Sustainable Material: Development Experiment of Bamboo Composite Through Biologically Binding Mechanism

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Abstract. Bamboo as stems have been widely manufactured for composite. However, fiber as the smallest constituent component of bamboo stems supporting the strength and flexiblility of the plant has not been widely employed as raw material. These strong and flexible properties, coupled with easy planting treatment and fast harvesting, apparently make bamboo highly potential developed as sustainable raw material for composite. Unfortunately, the current manufacturing process of bamboo for composite by using chemical substances would have ended bamboo up as no longer environmentally friendly. By utilizing lignocellulose content within its fiber, this research studied fabrication of a novel composite boards from bamboo fibers through biologically binding mechanism by using fungal mycelium. Gigantochoila apus bamboo stems are extracted into three types: long fibers, short fibers, and powder. Then, the bamboo fibers are added with water and some additional nutritions then sterilized together. These substrates are then inoculated with mycelium seed of Ganoderma lucidum. The fibers bound together along with the growth of mycelium. The result shows that this board is potential to be used for interior purpose in building especially high rise building with high need of light-weight insulation and partition board and expected to replace the need for building components that have been made from unsustainable raw materials and methods.

1. Introduction

Woody fiber still becomes the best option to fulfill daily material needs. Of the various plants producing woody fiber, bamboo is one of them. Bamboo stems are utilized as raw materials for various needs, such as musical instruments, furniture, and building components. Unfortunately, bamboo was once considered as "the poor timber" due to its low price and widely used by the low economy community. However, the value of bamboo as raw material begins to rise and even becomes the rich timber [1]. One of some factors that turns bamboo back in demand lies in its nature which is strong but flexible. Bamboo is easily cultivated without special treatment. Within one year, a bamboo hump can grow as many as 5 to 10 stems [2]. Furthermore, rapid growing causes bamboo stems to be harvestable at the age ranging from 3 to 5 years. With its superiorities, the needs of plant fibers as raw material which are usually supplied from wood can be gradually replaced by bamboo [3].

Bamboo (Bambusoideae) is a group of gigantic grass plant. It is estimated that there are about 2000 species of bamboo spreading around the world [4]. In Indonesia, the diversities of bamboo species which have been identified are as many as 145 species, which 75 species among of them are endemic. There are five bamboos which are found almost evenly across the five major islands in Indonesia, i.e.
Bambusa bluemana, Bambusa vulgaris (bambu ampel), Dendrocalamus asper (bambu petung), Gigantochloa atter, and Schizotachyum brachycladium [5]. Due to its different morphological characters and mechanical properties, each species of bamboo is used for specific purpose, for instance G. apus, which has relatively small diameter stems and long fibers, is generally used to make ropes. A bamboo stem is heterogeneous. Its cells are not uniformly distributed, both horizontally and vertically along the culm [3]. The morphology of bamboo stems comprises of culm wall, fiber bundle, and elementary fiber. The highest strength and flexibility of bamboo lies in its smaller size, which is in its elementary fiber, thus is highly potential to perform as reinforcing fibers in composite materials [6]. Bamboo fiber is also referred as lignocellulose fiber, because it contains 25% lignin, 55% cellulose, and 20% hemicellulose [3].

Besides being directly used after harvested, bamboo stem is also processed in industrial scale as raw material for making composite. Generally, the manufacturing process still involves artificial adhesive chemicals to bind bamboo fibers, such as epoxy and resin [7, 8]. Unfortunately, these chemical substances would make bamboo loose its environmentally friendly nature. Although it creates very strong binding, these chemicals change the nature of bamboo as natural fibers to be unable to decompose when the material is no longer used [9].

Various methods to achieve sustainability in the process of binding composite materials from plant fibers is still continuously being developed. Some biochemical adhesives to create natural products have been made among others are resin from plants extraction [10, 11, 12] and protein-based adhesive extracted from cattle nerve [13]. Nevertheless, other binding methods which are more environmentally friendly have been developed through biologically mechanism. This method is supposed to be more effective in achieving the sustainability of a material because it passes fewer phases. Through this mechanism, microorganisms are deliberately grown on biocomposite substrates to bind fibers [14]. The ability of microorganisms to process lignocellulose fibers from agricultural waste previously has been proven by using fungal mycelium in the process of making biocomposite panels [15], acoustic panels [16], and structural components [17]. The fungal mycelium frequently used came from mushroom belonging to the Ganoderma phylum [18, 16, 17].

