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# On the Effect of Heat Treatments on the Adhesion, Finishing and Decay Resistance of Japanese cedar (*Cryptomeria japonica* D. Don) and Formosa acacia (*Acacia confusa* Merr.(Leguminosae))

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**Abstract:** In Taiwan, it is important to maintain sustainable development of the forestry industry in order to raise the self-sufficiency of domestic timber. Japanese cedar (*Cryptomeria* D. Don and Formosa acacia (*Acacia confusa* Merr.(Leguminosae)) have abundant storage options and are the potential candidates for this purpose. Heat treatment is a new environment-friendly method used to enhance the dimensional stability and durability of wood. On treatment, a surface with new characteristics is produced because of wood component changes. Consequently, an inactivated surface and a weak boundary layer are generated, and the wettability for adhesives and coatings is reduced. Furthermore, it decreases the pH value of the wood surface, and results in delay or acceleration during the curing of adhesives. This phenomenon must be paid attention to for practical applications of heat-treated wood. Ideal heat-treated conditions of *C. japonica* and *A. confusa* woods with productive parameters such as temperature, holding time, heating rate, and thicknesses of wood were identified in our previous study. In this research work, we focus on the normal shear strength of heat-treated wood with adhesives such as urea-formaldehyde resin (UF) and polyvinyl acetate (PVAc), and the finishing performances of heat-treated wood with polyurethane (PU) and nitrocellulose lacquer (NC) coatings as well as assessing the decay-resistance of heat-treated wood. The results show that heat-treated wood had a better decay resistance than untreated wood. The mass decrease of heat-treated wood was only 1/3 or even less than the untreated wood. The normal shear strength of heat-treated wood with UF and PVAc decreased from 99% to 72% compared to the untreated wood, but the wood failure of heat-treated wood was higher than that of the untreated one. Furthermore, the adhesion and impact resistance of wood finished by PU and NC coatings showed no difference between the heat-treated wood and untreated wood. The finished heat-treated wood had a superior durability and better gloss retention and lightfastness than that of the untreated wood.

**Keywords:** heat-treated wood; decay resistance; adhesion; finishing

## 1. Introduction

Wood is an excellent and environment-friendly renewable material, which possesses good mechanical strength, low thermal expansion, aesthetic appeal and is easy to process for a variety of applications. Owing to these characteristics and its abundance, wood has been used for building, structure, furniture, and other objects that meet the demands of people in the modern world. However, being a biological material, it is susceptible to warping, splitting, photodegradation and biodeterioration, highlighting natural anisotropic and hygroscopic characteristics. These defects restrict its use in certain applications. It is thus necessary to enhance its dimensional stability and

durability to expand applications of the material. Wood treatments include chemical modification methods such as esterification and etherification [1,2] and using chromated copper arsenate (CCA) or alkaline copper quaternary ammonium compounds (ACQ) preservatives [3–5], which, however, cause environment concerns.

A new environment-friendly method used to enhance the dimensional stability and durability of wood is heat treatment. This technique is suitable for wood due to its non-toxic characteristics. In heat-treated wood, physical and chemical properties such as density, equilibrium moisture content, roughness, and strength are altered by submitting wood to high temperatures (150–230 °C) in an inert or restricted air environment. The dimensional characteristics and decay resistance of wood can be improved and the treatment results in a uniform dark color. However, its strength is decreased as compared to those of untreated control samples. The use of heat treatment as a wood modification method and its products have increased significantly over the last decade and have been well studied [6–15]. However, in practical utilization, the adhesion, finishing, and decay resistance performances of heat-treated wood have not been examined enough.

After heat treatment, new surface characteristics are produced because of wood component changes. The results affect the wettability of heat-treated wood and further affect its bonding strength [11,12,16]. In addition, the hydrophobic extractives and volatile organic compounds that are derived from the depolymerization of wood components, especially from hemi-cellulose [17], moved to or deposited on the wood surface. As a result, an inactivated wood surface and a weak boundary layer were produced. Consequently, the wettability of wood for adhesives and coatings [18–21] was reduced. Furthermore, it decreases the pH value of wood surface and results in delay or acceleration during the curing of adhesives [18,22]. This phenomenon must be paid attention to for practical applications of heat-treated wood.

In Taiwan, the domestic timber yield accounts for merely 0.5% of its timber consumption, which implicates that raw timber materials are almost completely imported. In view of this, relevant policies—such as enlarging planting area and increasing the utilization of domestic woods—should be formulated to raise the self-sufficiency of domestic timber, which is vital for Taiwan to maintain sustainable development of its forestry industry. Japanese cedar (*Cryptomeria japonica* D. Don), a softwood, and Formosa acacia (*Acacia confusa* Merr.(Leguminosae)), a hardwood, have abundant storage options and are potential candidates for this purpose. The total cultivation area of *C. japonica* in Taiwan is 39,100 ha (or 2.68%) and of *A. confusa* is 21,200 ha (or 1.43%) [23]. *C. japonica* and *A. confusa* woods be used for making furniture, building, structures and other objects.

