Optically Transparent Bamboo

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As environmental concerns and the desire to establish a sustainable civilization become more urgent, bamboo has been identified as a potential replacement for materials based on non-renewable resources. There are about 1500 species of bamboo and 36 million hectares of bamboo planting area widely distributed across America, Asia, and Africa. Indeed, bamboo is an important forest resource, having a higher yield, more rapid growth rate, and better mechanical properties than wood, as well as a high aspect ratio and excellent biodegradability. In terms of growth rate, bamboo has a short growth cycle of 3–5 years, whereas wood has a growth cycle of 20–60 years. Furthermore, single bamboo fiber has average tensile strength and modulus of 1.6 GPa and 33 GPa, respectively, which is significantly higher than other known natural fibers, such as cotton, coir, henequen, and ramie. Bamboo has been widely used to fabricate various structural composites, including bamboo scrimber composites, laminated bamboo lumber, and bamboo-fiber-reinforced epoxy composites.

transparent bamboo optical properties mechanical properties functionalization and application

1. Basics of Light–Bamboo Interaction

As light travels through the air and interacts with solids, its propagation can continue in the forward direction when refracted and/or absorbed, or it can be reflected backward at the air–solid interface. In order to effectively discuss the optical properties of transparent materials, it is necessary to define the corresponding terms [1]. The total optical transmittance of an object (often referred to simply as its transmittance) is the ratio of the transmitted light intensity (including the intensities of the directly transmitted light $I_{T,direct}$ and diffused transmitted light $I_{T,diffuse}$) to the incident light intensity I_{I0}; the total transmittance is, therefore $(I_{T,direct} + I_{T,diffuse})/I_{I0}$. The optical haze is the ratio of $I_{T,diffuse}$ to the total transmitted light and is therefore defined as $I_{T,diffuse}/(I_{T,direct} + I_{T,diffuse})$. Owing to the difference between refractive indexes, when light passes through an object, it will be refracted at an angle obeying Snell's law, expressed as $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n is the refractive index of each material and θ is the incident light angle in that material. Multiple factors can influence an object's optical transmittance and haze, including its surface roughness, thickness, refractive index, pore size distribution, porosity, etc. [2][3][4]. For two-phase materials, such as microscale composites, the higher the refractive index (RI) ratio between the two media, the stronger the light scattering, which corresponds to a larger proportion of reflected light and thus a lower transmittance. The attenuation of light occurs when light is transformed into other types of energy, such as heat. The more solid–solid interfaces in a composite or the greater its thickness, the lighter attenuation that occurs, thus reducing

transmittance. Thus, a transparent composite material can be realized by providing a low RI ratio between phases, low light attenuation, and lesser thickness, resulting in a higher transmittance.

Bamboo is opaque because of its optically heterogeneous nature, a result of its microscale porous structure, different chemical components with different RIs in the cell walls, and contents of strongly light-absorbing chemical entities.

Furthermore, lignin exhibits particularly strong light absorption among these components, accounting for 80–95% of all light absorbed by bamboo [5]. The details of this interaction depend on the light's wavelength and the bamboo's properties, such as its density, chemical compositions, and fiber direction. Generally, to make bamboo transparent, light absorption by chemical entities and light scattering at the air/cell wall interfaces and inside the cell walls must be reduced or eliminated.

2. Preparation of Transparent Bamboo (TB)

The preparation of TB can be divided into two steps. First, the color-producing compounds in bamboo are removed or modified (decolorization treatment); second, the bamboo is impregnated with a RI-matched resin. Removing or modifying the lignin and chromophoric groups of bamboo is a particularly crucial step. However, the delignified or lignin-modified bamboo is still opaque as the RIs of the substrate and air still do not match. Therefore, it is essential to impregnate the bamboo with a transparent resin providing matching RI to make the bamboo transparent.

2.1. Preparation of the Bamboo Template

The first key step in the preparation of TB is to remove or chemically modify the chromogenic substances in the bamboo (primarily lignin) to achieve a decolorized template. Decolorization is commonly achieved in wood and bamboo using acid delignification, alkali delignification, lignin modification, or enzyme delignification methods.

