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Translucent Pure Wood Prepared via a Simple Compression Process

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Keywords: compressed wood | optical materials | translucent wood | transparent wood

ABSTRACT

Transparent wood and translucent wood are attracting attention as promising sustainable optical materials. Typically, translucent wood is prepared through chemical treatments (bleaching, etc.); thus, there is a need for more ecofriendly, sustainable preparation methods. In this study, translucent wood was prepared by precisely controlling the compression conditions. Natural wood was densified to reduce internal voids that cause light scattering, resulting in a light transmittance of more than 60% for visible light (@600 nm, sample thickness: ~0.3 mm). This method was particularly effective for softwood and can be applied to hardwood, accelerating the development of ecofriendly optical materials.

1 | Introduction

Wood, which has been used by humans since ancient times, remains an essential material for building materials and daily necessities because of its excellent properties, such as light weight, high strength, and high thermal insulation. In addition, owing to functionalization processes such as waterproofing, processes to provide corrosion resistance and fire resistance, and reinforcement, wood remains highly valued even in today's world, where synthetic polymers are widely used.

In recent years, further functionalization of wood has been studied to realize a sustainable society [1–3]. In particular, efforts to make wood transparent are interesting approaches to expand the utilization possibilities of wood, such as in light-transmitting building materials and green substrates for electronic devices [4–13]. Wood is typically an opaque material. The main factors preventing light transmission are absorption of light by lignin in wood and diffusion/multiple reflection of light within voids [14, 15]. Translucent wood and transparent wood are prepared through two steps: chemical treatment, such as delignification, and removal of voids through resin impregnation or self-densification [4–13]. With respect to delignification treatment, the chemical treatments ($NaClO_2$ treatment, etc.) used in pulp manufacturing are frequently applied. Regarding densification processes, impregnation of resins (poly (methyl methacrylate) (PMMA), etc.) with a refractive index similar to that of cellulose or self-densification of delignified cell walls have been reported [4–13]. In these methods, lignin and hemicellulose are removed or modified through chemical treatment. Wood is sustainable; however, when it is modified through chemical treatment, the environmental impact of the chemicals and the properties of the modified wood must be carefully evaluated. For example, if nonbiodegradable resin is filled into wood, then its inherent biodegradability is lost. Ideally, additional chemical treatment should be minimized to achieve both sustainability and functionality, such as light transmittance.

