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Fabrication and characterization of transparent wood for next generation smart building applications

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ABSTRACT

A major fraction of the electricity that is generated in the world is used in the building sector, particularly as a source of light. One way to reduce the consumption of electricity in buildings is by utilizing natural light with the help of environmentally friendly resources such as transparent wood. Removing the lignin from wood followed by impregnating environmentally friendly polymers whose refractive index matches the refractive index of the cell wall helps in obtaining transparent wood. Hence, herewith we report a simple and low-cost method of fabricating transparent wood from beech wood (Fagus grandifolia) while retaining its 3-dimensional structure. The surface morphology of the synthesized transparent wood was studied by using scanning electron microscopy. Brunauer Emmet Teller measurements were carried out to determine the specific surface area. FTIR measurements were performed to study the wood chemistry. Optical measurements showed a maximum optical transmittance of 70% and a maximum haze of 49% for 0.1 mm and 0.7 mm thick wood samples, respectively. Mechanical testing showed that the transparent wood has a higher tensile strength and hardness when compared to the delignified wood. The fabricated transparent wood with high transmittance and enhanced mechanical properties is a potential candidate material for light transmitting building materials and transparent solar cell windows.

1. Introduction

Due to the enlargement of the global economy, there is an increase in the demand for energy consumption. A majority of this energy is supplied through fossil fuels such as coal, oil, and natural gas which result in the production of green-house gases and contributes to global warming. According to recent reports, the global temperature has been increasing continuously over the past 100 years [1,2]. According to the US department of energy resources, the U.S consumes about 47.6% of its energy through the building sector, 24.4% through industry and 28.1% through transportation [3–5]. One way to reduce the amount of energy being consumed through the building sector is to design semi-transparent buildings. These buildings can potentially reduce the utilization of artificial light by substituting it with the natural light. Furthermore, since they are not completely transparent, privacy is still retained.

One of the materials that plays a major role in the building sector is wood. Wood, due to its unique structure and natural growth process, possesses excellent mechanical properties relative to its cost. These include a high strength, good durability, high moisture content, and high specific gravity. Based on its structure, availability, and geographical differences, wood is classified into two types. They are the soft wood and hard wood. Soft wood has a high porosity due to its faster growth. Soft wood mainly includes cedar, pine, spruce, and redwood. In contrast to soft wood, hard wood has a higher density and is denser in structure [6]. Moreover, the longitudinal cells are shorter in length when compared to those in hard wood. However, both soft and hard woods possess similar hierarchical structure. In other words, the orientation of the cells is similar in the wood [7].

The structural anisotropy is a unique property of a wood. This is due to the alignment of the vertical channels across the cells present in the wood. It allows to pump ions and water for photosynthesis. Cells in the wood are mainly composed of cellulose which is a long chain of polysaccharides molecules containing at least 40% - 50 % glucose. Cellulose is also made up of lower molecular weight polysaccharide chains called hemicellulose. Lignin is the other major component that is present in the wood. It accounts for about 25% of the wood structure. It mainly acts as a glue which helps in

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bonding all the wood cells together. Furthermore, lignin provides high hardness and rigidity to the wood. Cellulose, which is the major component in wood, plays a vital role in development of flexible electronics such as optoelectronic devices. However, to make an optoelectronic device, the wood should be transparent to the relevant spectrum.

As mentioned earlier, the main components of wood are cellulose, hemicellulose and lignin. In contrast to cellulose and hemicellulose which are colorless, lignin possesses an extremely dark color. Therefore, this dark color leads to light scattering over the visible range. One way to make the wood transparent is to bleach it, which helps in removing the lignin and pulp. However, since all the color across the pores in the wood are not removed, polymer which can provide strength and transparency is impregnated into the pores of the wood which run vertically down. Several recent attempt have successfully been made to fabricate transparent wood. However, the process to fabricate transparent wood obtained so far is complicated and requires environmentally unfriendly reagents [8–12].

In this study, our objective is to develop a transparent wood from beech wood (Fagus grandifolia) using a novel two-step synthesis process. In a recent study, the wood-PMMA composite material [13] was shown to exhibit a high durability with excellent mechanical properties. In this paper, we report the synthesis of optically semi-transparent wood which possesses an optical transmittance of 60% along with a haze of 49%. Furthermore, its mechanical and microstructural properties have also been investigated in detail.

2. Materials and methods

2.1. Chemicals

Sodium chlorite ($NaClO_2$, Sigma Aldrich, USA, 98%), acetate buffer solution (pH = 4.6, Sigma Aldrich, USA), 2,2′ Azobis (Sigma Aldrich, USA, 80%), and pure methyl methacrylate monomer (MMA, Sigma Aldrich, USA, 99%) analytical reagents were used as received without any further purification.