Fungal mycelium is a network of hyphae that part of fungi anatomy which continues to grow along its vegetative period. Mycelium continues to grow by consuming lignocellulose substance from plant fibers which become the substrate for its life [19]. The nature of hyphae which continuously becomes wider and more complex is utilized in the process of making those biocomposite materials as binder of lignocellulose fibers [18]. Beside its strength and durability performance, the mycelium as biocomposite binder has several advantages, including non-toxic, fire resistant, hydrophobic, capability for thermal insulation, easy to form, and 100% biodegradable. Compared to conventional manufacturing industries, biocomposite materials which use mycelium as binder, require much less amount of water, energy, and CO₂ emissions [18, 20].

In this experimental study, a novel biocomposite board from bamboo fiber with fungal mycelium binder have been developed. This study uses lignocellulose content from bamboo fiber which is different from previous studies using lignocellulose fibers from agricultural waste, such as wood and grain. The high strength properties of bamboo is potential to increase the value of this biocomposite board. A series of tests on this material then have been carried out to find out the physical performance that the most compatible with function of this material in a building. This biocomposite board is expected to replace the need for building components that have been made from unsustainable materials and methods.

2. Materials

2.1. Bamboo fiber

The species of bamboo used in this study is Gigantochloa apus (bambu apus). This species is chosen because of its strong, flexible, and quite thick in diameter of its culm. The bamboo plant was cultivated in South Tangerang, Banten and harvested at the age of 5 years. Before being used in experiments, bamboo stems were first extracted to obtain its single long fibers. Bamboo stems with a length of 50 cm to 60 cm were split vertically into some thin bamboo sheets. The bamboo sheets were then
flattened with hammer until its long fibers could be released one by one (Figure 1(a)). To get shorter fibers, some amount of long fibers then were cut into 1 cm to 2 cm in length (Figure 1(b)). Meanwhile, some other amount were crushed to get bamboo powder (Figure 1(c)). By this extraction process, three types of bamboo fibers were obtained; long fibers, short fibers, and powder. These three types of fiber were then used as substrate variables in the experimental process.

![Figure 1](image1.png)

**Figure 1.** Three types of bamboo fibers: (a) long fibers, (b) short fibers, and (c) powders.

2.2. Fungal mycelium

The fungal mycelium used in this experiment comes from species of *Ganoderma lucidum*. This species originates from Basidiomycotina macrofungi group and Homobasidiomycetes family. This species is chosen based on previous research, its terrestrial habitat on wood trunk, so it has strong mycelium bond and capability to break down woody substances and grows relatively fast. Mycelium is in the form of F1 seeds in chopped corn medium (Figure 2). Mycelium seeds were cultured in the Microbiology division of Biology Research Center LIPI, Cibinong, Indonesia.

![Figure 2](image2.png)

**Figure 2.** Fungal mycelium seeds in corn chopped medium.

3. Methods

3.1. Experimental method

The experiment was conducted in the Culture Laboratory at the Faculty of Engineering, Universitas Indonesia. This experimental method was carried out by following the previous studies [16, 17, 18], but with modified materials and steps’ details. Three material samples, each contained different type of bamboo fiber as the main substrate were labeled as A1 for long fibers, A2 for short fibers, and A3 for powder. Into each sample, some ingredients were added to provide ready sources of C, N, and Ca which are generally needed by organisms. Then all ingredients were mixed together with water in a heat-resistant plastic molding container. After that, the samples were pasteurized to sterilize contaminants. The samples were then left until the temperature decreases. The mycelium seeds then were inoculated into the substrate. The containers were then resealed and stored in a storage box at room temperature of 30°C to 35°C. The mycelium process to incubate the entire substrate took 20 days.

After the mycelium incubated the entire substrate, the samples were removed from its container. The samples were then pressed using two boards placed on the top and bottom sample’s surfaces so
that its thickness became 3 times thinner. Then, the samples were dried in a drying oven at temperature of 80°C with normal pressure for 9 hours.