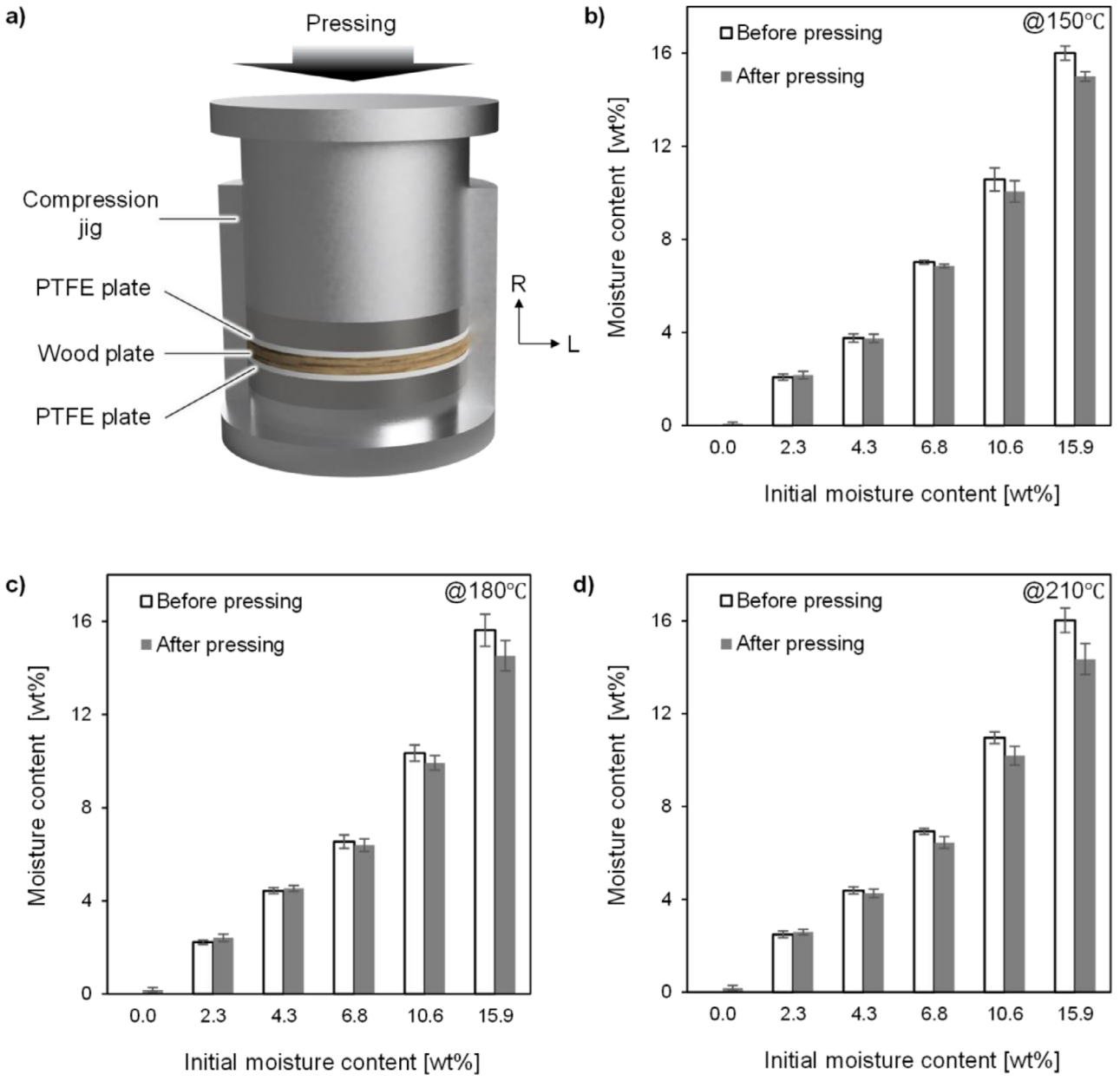

FIGURE 1 | (a) Overview of the Compression System. Moisture Content of Wood Plates before and after Pressing at (b) 150°C, (c) 180°C, and (d) 210°C.

To achieve light transmittance, resin impregnation or densification to remove voids is essential to suppress multiple reflections within wood [14]. In contrast, delignification is not always necessary. For example, lignocellulose films with the same components as wood exhibit high light transmittance in the long-wavelength region, thereby maintaining consistent light transmittance [16–19]. In other words, in terms of achieving light transmittance, densification is more important than delignification. Densification and strengthening of wood through compression have been studied for many years [20–23]. By applying an appropriate pressure and using heat and moisture to soften the lignin and hemicellulose in wood, wood with a density of ~0.4 g/cm^3 can be compressed to ~1.4 g/cm^3 [21, 22]. Owing to the high industrial interest in increasing the strength and hardness of wood through the simple and scalable process of compression, commercial production of compressed wood began with the development of Lignostone in the 1910s, followed by Staypak and Compreg, for which resin impregnation was used, in the 1940s [24]. It has attracted considerable attention in academic research, and in recent years, there have been many reports on compressed wood, which has achieved strengths comparable to those of steel [25–27]. However, most research on compressed wood has focused on its mechanical properties as a high-strength material or an acoustic material, with few reports on its other characteristics.

In this study, we aimed to prepare translucent wood via a simple compression process without chemical treatment. By controlling the initial moisture content of the wood, the moisture content during pressing, and pressing temperature, we successfully prepared translucent wood with a transmittance of over 60% for visible light with a wavelength of 600 nm.