2.1.1. Acid Delignification Method

The preparation of delignified bamboo templates using the relatively simple acid delignification method was demonstrated by Wu et al. [6], who employed a certain concentration of sodium chlorite ($NaClO_2$) mixed with water and acetic acid (CH_3COOH) to treat bamboo at a pH value of 4.6 and a temperature of 80–90 °C until it turned white. The time required for delignification differed according to the size of the bamboo sample. Under this method, the $NaClO_2$ forms unstable chlorous acid in an acidic environment; this chlorous acid decomposes into Cl_2, ClO_2, and H_2O, which interact with the benzene ring structures in the conifer aldehyde and aromatic ketone in the lignin through an oxidative ring-opening reaction to form an acidic group, causing the material to degrade and dissolve in water. Furthermore, the hypochlorous acid produced by the reaction of Cl_2 with water is also a strong oxidant that reacts with lignin to finally produce o-quinone, small molecules (e.g., carboxylic acid) and corresponding alcohols. Lignin macromolecules are broken and dissolved through these reactions, thereby achieving the purpose of decolorization. When sodium hypochlorite (NaClO) is used to remove lignin instead, the main reactions include chlorination and oxidation, and the main reaction objects are the benzoquinone structure of the lignin benzene ring

and the conjugated double bond of the side chain. These reactions are able to generate small molecules (such as CO_2 and carboxylic acid) and thereby remove lignin and other coloring substances from the sample [7][8].

In addition, the use of 1% sodium hydroxide (NaOH) to pretreat natural bamboo prior to acid delignification has been observed to help prepare TB with high optical transmittance [9].

2.1.2. Alkali Delignification Method

Researchers have also prepared TW templates by treating wood samples with a mixed solution of NaOH and sodium sulfite (Na_2SO_3) at 100 °C for 12 h, as SO_3^{2-} can sulfonate lignin in alkaline conditions [10][11]. The purpose of this lignosulfonalization is to introduce sulfonic acid groups into the side chain of the benzene rings in lignin. The reaction products are not only soluble in water but can also break the bonds of various ethers. Considering that the quinone structure formed during alkaline sulfite treatment will darken the color of the sample, further bleaching with hydrogen peroxide (H_2O_2) is required [12]. Notably, H_2O_2 bleaching is also a delignification process. First, H_2O_2 is dissociated in an alkaline solution to form hydrogen peroxide anion (HOO^-), which can decompose the quinone structure and even degrade it into small molecule esters. It should be noted that the bleaching effect of HOO^- is closely related to the pH of the solution. When the pH increases, the concentration of HOO^- increases, leading to an improved bleaching effect. However, when the pH exceeds 10.5, HOO^- is easily decomposed into O_2, and the bleaching effect will deteriorate [12]. Critically, the alkali delignification method is complex and can readily cause sample deformation [13].

2.1.3. Lignin Modification (Lignin Retaining) Method

The lignin modification method has been used to prepare bamboo templates for TB by retaining the lignin while modifying the chromophoric groups within. Because the lignin composition is retained, the mechanical strength of the resulting TB is typically higher than that of TB prepared by removing the lignin [14]. Moreover, the lignin modification method also avoids wasting the lignin components. For example, Wang et al. [14] removed the light-absorbing chromospheres (aromatic ketone, coniferaldehyde, and orthoquinone) of lignin using an alkali H_2O_2 treatment while retaining the aromatic skeleton lignin structure. To do so, sodium silicate (3.0 wt%), sodium hydroxide (3.0 wt%), diethylenetriamine pentaacetate (0.1 wt%), magnesium sulfate (0.1 wt%), and H_2O_2 (4.0 wt%) were dissolved in deionized water to prepare the lignin modification solution in which the bamboo samples were immersed at 70 °C until they turned completely white. The lignin-modified bamboo was then thoroughly rinsed three times with boiled deionized water to remove any residual chemicals. Finally, the resulting bamboo templates were solvent exchanged using acetone and ethanol. This lignin modification method was confirmed to selectively remove or react the chromogenic groups in the bamboo while retaining most of the lignin. The resulting high-lignin-content TB had a transmittance of 87% and haze of 90%.

