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RESEARCH PAPER

Investigation of the tensile strength and thermal properties of the transparent wood for ultraviolet resistance

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Abstract

Transparent wood is a new, renewable and sustainable material that has the potential to replace glass as a window material. This research aimed to treat transparent wood with epoxy resin, investigate the mechanical and thermal properties of transparent wood, and examine the suitability of transparent wood as an ultraviolet-resistant material. Transparent wood is made by delignifying wood using a chemical method, and then an infiltrating epoxy resin polymer is used. The bending and cracking of transparent wood samples were observed after exposure to natural UV light. The density, tensile strength and thermal conductivity measurements of balsa wood, transparent wood, and epoxy resin were measured. The effect of UV exposure was observed within weeks; the samples became yellow and cracked. This change is due to epoxy resins' UV resistance and chemical substances remaining in delignified wood. The tensile strength of transparent wood is 0.02 MPa. The high viscosity of epoxy resin causes incomplete infiltration of delignified wood. The thermal conductivity of transparent wood is lower than that of glass. In conclusion, the type of epoxy resin used for fabricating transparent wood should have high UV resistance, low viscosity, and long working time. The thermal conductivity of transparent wood is lower than that of glass.

1. Introduction

Wood is a natural material widely used in human activity. Wood is a renewable and earth-abundant resource. Wood has a natural growth process, is an earth-abundant resource, has a unique structure, and has attractive mechanical properties. It is a sustainable and renewable material that is environmentally friendly (Yaddanapudi *et al.*, 2017; Wachter *et al.*, 2021). Transparent wood is delignified wood submerged with a polymer because of its high transmittance and improved mechanical properties. It is a good candidate for light-transmitting building materials and transparent solar cell windows. The development of transparent wood replaces the commonly used glass or provides a new material selection for solar cell windows and building materials. Transparent wood has lower thermal expansion, is lighter, has better insulation, and is more robust than glass (Li *et al.*, 2017; Mi *et al.*, 2019).

Nowadays, energy consumption and energy demand are growing every year. Meanwhile, the air pollution caused by burning coal and natural gas has become a significant concern in all countries. Electricity is the most critical energy source in human activity in this generation. Urbanisation of low-income countries will increase energy consumption (Wang *et al.*, 2014). Primary electricity resources are generated by burning coal, natural gas, and oil, which release a lot of carbon dioxide and change the atmosphere's composition, trapping heat with a similar effect as the glass roof of a greenhouse. To reduce air pollution, scientists and engineers must develop new sustainable and green energy sources, such as solar cells and wind turbines, to replace coal and natural gas, which release massive greenhouse gases. Furthermore, engineers develop methods to reduce energy consumption and increase energy efficiency—for example, window panels made of low thermal conductivity materials. Transparent wood can become energy-efficient building materials and light management layers for solar cells. Transparent wood has excellent thermal insulation, mechanical properties and desired optical transmittance compared to conventional glass. High thermal insulation and optical properties can reduce the light source and air conditioning equipment's electrical consumption (Mi *et al.*, 2019).

Cells in the wood are mainly composed of cellulose, hemicellulose, and lignin. The hierarchical structure and

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the strong interactions among cellulose, hemicelluloses, and lignin lead to excellent mechanical properties in wood. Cellulose and hemicelluloses are optically colourless, and lignin, caused by complex structures, is opaque and dark. Lignin provides high hardness and rigidity to the wood (Yaddanapudi *et al.*, 2017; Kai *et al.*, 2018).

The fabrication process of transparent wood uses a chemical reaction to bleach the wood (remove lignin to increase transparency) and infiltrate a refractive index-matched polymer. Due to the removal of lignin, wood becomes weak because the hierarchical structure of wood is destroyed. Hence, polymers were used to replace lignin as the adhesive to form a new structure of transparent wood. Transparent wood's hardness is related to the type of polymer used. (Ali *et al.*, 2015; Wang *et al.*, 2018). To make a high toughness, one needs to use a suitable polymer. Suppose transparent wood is the potential material for building materials and solar cell windows. Investigating its performance on weather resistance is necessary. The weather will corrode transparent wood by wind, acid rain, and other natural weather.