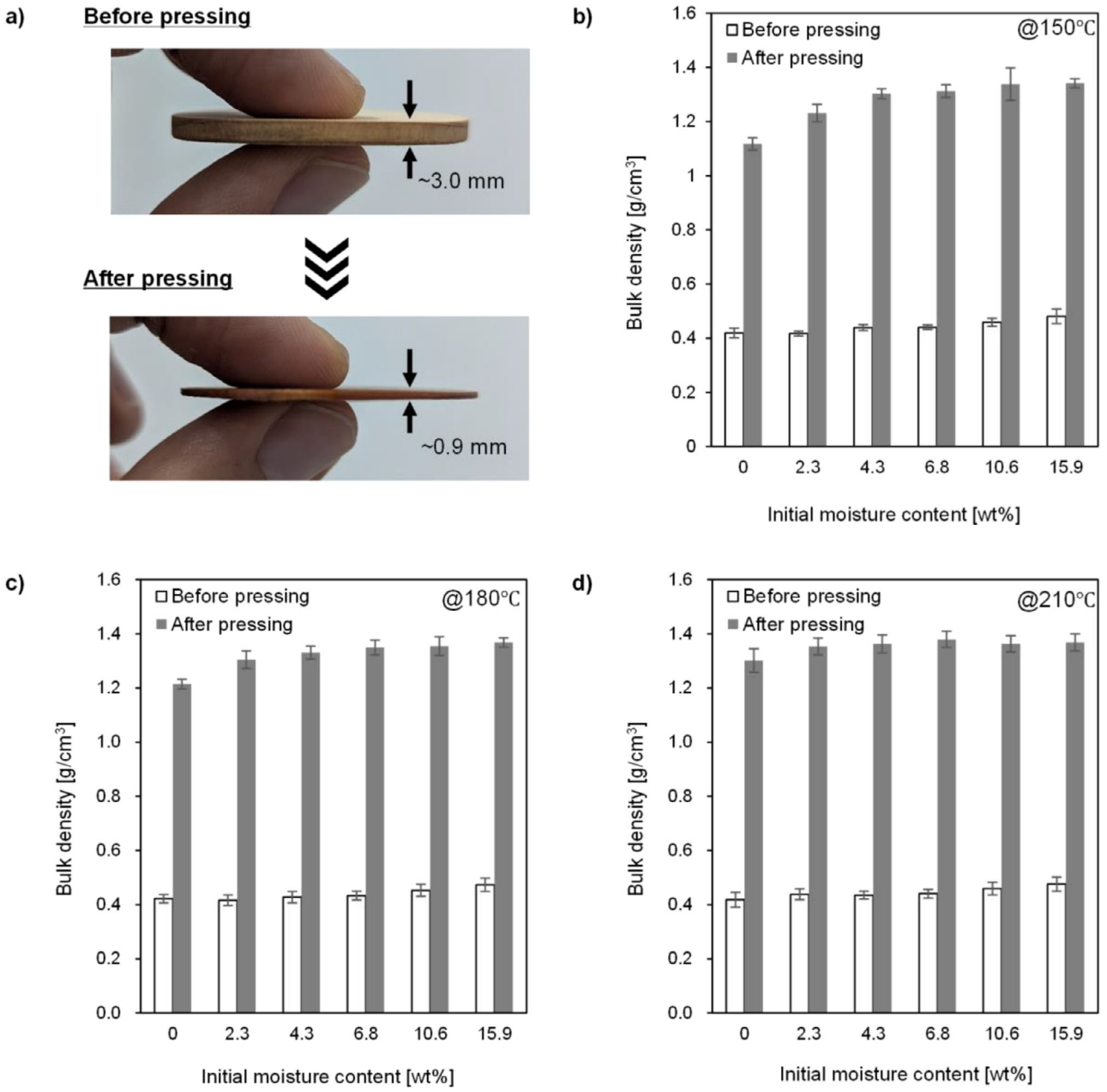

FIGURE 2 | (a) Appearance of a Wood Plate before and after Hot Pressing. (b) Bulk Density of Wood Plates Before and After Hot Pressing at (b) 150°C, (c) 180°C, and (d) 210°C.

The prepared translucent wood not only retained the original properties of the wood but also exhibited both translucency and high strength. Furthermore, the developed process is applicable to both softwood and hardwood and is expected to contribute to the development of sustainable wood-derived functional materials.