In our previous study, the heat treatments of *C. japonica* and *A. confusa* woods with moisture content of 12% were performed using a steel kiln under an N<sub>2</sub> atmosphere. The parameters of heat-treated conditions such as temperature (130, 160, 190, 220, 250 and 280 °C), holding times (1, 2 and 3 h), thicknesses (30, 50 and 70 mm) and heating rates (10, 20 and 30 °C/h) were examined for the best performances of heat-treated woods. The results indicated that the best heat-treated conditions for the superior of dimensional stability, hardness and static bending strength of woods included heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and holding time of 2 h for *C. japonica* and 3 h for *A. confusa* [24]. Furthermore, for practical utilization, in this report, we focus on the normal shear strength of heated *C. japonica* and *A. confusa* woods with urea-formaldehyde resin (UF) and polyvinyl acetate (PVAc) wood adhesives, the performances of finishing properties of woods with polyurethane (PU) and nitrocellulose lacquer (NC) wood coatings, and decay-resistance of woods by soil block test.

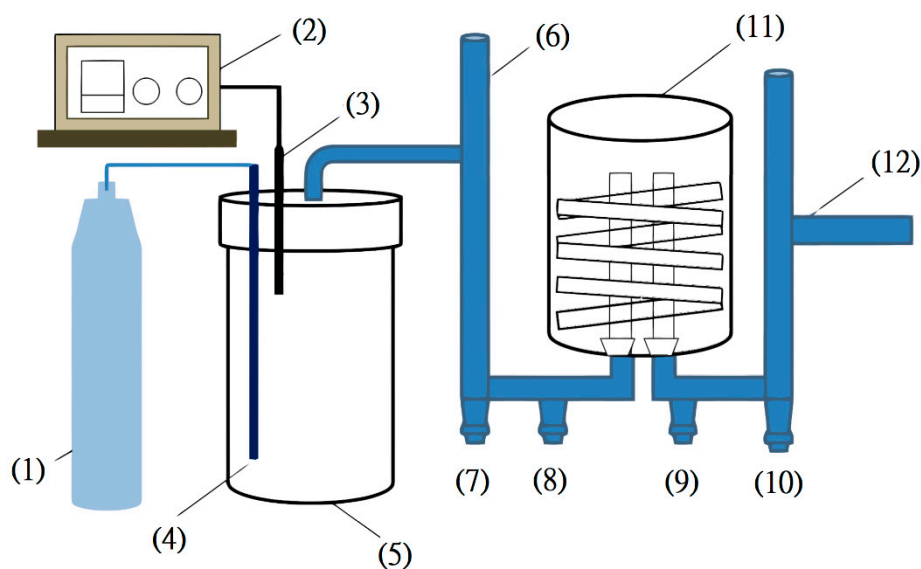
## 2. Materials and Methods

20–30-year-old *A. confusa* and *C. japonica* woods were obtained from Hui-Sun Forest Station of the Experimental Forest of National Chung Hsing University in Nan-Tou County, Taiwan. The wood was cut into the desired dimensions after air-drying and then conditioned for one week at 20 °C and 65% relative humidity. The adhesives, including urea-formaldehyde resin (UF) with a solid content of 65%,

was purchased from Wood Glue Industrial Co., Ltd., Tainan, Taiwan. Polyvinyl acetate (PVAc) was supplied by Nan Pao Resins Chemical Co., Ltd., Tainan, Taiwan. The coatings, including two-package polyurethane resin (PU) and nitrocellulose lacquer (NC), were purchased from Yan Chang Trading Co., Ltd., Taichung, Taiwan.