Transparent wood is a new type of transparent, sustainable composite material. It has the potential for an engineering application as a new material, especially in the building sector. Transparent wood is a potential material to replace ordinary glass. Transparent wood has excellent mechanical and optical properties like hardness, tensile strength, transmittance and haze, and refractive index. For fabrication, transparent wood must degrade the lignin and retain transparent cellulose and hemicellulose. The wood's structure is altered and weakened by removing opaque lignin from wood. Polymer is infiltrated into wood. The polymer acts as an adhesive and replaces lignin to form the structure of transparent wood. The type of wood and polymers used will affect the properties of the transparent wood made. Research the relation between the method of fabricating transparent wood and the mechanical properties of transparent wood. Transparent wood will mainly be used in the outdoor sector. UV resistance has become an essential factor for engineers to consider. Sunlight has an impact on the durability of transparent wood. It is necessary to investigate the performance of transparent wood in a natural setting.

From this research, transparent wood is fabricated from the bulk of the raw material. The type of wood used is balsa wood, and the polymer used is epoxy resin. The samples are made of different thicknesses with the same surface area. The properties of transparent woods were analysed by conducting test procedures to determine their thermal conductivity, tensile strength, and UV resistance. Among the information that can convey and fill the gap from the previous and current research were the mechanical, thermal, UV resistance, performance, and durability of transparent woods properties can be determined, and lastly, basic knowledge before developing further application of transparent woods in other sector areas can be strategised especially in environment-friendly biobased packaging in the food industry.

2. Materials and methods

2.1 Materials

The materials used in this study included balsa wood, sodium sulphite, sodium hydroxide, hydrogen peroxide, ethanol, acetone, epoxy resin, hardener, and deionised water.

2.2 Methods

Balsa wood was cut into pieces measuring 5 cm × 5 cm with a thickness of 3 mm in the transverse direction using an electric table saw. The surfaces of the wood pieces were polished using sandpaper. To remove surface contaminants, the wood samples were rinsed with water. They were then placed in a furnace at 110°C for 24 h to undergo dehydration.

A two-step delignification method was employed to remove lignin from the wood. A 1.25 mol/L sodium hydroxide (NaOH) solution and 0.4 mol/L sodium sulphite (Na_2SO_3) were prepared. The dehydrated wood samples were submerged in the solution at 100°C for 6 h, following the method described by (Li *et al.*, 2020). During this process, the double bonds in the lignin within the cell walls were degraded, resulting in the dissolution of lignin into a dark red solution. The delignified wood samples were washed sequentially with deionised water, ethanol, and acetone. Subsequently, the samples were immersed in a solution containing 10 wt% sodium hydroxide and 30 wt% hydrogen peroxide (H_2O_2) for 3 h, as outlined by (Xia *et al.*, 2021). After treatment, the samples were rinsed with deionised water and suspended in ethanol.

The delignified wood samples were carefully removed from the ethanol and rested for 1 h to eliminate excess ethanol before epoxy resin infiltration. Epoxy resin was prepared by mixing the resin and hardener in a 1:1 volume ratio in a disposable plastic cup. The mixture was stirred slowly using a wooden stick to minimise air bubble formation. Once thoroughly mixed, the delignified wood samples were placed into a mould made of plastic or silicone, along with the epoxy resin mixture. The filled mould was placed in a vacuum chamber for 30 min to extract air bubbles from the epoxy

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and the delignified wood.

Following vacuum treatment, the mould was kept at room temperature for 24 h to allow the epoxy resin to cure completely. Once hardened, the transparent wood samples were removed from the mould. A summary of the methodology is presented in Figure 1.