2 | Methods

2.1 | Preparation of Translucent Wood

Japanese cypress (*Chamaecyparis obtusa*) was used as the model material to prepare translucent wood. All the samples were compressed in the radial direction. Wood plates with a diameter of 40 mm and a thickness of 1–3 mm were used for compression. The moisture content was adjusted by placing the samples in different relative humidity (RH) environments (23°C, 10%–90% RH) for 2 weeks. The samples were compressed while sandwiched between polytetrafluoroethylene (PTFE) plates (thickness: 1 mm) and set inside a compression jig with an inner diameter of 40 mm. The samples were hot pressed for 10 min at a temperature of 150°C, 180°C, or 210°C and a pressure of 40 MPa using a hot-pressing machine (AYSR-5, Shinto Metal Industries, Ltd., Japan). After being hot pressed, the samples were cooled to 30°C for 1 h while maintaining the pressure to suppress spring back. After pressing, the samples were dried by placing them in a 23°C, 0% RH environment with phosphorus pentoxide for at least one month until the moisture content was less than 1 wt.%.

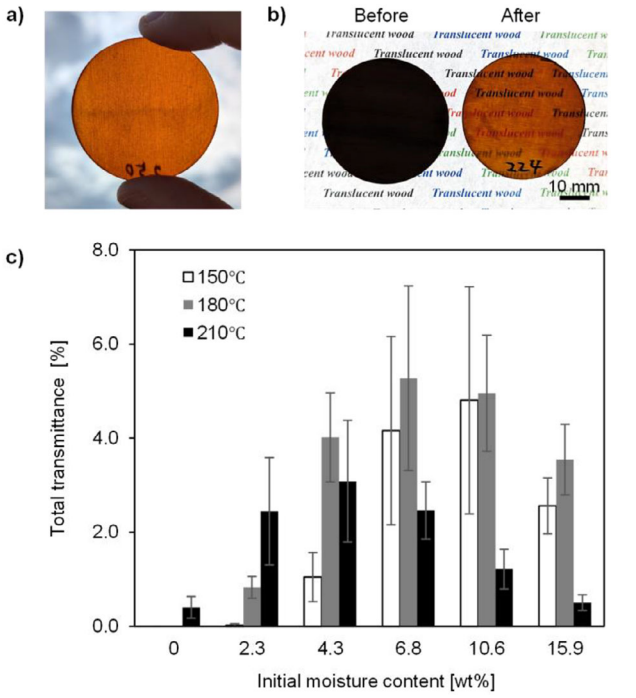

FIGURE 3 | (a) Appearance of a Wood Plate after Compression (Thickness: ~0.9 mm). (b) Comparison of the Appearance of Wood Plates before and after Compression. (c) Total Light Transmittance of Wood Plates after Compression (D65 Light Source).

2.2 | Characterization

The total transmittance for a D65 light source was measured using a haze meter (NDH 8000, Nihon Dempa Kogyo Co., Ltd., Japan). The total transmittance for visible light was measured using a UV–vis–NIR spectrophotometer (UV-3600 Plus, Shimadzu Corp., Japan). Three-point bending tests were performed at 23°C and 50% RH using a universal testing machine (model 3365, Instron, USA) equipped with a 5 kN load cell. Three samples with dimensions of 0.9 mm × 10 mm × 35 mm were subjected to the bending tests. The span length and crosshead speed were set to 20 mm and 7.8 mm/min, respectively. The Shore hardness of each sample was measured using a Type-D durometer (GS-720N, Teclock, Japan).

3 | Results

3.1 | Moisture Content and Bulk Density of Wood Plates Before and After Compression

In this work, Japanese cypress, a softwood, was used as the model material. Wood plates with a thickness of 3 mm and a diameter of 40 mm were kept in different RH environments to adjust the moisture content to 2.3–15.9 wt.% (Figure S1). After the moisture content was adjusted, the wood plates were sandwiched between PTFE plates, set in a stainless-steel compression jig, and pressed at 40 MPa for 10 min (Figure 1a). The radial (R) direction was selected for compression. The pressing temperature was set to 150°C, 180°C, or 210°C. The PTFE plates were used as backing material to apply a uniform pressure to the entire sample and as sealing material to prevent drying during pressing. As a result, the moisture content remained almost unchanged after hot pressing (Figure 1b–d). This behavior occurred because the PTFE plate deformed slightly during pressing, creating a semi-sealed state inside the jig, which suppressed evaporation of moisture from the wood. After hot pressing, the thickness of the wood plates decreased from ~3 to ~0.9 mm (Figure 2a; Figure S2). The bulk density before pressing was approximately 0.43 g/cm^3, consistent with previously reported values (Figure 2b–d) [28]. The density after hot pressing ranged from 1.1 to 1.38 g/cm^3, and a tendency toward increased bulk density with increasing moisture content and temperature was observed (Figure 2b–d). These trends are consistent with those in previous reports and can be explained by softening of lignin and hemicellulose and deformation of wood cell walls due to heat, moisture, and pressure [20–23].