2.1.4. Biological Enzyme Delignification

Delignification using the biological enzyme method represents an environmentally friendly process, as the need for harmful chemicals is minimized. Jichun and Yan [15] used biological enzymes to degrade lignin and thereby achieve

the decolorization of wood by employing the following procedure. The dried wood samples, pure water, biological enzyme (synthetic laccase/xylanase system at a dosage of 10 IU/g), and glacial acetic acid were combined in a 1:30–40 mass ratio of sample to water, and the pH was adjusted to 3–5 by adding trace quantities of hydrogen peroxide (up to 4% of the sample mass). A treatment temperature of 35–50 °C was then applied for 1–2 h, after which the samples were washed with deionized water. Next, the samples were extracted using 30 wt% dioxygen water and 25 wt% ammonia water at a volume ratio of 10:1. The extracted samples were then washed with deionized water and dehydrated by ultrasonic extraction to obtain the TW templates.

3. Properties of TB

3.1. Optical Properties

Ongoing research has produced TB with excellent optical transmittance and high haze (**Table 1**). There are three main interactions with light to consider when evaluating the optical properties of TB: (1) reflection at the outer gas/TB interface, (2) scattering in the form of reflection and refraction, and (3) absorption inside the TB. In TB, light scattering mainly occurs at the interface between the bamboo tissue and the polymer. The lower the difference between the RIs of the bamboo template and polymer, the less scattering will occur at their interface. High haze is primarily a result of collective scattering inside the composite material.

Table 1. Summary of TB preparations and properties.

Ref.	Template Preparation Method; Temperature; Time	Polymer	Variable	Optical Property			Mechanical Property	
				t (mm)	Tr (%)	haze (%)	l × w × t (mm^3)	TS (MPa)
Wu et al. [6]	Delignification: $NaClO_2$; 80–90 °C; 2–4 h	Epoxy (E51) (RI = approximately 1.5)	inner	1.1	approximately 12	—	3 × 4.4 × 1.1	35.31
			outer	1.8	approximately 2	—	3 × 7.8 × 1.8	82.18
Wang et al. [9]	Delignification: preconditioned in NaOH + 10 h; $NaClO_2$; 85 °C; 3 h	Two-part epoxy resin (Clearcast 7000) (RI = approximately 1.5)	—	1	approximately 80	80	165 × 13 × 1	92
			—	1.5	approximately 75	80	165 × 13	—

Ref.	Template Preparation Method; Temperature; Time	Polymer	Variable	Optical Property			Mechanical Property	
				t (mm)	Tr (%)	haze (%)	l × w × t (mm^3)	TS (MPa)
							× 1.5	
			—	0.3	92.4	43.5	40 × 20 × 0.3	47.1
			multi-layer (3 layers)	1.2	78.6	70	40 × 20 × 1.2	61.89
			multi-layer (5 layers)	2.3	67.1	70.55	40 × 20 × 2.3	approximately 60
Wu et al. [16]	Delignification: $NaClO_2$; 80–90 °C; 2–3 h	Epoxy (E51) (RI = 1.52)	multi-layer (7 layers)	2.9	23.7	82.95	40 × 20 × 2.9	approximately 60
			single layer	1.2	10.4	97.02	40 × 20 × 1.2	61.15
			single layer	2.3	5.5	~100	40 × 20 × 2.3	approximately 30
			single layer	2.9	1.7	~100	40 × 20 × 2.9	approximately 10
Wang et al.	Lignin modification:	Epoxy (E51) (RI =	inner	1.5	87	—	—	—

Ref.	Template Preparation Method; Temperature; Time	Polymer	Variable	Optical Property			Mechanical Property	
				t (mm)	Tr (%)	haze (%)	l × w × t (mm^3)	TS (MPa)
[14]	lignin-modification solution; 70 °C; until become white	approximately 1.5)	middle	1.5	74	—	—	—
			outer	1.5	66	—	—	—
		[14]	radial	1.5	—	90	20 × 8 × 1.5	30
			longitudinal	1.5	80	70	50 × 10 × 1.5	118

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content, cell structure morphology, and d veen the bamboo template and the impregnating resin. In addition, a summary including mechanical and physical properties of natural fibres is shown in **Table 2**.