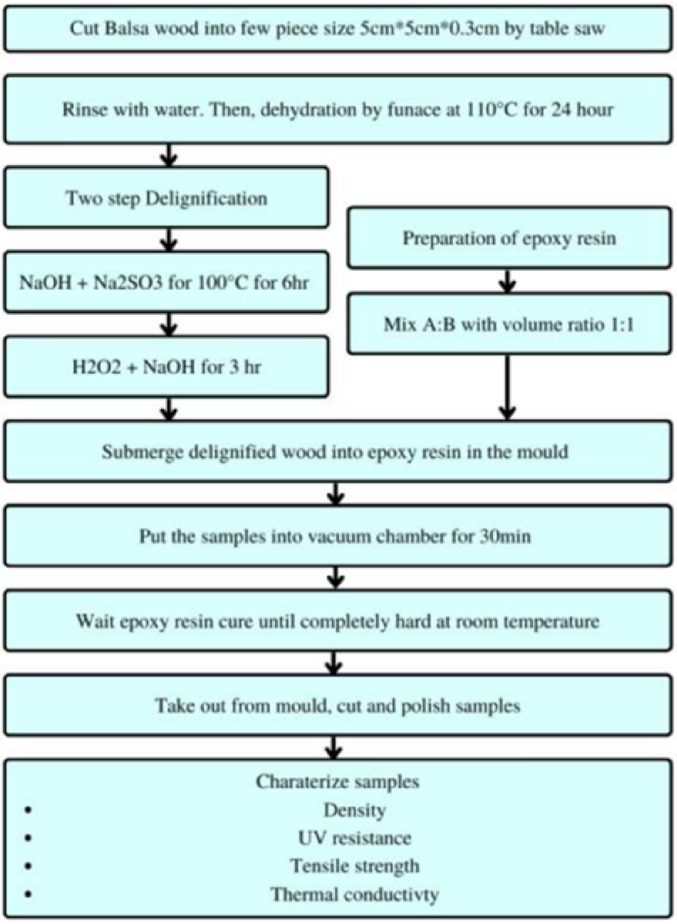

Figure 1. Research flowchart.

2.3 Sample characterisation

2.3.1 The measurement of density

This study measured mass, m and volume, v of original wood, delignified wood, and transparent wood samples. Then, the change in density of actual wood, delignified wood, and transparent wood will be compared. The density of the wood sample was calculated using the equation (1) (Cammack *et al.*, 2006):

$$\rho = \frac{m}{v} \tag{1}$$

2.3.2 UV resistance

UV resistance measures the ability of a material to endure exposure to ultraviolet. Put the samples in a room near the window at room temperature. Observe the change in samples after two weeks. Olympus DSX-CB Opto Digital Microscope equipment was used to observe the surface of transparent wood.

2.3.3 Tensile strength

The LLOYD LR 30K universal testing machine measures the samples' mechanical properties. Measure the mechanical properties of the balsa wood, delignified wood, transparent wood, and epoxy resin. The tensile speed was 2 mm/min (Wu *et al.*, 2019). All parameters are measured using the following equation (Engineering Technology, 2025).

$$\sigma = \frac{F}{A} \tag{2}$$

$$\varepsilon = \frac{\Delta L}{L} \tag{3}$$

$$\sigma = E\varepsilon \tag{4}$$

Where σ = stress, F = force, A = area, ε = strain, ΔL = Change in length, L = length and E = Young's modulus

2.3.4 Thermal conductivity

SOLTEQ HE116 Thermal Conductivity of Solid, Liquid and Gas performs the thermal conductivity measurement of samples. The SI unit of thermal conductivity is watts per meter- kelvin ($Wm^{-1}K^{-1}$). Using the Thermal conductivity of Solid, liquid, and Gas, measure the thermal conductivity of balsa wood, transparent wood and epoxy resin (Zohuri and Fathi, 2015).

$$q = -kA\frac{\partial T}{\partial x} \tag{5}$$

$$k = -\frac{q \cdot x}{A(T_H - T_C)} \tag{6}$$

Where x = thickness of samples, T = temperature of samples, A = surface area of samples, q = heat transfer rate and k = thermal conductivity.

3. Results and discussion

3.1 The density measurement of the samples

Measure the mass and volume of balsa wood, transparent wood, and epoxy resin to calculate the density of the samples. The density of different materials is shown in Table 1. The epoxy resin has the highest mass and volume. Balsa wood is the lowest mass and density material in this research. Meanwhile, epoxy resin has the highest density. Transparent wood is balsa wood after delignification, and then infiltrated by epoxy resin.