3.2 | Optical Properties of Translucent Wood

Next, the light transmittance of the compressed wood plates was evaluated. First, as a screening test for the light transmittance after the samples were subjected to different compression conditions, the total light transmittance for the D65 light source was measured. Interestingly, the wood plates exhibited light transmittance after compression (Figures 3 and 4). In this study, the wood plates compressed at 180°C with an initial moisture content of 6.8 wt.% presented the highest light transmittance. In comparison, for 150°C hot pressing, the total light transmittance peak tended to shift toward a high moisture content (Figure 3c). In contrast, for 210°C pressing, the peak shifted toward a low moisture content. The reflectance of translucent wood decreased with increasing hot-press temperature (Figure S3). At low temperatures and low moisture contents, lignin and hemicellulose did not sufficiently soften, resulting in reduced light transmission due to internal voids [14, 29]. In contrast, at high temperatures and high moisture contents, while softening progressed well, high-temperature treatment caused discoloration, which increased light absorption in the visible light range (Figures 2 and 3). It is well known that discoloration associated with heat treatment of wood is caused by the condensation of lignin or thermal decomposition of hemicellulose [30–34]. There is considered to be a tradeoff between the reduction in internal voids caused by compression and the increase in light absorption. The results suggest that compression at 180°C and at an initial moisture content of 6.8 wt.% corresponds to the most balanced conditions for preparing translucent wood.

Under the compression conditions used in this study, the moisture content of the wood plates remained almost unchanged after compression (Figure 1). To confirm the effect of the moisture content in wood on light transmittance, changes in light transmittance due to drying were investigated. After the samples compressed at 180°C were dried until their moisture content was 1 wt.% or less, the total light transmittance was measured. Although the light transmittance slightly decreased after drying, the wood plates retained their light transmittance (Figures 5 and 6). However, the wood plates with high moisture contents presented a significant decrease in the total light transmittance upon drying (Figure 5). Compared with those with a low moisture content, these wooden plates showed a significant decrease in the bulk density after drying, suggesting an increase in internal voids (Figure 7). These results suggest that adjustment of the