Table 2. Summary of mechanical and physical properties of natural plant fibres.

Ref.	Type of Fibre	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (MPa)
Abdul Khalil et al. [19]	Moso bamboo (*Phyllostachys pubescens*)	1.2–1.5	500–575	27–40
Liu et al. [20]	Oil palm	0.7–1.6	248	3.2
Liu et al. [20]	Pineapple	0.8–1.6	1.44	34.5–82.5
Cai et al. [21]	Abaca	1.5	717	18.6
Vijaya Ramnath et al. [22]	Jute	1.3–1.49	393–800	13–26.5
Ramesh et al. [23]	Sisal	1.41	350–370	12.8
Mohamad et al. [24]	Kenaf	1.2	282.6	7.13
Asim et al. [25]	Coconut	1.2	140–225	3–5

As shown in **Table 1**, the mechanical properties of TB produced using the same resin exhibit substantial differences based on the applied preparation method. Notably, as the lignin modification method removes the light-absorbing chromophore groups without entirely destroying the aromatic structure of lignin, the mechanical

properties of the resulting TB are much better. As a result, the tensile strength of TB obtained by lignin modification can be as high as 118 MPa [14].

The mechanical properties of TB are strongly dependent on the mechanical properties of the bamboo template. Density, which mainly depends on the fiber diameter, fiber content, and cell wall thickness, exerts a considerable influence on the mechanical properties of bamboo. The bamboo fiber density increases with increasing fiber content. As mentioned, the bamboo fiber volume fraction increases from the inner side to the outer side of the bamboo culm, resulting in different bamboo layer densities according to their original locations within the stalk. Thus, TB made from an outer bamboo layer is often stronger than TB made from an inner layer, as shown in **Table 1**. Note that **Table 1** also indicates that the tensile strength of multi-layer TB is higher than that of single-layer TB with the same thickness. In the beginning, the tensile strength of 1.2 mm thick multi-layer TB was found to be 61.89 MPa, whereas that of 1.2 mm thick single-layer TB was found to be 61.15 MPa [16]. As the TB thickness increases, the difference in tensile strength grows larger. This result is related to interfacial compatibility. As mentioned, multi-layer TB enables more uniform resin impregnation through the laminations, whereas it is difficult for the resin to infiltrate into the bamboo cells of single-layer TB. Therefore, the tensile strength of multi-layer TB is greater, making it more suitable as a structural material in electronics, household, and construction applications. Furthermore, the tensile strength of TB first increases and then decreases with increasing bamboo template thickness. A thicker bamboo template makes it difficult to completely remove lignin but and hinders the ability of the resin to infiltrate into the template. In contrast, a relatively thinner bamboo template exhibits more extensive lignin removal and can easily be impregnated with resin. The properties of TB can thus be tailored by compression of the bamboo template to provide different densities and thicknesses. Furthermore, owing to the anisotropic structure of bamboo, which has no radial cell elements, the tensile strength of TB is much higher in the longitudinal direction (about 118 MPa) than in the radial direction (about 30 MPa) [14].

3.3. Thermal Conductivity

Excellent thermal insulation performance with low heat conductivity is critical to realizing energy-efficient building materials [26][27]. The thermal conductivity of TB (0.203 W m^{-1} K^{-1}) is accordingly compared with that for common glass (0.974 W m^{-1} K^{-1}), TW (0.225 W m^{-1} K^{-1}) [9], and other materials. Notably, the figure indicates that TB has a lower thermal conductivity than TW. The low thermal conductivities of both TB and TW can be attributed to the interfacial heat resistance and the phonon dispersion between the air and cell walls [28]. Thermal conduction in TB is also anisotropic, like its optical and mechanical properties. Indeed, the thermal conductivities of TB in the longitudinal and radial directions were found to be about 0.44 and 0.33 W m^{-1} K^{-1}, respectively [14]. This indicates that the thermal energy tends to spread more in the direction parallel to the direction of bamboo growth owing to the orientation of the cellulose nanofibers [29]. Because of its low thermal conductivity yet relatively high light transmittance, TB represents a promising window material that can prevent heat dissipation and thus reduce the energy consumption of buildings.

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