Table 1. Density of the samples

Material	Mass, m (g)	Volume, V (cm^3)	Density, ρ (g/cm^3)
Balsa wood	1.6482	9.75	0.16
Transparent wood	3.20	4	0.8
Epoxy resin	29.13	28.32	1.028

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3.2 UV resistance of transparent wood

Figure 2 shows the transparent wood infiltrated by epoxy resin. Figure 3 (a) shows the transparent wood placed in the room after two weeks. Figure 3 (b) shows a Microscope image of a transparent wood sample. Transparent wood was cracked without external forces. The main reason transparent wood cracked was caused by using epoxy resin as a polymer infiltrate in delignified wood. Epoxy resin will react with UV light and then become yellow and crack (Nikafshar *et al.*, 2021). Epoxy resins had high UV resistance. It will degrade after a long period under the sun. However, another chemical substance that remained in delignified wood affects the chemical bonding of the chemical structure of epoxy resin. In fabricating delignified wood, sodium sulphite, sodium hydroxide, and hydrogen peroxide were used to remove and retain lignin, Acetone, and Methanol to rinse the samples. While mixing epoxy resin with delignified wood, methanol remains in the porous of delignified wood. Chemicals remaining in delignified wood may react with unknown chemicals, causing changes in the structure of epoxy resin.

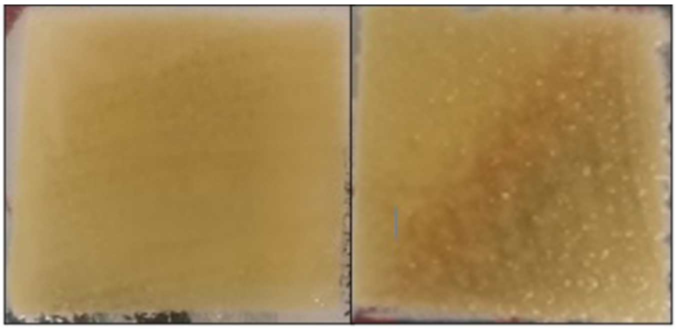

Figure 2. The transparent wood samples, after being infiltrated by epoxy resin.

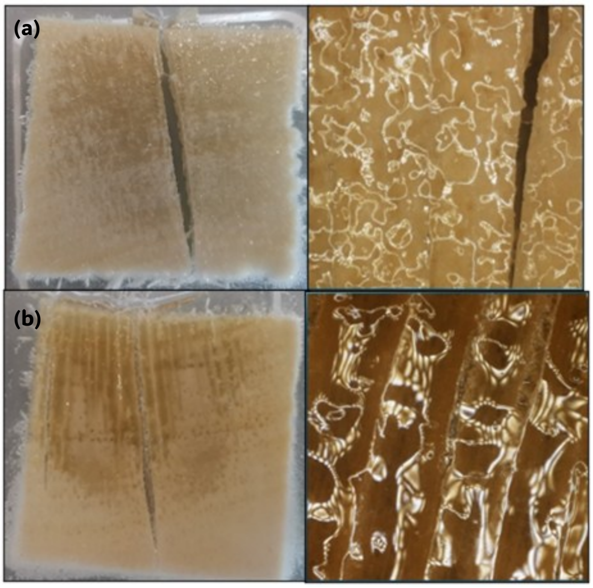

Figure 3. a) The transparent wood samples (a) after two weeks b) microscope image.