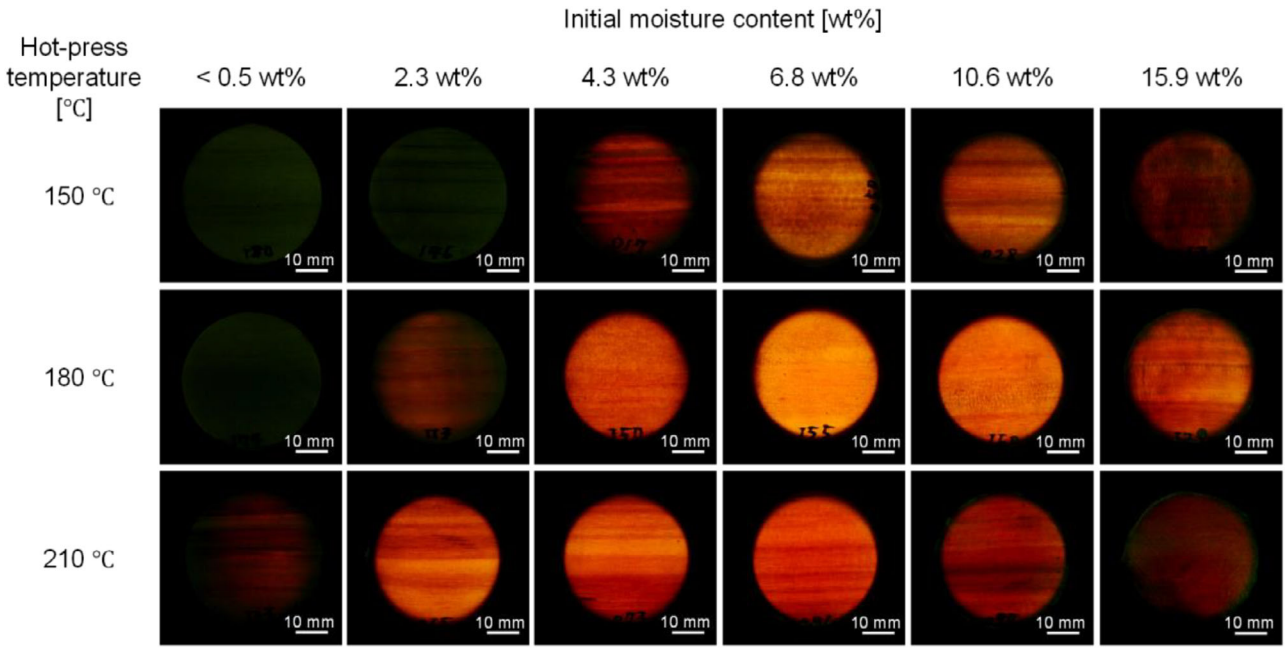

FIGURE 4 | Comparison of the Light Transmittance of Wood Plates Compressed Under Different Conditions (Thickness: ~0.9 mm).

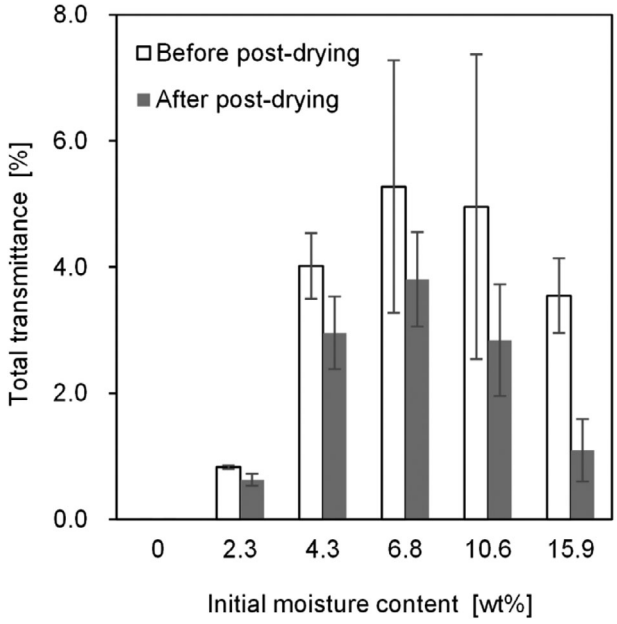

FIGURE 5 | Total Light Transmittance after Compression and Drying (Thickness: ~0.9 mm).

initial moisture content is important in terms of stability after compression and that managing the moisture content after compression is also important.

The total light transmittance of the translucent wood prepared in this study with a thickness of ~0.9 mm was ~15.8% at 600 nm (Figure 8; Figure S4). Significant improvements in light transmittance were observed after compression, and the translucent wood presented greater light transmittance than the original wood plates of similar thickness (Figure 3b; Figure S4). Additionally, the light transmittance depends on the thickness, as the factors inhibiting light transmittance include absorption by lignin and the nonuniform structure (voids, etc.) of compressed wood [14, 15, 29, 30]. For example, when 1 mm thick wood plates were compressed under the same conditions such that the thickness after pressing was ~0.3 mm, the total light transmittance at 600 nm increased to ~60.0% (Figure 8). The transmittance of light with a wavelength of 500 nm or higher was equivalent to that reported for lignocellulose films [16–19]. In addition, the translucent wood effectively absorbed light below 500 nm. This characteristic is common to all lignocellulosic materials and is promising for their use as light-controlling materials that block blue light and UV light, which are harmful to humans [16–19].