3.2. Testing method

Tests on samples were carried out to find out physical properties: density, swelling thickness, and internal bond. These tests aimed to determine the classification of the material function and the bonding strength of mycelium as binder. Tests were conducted at Indonesia Institute of Sciences (LIPI) Biomaterial Research Center, Cibinong by referred to the Japanese Industrial Standard (JIS) A 5905: 2003 for Fibreboards [23]. The dimension of the specimens for testing was normative size 5 cm x 5 cm. Each test was repeated 3 times. The density is calculated by the following Equation (1).

$$\rho = \frac{W}{p \times l \times t}$$

where $\rho$ is the density (g/cm$^3$); $W$ (g), $p$, $l$, and $t$ (cm) are respectively the mass, length, width, and thickness of the specimen. Meanwhile, swelling thickness testing is carried out by immersing sample specimens in water for 24 hours. Calculation of swelling thickness is done by the following Equation (2).

$$St = \frac{t_2 - t_1}{t_1} \times 100$$

where $St$ is the swelling thickness (%), $t_1$ and $t_2$ (cm) are specimen’s thickness before and after immersed in water. Meanwhile, internal bonding strength test is carried out with Universal Testing Machine (UTM) AG-IS Shimadzu 50 kN with a tensile speed of 2 mm/minute. The test result is obtained by the following Equation (3).

$$Ib = \frac{P'}{b \times l}$$

where $Ib$ is the internal bond (N/mm$^2$); $P'$ (N), $b$, and $l$ (mm) are maximum load, specimen’s width and length.

Observation on material’s morphology to examine the distribution of mycelium to bamboo fiber is also carried out by scanning electron microscope (SEM). The process is conducted with JEOL JSM-6390 machine at Metalurgic Center for Laterite LIPI, Serpong. Because of the low density of material, the three specimens were firstly vacuumed and coated with gold to avoid charging during the scan process.

4. Results

4.1. Manufacturing Material

The growth of mycelium to incubate the entire substrate required total of 20 days (Figure 3). During the growth period, the circulation of clean fresh air into and out of the container is necessary for optimal mycelium growth. To optimize the mycelium incubation on the other sides, the substrate, which has formed a sufficiently solid volume, could be removed from molding container on the day-15. The replacement of substrate from its container is intended to let these other sides to be perfectly incubated by mycelium. Overall, there is no significant difference in the speed of mycelium growth from the three variables. Observations were also made on changes of substrate mass on day-0 and day-21 when the material is ready after being dried and pressed. Average weight loss of these three variables are about 61% to 64%.
4.2. Material’s morphological characters

The final appearance of all substrate variables materials are white with brown spots in several parts. The material’s surfaces are smooth and doff textured. There is no special characteristics of visual appearance to distinguish among three variables. The texture of material’s surfaces actually comes from the layer of fungal mycelium that grows on the surfaces of the substrate. Initially, when the incubation period was complete, the outer layer of mycelium on the substrate’s surfaces had a foam-like texture. Then, when the material has been pressed and dried, this outer layer of mycelium became dry and dense.

The long fiber (A1) sample feels most tenuous among the three variables, while the powder (A3) sample feels the most dense. Through SEM observation, there are relatively many cavities in long fiber (A1) specimens, which cause specimens to feel more tenuous. Likewise, in short fiber specimens, there are still many empty cavities found inside the material. This is different from powder (A3) specimen which relatively has fewer cavities (Table 1).

Table 1. Comparison of observations of material specimens through direct observations and SEM.

| Direct observation | SEM observation at 200x magnification |
|--------------------|-------------------------------------|
| Long Fiber Specimen (A1) | ![SEM image of Long Fiber Specimen (A1)](image1) |
| Short Fiber Specimen (A2) | ![SEM image of Short Fiber Specimen (A2)](image2) |
| Powder Specimen (A3) | ![SEM image of Powder Specimen (A3)](image3) |

* indicates hyphae networks.
— indicates bamboo fiber which is covered with hyphae networks (mycelium).

Through direct observation, the mycelium is identified as a white substance, while through SEM photos, the mycelium is a thin hyphae network that grew covered the bamboo fibers. Meanwhile, bamboo fiber is identified as a thicker, longer, and more straight diameter substance. The distribution
of mycelium is found more widely in powder (A3) specimens. Meanwhile, the distribution of mycelium in long fiber specimens is more likely found covering some areas of bamboo fibers.

4.3. Testing Results
From three variables of materials, average range of density are obtained between 0.18 g/cm$^3$ to 0.23 g/cm$^3$. Average density of three variables from the most dense to most tenuous are powder (A3) 0.23 g/cm$^3$, short fiber (A2) 0.21 g/cm$^3$, and long fiber (A1) 0.18 g/cm$^3$. The density trend shows that the smaller the fiber shape, the higher the density (Figure 4(a)). Range of average materials’ density are relatively low. Based on Japanese Industrial Standards (JIS) A5905 for Fibreboards, these materials are classified as insulation boards category which allows material’s density under 0.35 g/cm$^3$.