3.3 Tensile strength of samples

Figures 4 to 7 show the load graph applied on the sample against time for original balsa wood, delignified wood, transparent wood, and epoxy resin. The material's tensile strength depends on the composition and chemical structure (Wu *et al.*, 2019). Table 2 shows the mechanical properties of balsa wood, delignified wood, transparent wood, and epoxy resin. The epoxy resin had the highest maximum load compared with other samples. Meanwhile, the delignified wood had the lowest maximum load. Delignified wood's structure was destroyed by a chemical reaction that broke down the bonding between lignin, cellulose, and hemicellulose. Transparent wood was stronger than delignified wood but weaker than the original wood. Transparent wood is made by delignifying wood infiltrated by epoxy resin. As expected, at least transparent wood's strength is higher than that of wood's. However, the type of epoxy resin used in this experiment is unsuitable for fabricating

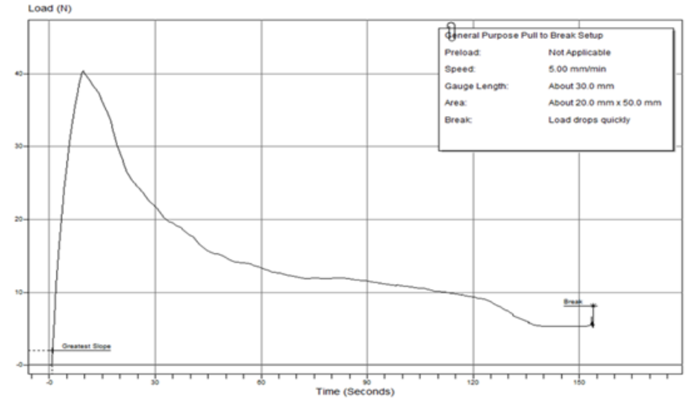

Figure 4. Load v/s time of original balsa wood.

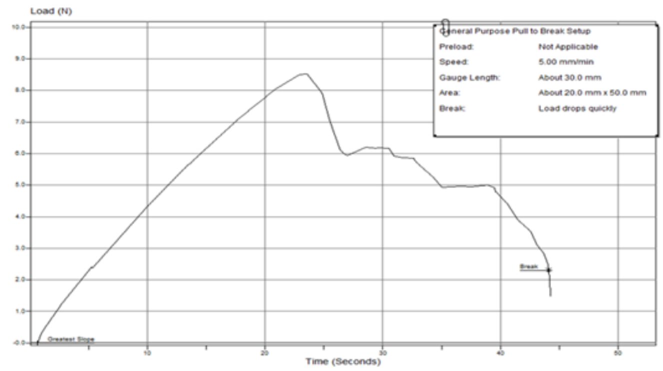

Figure 5. Load v/s time of delignified wood.

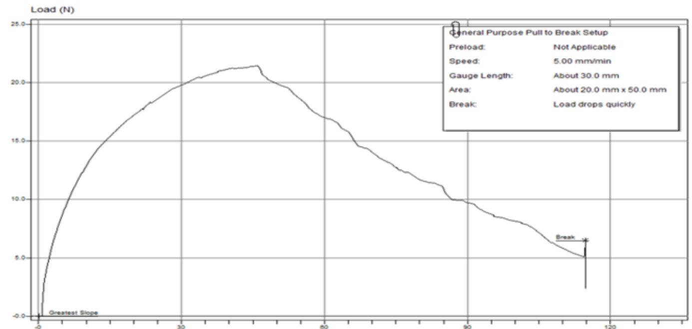

Figure 6. Load v/s time of transparent wood.

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Table 2. Comparison of mechanical properties of original wood, delignified wood, transparent wood, and epoxy resin

Type of samples	Maximum Load (N)	Stress Maximum (MPa)	Strain at Maximum Load (%)	Stiffness (N/mm)	Young's Modulus (MPa)
Original wood	40.43	0.04	2.52	97.82	2.93
Delignified wood	8.52	0.01	6.40	8.87	0.26
Transparent wood	21.44	0.02	12.64	76.79	2.30
Epoxy resin	52.01	0.05	14.81	167.13	5.01