3.3 | Mechanical Properties of Translucent Wood and Applicability for Other Tree Species

The resulting translucent wood exhibited excellent mechanical properties. The Young's modulus and strength measured by a three-point bending test of translucent wood prepared from Japanese cypress in the fiber direction were 31 GPa and 368 MPa, respectively, surpassing those of common plastics and metal alloys such as duralumin (Figure S5) [32]. In addition, the Shore hardness (Durometer Type D) increased from 54 before compression to 90 after compression (Table S1). The hardness after compression exceeded that of hardwood (e.g., Maple) and was equivalent to that of acrylic plates (Table S1). This result indicated that softwood was converted into a hard material by simple compression.

The improvement in light transmittance through compression was also effective for other tree species. The moisture contents of wood plates (Japanese cedar, cherry, and maple) with a thickness of ~1 mm were adjusted to ~6.8 wt.%, and the wood plates were hot pressed at 180°C and 40 MPa for 10 min. The thicknesses after pressing were 0.3–0.6 mm, and the compressed wood plates

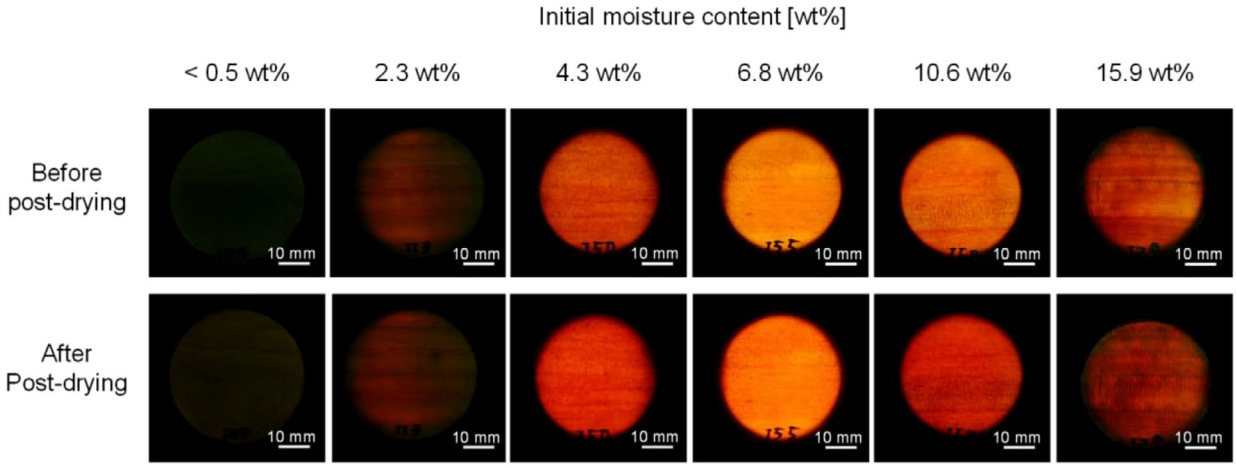

FIGURE 6 | Comparison of Light Transmittance after Compression and Drying (Thickness: ~0.9 mm).

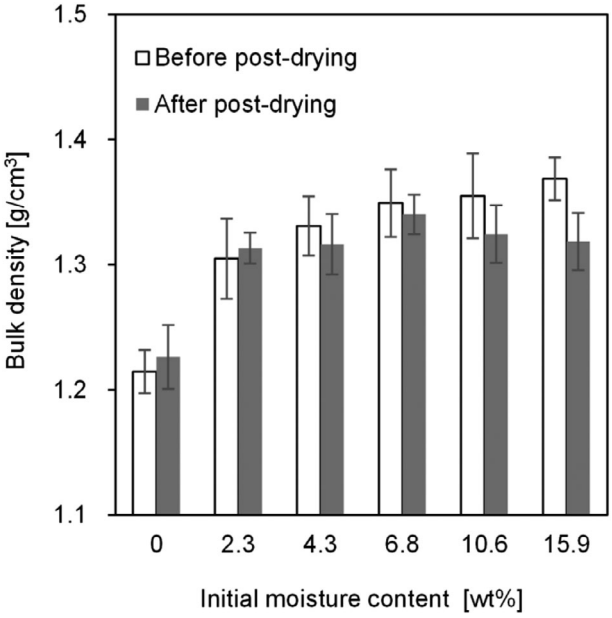

FIGURE 7 | Bulk Density of Compressed Wood Plates before and after Drying.