Materials from three variations have range of average internal bonding strength between 0.0074 N/mm$^2$ to 0.0248 N/mm$^2$. Average internal bonding strength from the strongest to the weakest are powder (A3) 0.0248 N/mm$^2$, short fibers (A2) 0.0112 N/mm$^2$, and long fibers (A1) 0.0074 N/mm$^2$. The internal bonding strength trend shows that the smaller the fiber shape, the higher the internal bonding strength (Figure 4(b)). Range of average internal bonding strength is very low. Based on the JIS A5905 of insulation board category, the value of internal bonding strength is actually not required. But, to compare further with higher category over insulation board, namely MDF board category, this material’s property of internal bonding strength is still far under the minimum of 0.2 N/mm$^2$ (Figure 4(c)).

All material variations have range of average swelling thickness between 0.89% to 2.48%. Average swelling thickness percentage from the smallest to the largest are powder (A3) 0.89%, long fiber (A1) 1.53%, and short fiber (A2) 1.98%. The trend shows that the smallest shape of bamboo fiber expands the least. Material’s property of swelling thickness percentage is very good because of the low number. This material meets the standard values required by JIS A5905 category of insulation board which maximum number of 10%.

5. Discussion
Based on the comparison with the standard JIS A5905 for Fibreboards, these composite boards from bamboo fiber with fungal mycelium in this study show the function of the material for non-structural purpose, that is insulation boards (Table 2). The low number of particle’s density is the main indicator of the non-structural material category. In addition, the internal bonding strength also has a low
number. On the other hand, the percentage of swelling thickness is considered very good, making the material very interesting and unique compared to other biocomposite boards that have been marketed.

**Table 2.** Comparison of material’s testing result to JIS A5905 for Fibreboards.

| Testing Type                  | JIS Standard A5905 for Fibreboards | Result of this study | Valuation |
|-------------------------------|------------------------------------|----------------------|-----------|
| Density (g/cm³)               | ≤ 0.35 ≥ 0.35 ≥ 0.80              | 0.18 – 0.23          | Fulfilled |
| Internal bond (N/mm²)         | - ≥ 0.2 -                          | 0.0074 – 0.0248      | Unfulfilled |
| Swelling thickness (%)       | ≤ 10 ≤ 17                          | 0.89 – 2.48          | Fulfilled |

Compared to several previous studies which reported basic properties of similar biocomposite materials with fungal mycelium [15, 21, 22] (Table 3), biocomposite board from bamboo fiber produced in this study had advantage from its good swelling thickness number. Meanwhile, the board’s density in this study is still within the range of similar materials that have been made in previous studies even, it is potential to be improved.

Furthermore, bamboo fiber as raw material used in this study gives a high novelty value in this study. Kenaf, hemp, flax, wood, and other agricultural wastes are some of raw materials commonly used in previous studies. These lignocellulosic fibers are the natural resources which available in their research location context. But, in this study, bamboo contributes special value to this board by aspect of study’s location context, Indonesia, which has rich diversity of bamboo species. In addition, bamboo fiber has its own uniqueness by aspect of its long fiber form, giving benefit to be adjusted into different smaller size particles purposed to make different type and function of future materials.

**Table 3.** Comparison of material’s testing resulted in this study with previous researches.

| Material’s function       | Insulation Board | Packaging and furniture [21] | Insulation [22] | Product packaging [15] |
|---------------------------|------------------|-------------------------------|-----------------|------------------------|
| Raw material              | Bamboo Fiber     | Wood                          | Hemp, flax, straw, wood | Burlap                  |
| Density (g/cm³)           | 0.18 – 0.23      | 0.3 – 0.6                     | 0.05977 – 0.18645 | *Specific gravity: 0.10 – 0.14 |
| Internal bond (N/mm²)     | 0.0074 – 0.0208  | 3                             | -               | -                      |
| Swelling thickness (%)    | 0.89 – 2.48      | ~ 43 – 44                     | -               | -                      |

**6. Conclusions**

The sustainable composite board of bamboo fiber through biologically binding mechanism with fungal mycelium is a novel biocomposite. The three variations of composite boards are highly potential to be developed for building non-structural function. Of three variations, the boards made of bamboo powder are assessed very well from the aspect of density, internal bonding, and swelling thickness. In architecture, this novel biocomposite board is expected to replace the need of non-structural composite boards which are not environmentally friendly and have been widely used in buildings. The function of this material as the insulation board is expected to be used for interior space purposes, including as thermal insulation boards, acoustic boards, space partitions, ceiling boards, and decorative boards in low-rise buildings such as residential houses to high-rise buildings with high demand of insulation components. To achieve better performance of this board, further research to determine acoustic and thermal performance needs to be done.
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