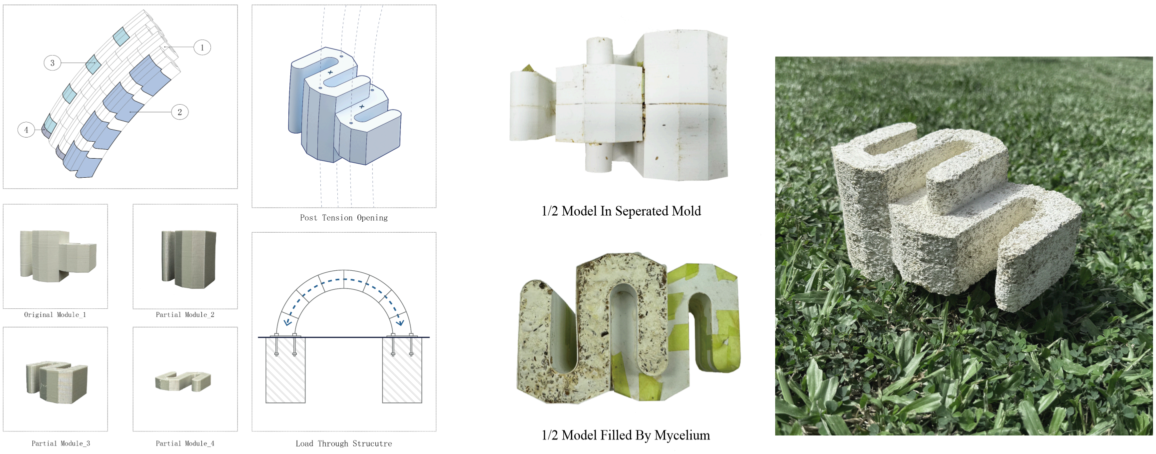


Figure 8: Cubic Bounding box. Figure 9: Module Ergonomic Analysis.

4.2. Construction Mechanism & Production

To further stabilize the structure, a post-tension cable system was positioned within the module, spanning the entire structure. The post-tension location avoided the primary stress line location while allowing the module to connect with the neighboring module (Fig. 10-A). While the standard module can construct nearly the entire barrel vault, the remaining three partial modules on the edge are necessary to complete the barrel vault (Fig. 10-A).

The 1:2 scale mold was 3D printed with a 1mm thickness in two mirror molds. Each mold was filled separately with bamboo substrate and mycelium and then temporarily secured with tape. As the mycelium grows, it will adhere to the overlapping sections, forming a complete module (Fig. 10-B). The 3d printed molds will be bent during the growing process because of the thickness and the elasticity of the PLA material. Based on the ongoing experiment, the 1:1 mold will be created by a manual thermo molding machine using the 3D printed mold to get a more rigid and stable mold separately and then combining them using the same method. Aligning with the concept of modularity, the vacuum press molds can produce modules with greater precision and efficiency. (Fig. 10-C)



(A) (B) (C)

Figure 10: (A) Customized Module, (B) 1:2 Mold Filled with bamboo mycelium, (C) 1:2 Final Module

5. Discussion & Conclusion

Based on existing research on bamboo mycelium composite and experiments conducted, it has been discovered that mycelium can thrive on local bamboo fibers. Considering known limitations and material characteristics, a unique modular system for construction has been developed. Currently, the mycelium grows well within the 1:2 mold. Further research is required to investigate the mechanical properties of the bamboo mycelium composite module after drying in the oven.

Although the shapes and sizes have been confirmed, new methods have been utilized to infill the mold, and the feasibility of the structure is currently only known through a 3D printing model in PLA. An actual module should be produced on a 1:1 scale to test the individual units' mechanical properties and experiment with whether the method combined through mycelium causes weaknesses in the structure. Furthermore, the structure must be tested after assembly, and its stability evaluated under additional load. Tolerance is also a concern; efforts should be made to minimize and optimize the manufacturing SOP for producing these modules.

The paper showcases PO mycelium's successful cultivation and incubation at specific ratios on PM substrate mixtures. Further investigation is necessary to ascertain the mechanical characteristics of PO mycelium grown on PM substrate composites. In the future, there will be more experimentation and exploration opportunities.

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