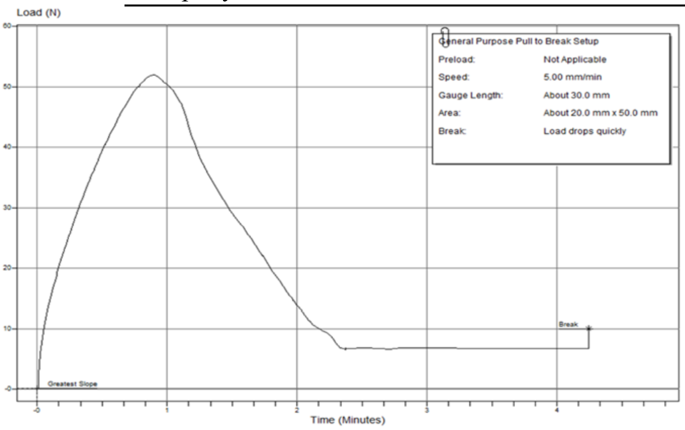

Figure 7. Load v/s time of epoxy resin.

transparent wood. The high viscosity and short working time of epoxy resin do not enable ultimate submerging into delignified wood. High-viscosity epoxy resin was hard to infiltrate into porous delignified wood. It did not have enough time to use a vacuum chamber to eliminate air in delignified wood and infiltrate epoxy resin into delignified wood. That caused the strength of transparent wood to be partially enhanced by epoxy resin.

3.4 Thermal conductivity of samples

The thermal conductivity of a material determines its ability to transfer heat. Transparent wood had lower thermal conductivity compared to conventional glass. The typical glass's thermal conductivity is approximately $1Wm^{-1}K^{-1}$. The thermal conductivity of window glass will affect the building's energy efficiency (Mi *et al.*, 2019) - Table 3 shows the thickness and Area of Samples. Table 4 shows the thermal conductivity of balsa wood, transparent wood, epoxy resin and glass. Transparent wood's thermal conductivity was $0.061Wm^{-1}K^{-1}$. It has lower thermal conductivity than the typical glass ($1Wm^{-1}K^{-1}$). It was given evidence that transparent wood could replace conventional glass.

4. Conclusion

Throughout this research, the objective has been successfully achieved. Fabricate transparent wood by using epoxy resin polymer. Measure transparent wood's mechanical and thermal properties using a Universal Testing Machine and thermal conductivity tester. The results obtained from this research show that the epoxy resin type used was unsuitable for fabricating transparent wood. The epoxy resin has high viscosity and a short working time. The high viscosity of epoxy resin makes it challenging to submerge into the small pores of the delignified wood. Short working causes the short epoxy resin to infiltrate into delignified wood. To fabricate high transparency, transparent wood must be filled with a refractive index-matched polymer. However, another epoxy resin is not resistant. When epoxy resin is exposed to sunlight for long periods, it will break down and deform.

Table 3. Thickness and surface area of samples

Type of Material	Thickness, x $\times 10^{-3}$ (m)	Area, A $\times 10^{-3}$ (m^3)
Wood	4	2.50
Transparent Wood	9	2.56
Epoxy Resin	9	3.42

The tensile strength of transparent wood is lower than expected. Epoxy resin did not fully submerge into delignified wood. Epoxy resin cannot stick the cellulose and hemicellulose to form a new structure. The incomplete infiltration of epoxy resin causes low tensile strength in transparent wood. Select the type of polymer with low viscosity to fill all the pores of delignified wood. The thermal conductivity of transparent wood is lower than that of glass. It has been proven that transparent wood has the potential to replace glass as a window material to increase energy efficiency and reduce energy consumption. Epoxy resin has slightly higher thermal conductivity compared to transparent wood. Therefore, this research discusses some issues related to fabricating transparent wood. This research provides the information as a reference for future research and analysis of transparent wood materials.

Table 4. Comparison of thermal conductivity of wood, transparent wood, epoxy resin, and glass

Type of Material	Heat Flow Density, q (W/m^2)	Hot Plate Temperature, T_H (°C)	Cool Plate Temperature, T_H (°C)	Thermal Conductivity, k (W/m·K)
Wood	109	45.0	29.4	0.027
Transparent wood	104	45.0	29.8	0.061
Epoxy resin	139	45.0	31.1	0.09
Glass	-	-	-	≈1

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Select a more suitable polymer to fabricate transparent wood.

Conflict of interest

The authors declare no conflict of interest.

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