2.2. Fabrication of transparent wood

First, beech wood (BW) was cut into disc-shaped samples which were rinsed with water. The rinsed wood pieces were then transferred to a box furnace for dehydration at 120 °C for 24 h. The dehydrated wood samples were then transferred to a solution containing 5 wt % sodium chlorite in acetate buffer solution and allowed to sit at 95 °C for 12 h. This process bleached the wood and removed lignin from the cell walls. The wood pieces were then washed with deionized water. Later, these samples were washed with ethanol, a solution of ethanol and acetone, and acetone so as to remove any remaining water. The washed samples are referred to as delignified wood (DW). Upon delignification, the samples change from brown to white. The delignified wood samples were stored in ethanol until further use. Later, the delignified wood samples were impregnated with poly methyl methacrylate (PMMA) by vacuum infiltration. The impregnation was performed for one hour with three repetitions. Finally, the polymer-impregnated wood was sandwiched between aluminum-wrapped glass slides for heat treatment. The heat treatment was performed in a box furnace at 85 °C for 12 h. The heat-treated wood is labeled as transparent wood (TW). A schematic of the fabrication process is shown in Fig. 1.

2.3. Preparation of poly methyl methacrylate

PMMA was prepared by MMA monomer and 2, 2′ Azobis initiator. The initiator was 1 wt % of the monomer. The mixture of the monomer and initiator was pre-polymerized at 90 °C for 5 min. The mixture was then cooled to room temperature in an ice-water bath so as to terminate the polymerization.

2.4. Vacuum infiltration technique

To impregnate PMMA into the delignified wood with the help of vacuum infiltration, a vacuum chamber and a vacuum pump. The amount of vacuum pressure that is applied as well as the time of vacuum infiltration, and stabilization of delignified wood plays a vital role in the impregnation of PMMA into the delignified wood. At first, to stabilize the wood in the vacuum chamber, the wood is immersed in the PMMA solution. During the stabilization, i.e. when the wood + PMMA solution is under vacuum, the air that is present in the pores of the wood is released as bubbles (shown in Fig. 1(b)). An optimal time of an hour with three repetition at chamber pressure of 0.1 bar has been chosen to completely remove the air that is present inside the wood. Once, the wood + PMMA solution is stabilized, the chamber is disconnected from the vacuum pump and is retained under vacuum. During this stage, the amount of PMMA level that is immersed in the wood goes down which is mainly because of the impregnation of PMMA into the wood. Furthermore, PMMA hardens the wood and increases the ability to stick to it. The PMMA impregnated wood is then further sandwiched in between the glass slides and further wrapped with aluminum foil for heat treatment. The heat treatment is performed in a box furnace at 85 °C for 12 h. This heat-treated wood is then labeled as transparent wood.

2.5. Characterization

The surface morphology of as-prepared wood samples was measured by using an FEI Quanta 600 FEG scanning electron microscope. The non-conducting samples were coated with gold before SEM measurements. Brunauer, Emmett and Teller (BET) nitrogen adsorption measurements were carried out on the beech wood and delignified wood samples using a Micrometrics Gemini V analyzer to determine their specific surface area. Before analyzing the samples at −196 °C by N_2 physisorption, the samples were degassed at 110 °C for 24 h. At relative pressure ranging from 0.01 to 0.25, the data for all the samples were collected. Fourier transform infrared spectroscopy (FT-IR) spectra was measured by using attenuated total reflection (ATR) technique. The spectra were recorded using a Varian 3100 FT-IR Excalibur. Spectral data were collected over a range of 400 cm^{-1} to 4000 cm^{-1} by averaging 40 scans with a resolution of 8 cm^{-1}. The transmittance and haze measurements were performed using a Lambda 950 UV/VIS NIR spectrophotometer with a wavelength ranging from 300 nm to 850 nm. For haze experiment, an integrating sphere with three ports, of which two of them are aligned to the sphere's center allowing passage of the transmitted light through the center of the sphere, was used for performing both measurements. ASTM standards - ASTM D1003 “Standard Method for Haze and Luminous Transmittance of Transparent Plastics” was followed to measure the percentage of haze in the samples [14]. The percentage of Haze determined is given by,

$$Haze = \left(\frac{T4}{T2} - \frac{T3}{T1}\right) \times 100\ \%$$

Where, T1, T2, T3, and T4 are the amount of transmission of the