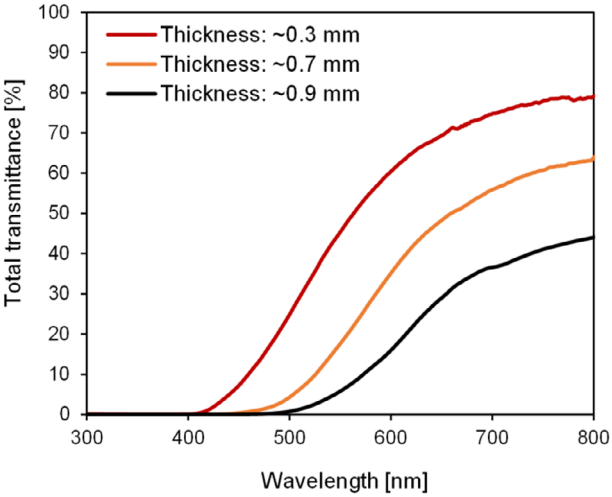

FIGURE 8 | Total Light Transmittance of Translucent Wood of Different Thicknesses.

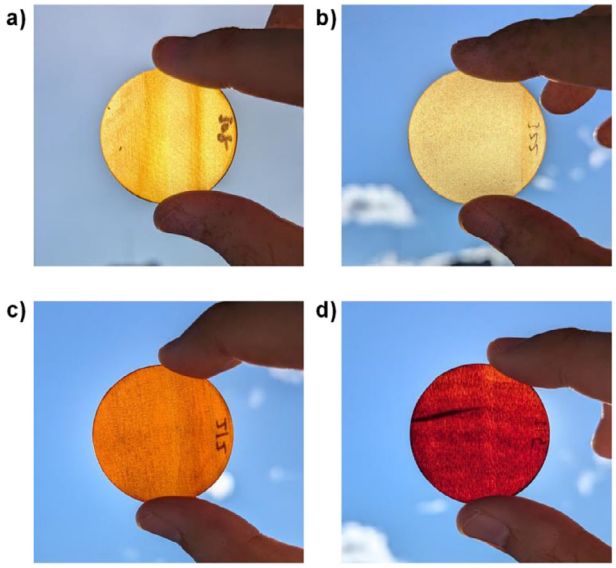

FIGURE 9 | Translucent Wood Prepared from Different Tree Species: (a) Japanese Cypress (thickness: ~0.3 mm), (b) Japanese Cedar (thickness: ~0.3 mm), (c) Cherry (thickness: ~0.5 mm), and (d) Maple (thickness: ~0.6 mm).

exhibited light transmission (Figure 9; Figures S6 and S7). In particular, the effect was significant for Japanese cedar, which is a softwood similar to Japanese cypress, and it exhibited similar light transmittance to that of Japanese cypress. In contrast, the increase in light transmission was limited for the hardwood's cherry and maple. The differences in light transmission depending on the tree species are likely caused by differences in the hierarchical structure, initial density, and composition of the wood. Further research is needed to optimize the compression conditions according to the tree species.

4 | Conclusion

In conclusion, we proposed a simple compression process that enables the preparation of translucent wood without chemical treatment. We focused on the effects of the initial moisture content and pressing temperature on wood and succeeded in

significantly improving the light transmittance of wood, which is normally opaque, by controlling these factors. In addition, this method was effective for tree species other than Japanese cypress, which was used as a model material, and improvements in light transmission were confirmed. This study provides a new perspective on the development of transparent wood, which has typically been focused on chemical treatment, by highlighting the importance of the initial moisture content and pressing temperature as fundamental parameters, thereby accelerating the development of sustainable functional optical materials.

Author Contributions

T. K. was responsible for the project idea, manuscript preparation, and experiments. A. M. contributed to the experiments. S. I., H. K., and M. N. provided critical feedback on the results and contributed to data interpretation. All the authors provided feedback and endorsed the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting file: mame70095-sup-0001-SuppMat.docx