### 2.1. Heated Treatment of Wood

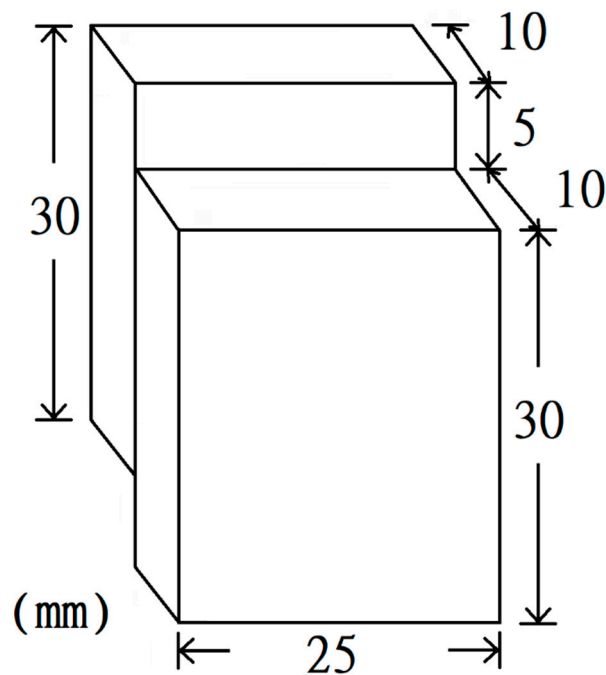
*A. confusa* and *C. japonica* with dimensions of 50 mm (T) × 50 mm (R) × 330 mm (L) and moisture content of 12% were placed in a stainless steel cylindrical equipment (390 mm diameter and 800 mm height), as shown in Figure 1. The autoclave body was flushed with a continuous N<sub>2</sub> gas flow first with a flowing rate of 500 mL/min for 30 min and then the flowing rate was adjusted to 50 mL/min for the heated procedure. The temperature was first heated from room temperature to 100 °C at a heating rate of 10 °C/min and holding time of 6 h and then heated to 190 °C under the same heating rate and holding time of 2 h for *C. japonica* wood and 3 h for *A. confusa* wood. After the heated treatment, the wood samples were cooled to room temperature and conditioned for one week at 20 °C and 65% relative humidity. The moisture content, density, environmental moisture content (at 40 °C, a relative humidity of 65%), contact angle of radial section, modulus of rupture were measured in our previous study [24], and the results were 2.6%, 387 kg/m<sup>3</sup>, 2.7%, 23.4%, 57.2 MPa for *C. japonica* heat-treated wood, and 2.6%, 684 kg/m<sup>3</sup>, 5.4%, 37.8%, 44.4 MPa for *A. confusa* heat-treated wood.



**Figure 1.** Schematic diagram of the heat-treated equipment. (1) N<sub>2</sub> cylinder, (2) Controller, (3) Thermocouple, (4) Air supply tube, (5) Heat-treated body, (6) Condenser, (7–10) Liquid-collecting vessels, (11) Water cooling tower, (12) Exhauster.

### 2.2. Compression Shear Bonding Strength of Heat-Treated Wood

The shear bonding strength of heat-treated wood specimens were measured by compression loading in accordance with Chinese National Standards (CNS) 5809. The heat-treated and untreated woods were cut into thickness of 10 mm specimens and the out-layer with radial section of the heat-treated wood was as a glue surface. The UF resin (with adding 1% NH<sub>4</sub>Cl as a catalyst) and PVAc were applied on both sides of the interface (200 g/m<sup>2</sup> for each layer), respectively. The specimens were pressed by compression molding machine at room temperature and pressure of 1.47 MPa for 48 h. After conditioning at room temperature for 48 h, the glued samples were cut into 30 mm (L) × 25 mm (R) × 20 mm (T) as shown in Figure 2. Normal shear strength test of the specimens was conducted with a Universal Testing Machine (Shimadzu UEH-10, SHIMADZU Co., Kyoto, Japan) at a crosshead speed of 1 mm/min with duplicates of 10, and wood failure was noted.



**Figure 2.** Dimension of testing sample for the compression shear bonding strength test.

### 2.3. Heat-Treated Wood Finishing and Characterization of Finishing Performances

The specimens for wood finishing were quarter-sawed, and had a dimension around 15 cm (L)  $\times$  10 cm (R)  $\times$  1.5 cm (T). The viscosity of 2-package PU coating (polyol mixed with aliphatic isocyanate hardener by wt. of 1:1) and NC lacquer were adjusted to 20 s with thinner using No. 4 Ford cup at room temperature. The two coatings were finished on the heat-treated and untreated woods, respectively, by using an air spray gun with the proper ratio of compressed air and fluid coatings to obtain a smooth pattern of spray flow, and thickness of films. The thickness of the dry film on the wood specimens surface were 100  $\mu$ m and 60  $\mu$ m for the PU coating and NC lacquer, respectively. The finished specimens were then reconditioned at room temperature for 1 week prior to examination of the properties of the films.

The adhesion of tested films was determined by the cross-cut method according to CNS K 6800 with duplicates of 3; the best adhesion was 10 grade followed by 8, 6, 4, 2 and 0 grade. The impact resistance of the films was determined based on the striking height of the finished wood panels that do not crack on a knowing falling weight of 300 g and impact hammer diameter of 1/2 inch by using a Dupont Impact Tester IM-601 (DU PONT Co., Wilmington, DE, USA) according to American Society for Testing and Materials (ASTM) D5420. The gloss of films finished on wood and parallel to grain was detected by using Dr. Lange Reflectometer 60° Gloss Meter (DR LANGE Co., Dusseldorf, Germany) according to Deutsches Institut für Normung & International Organization for Standardization (DIN ISO) 4630 with duplicates of 10. The durability of films was evaluated using hot and cold cycling tests, in which one tested cycle of the specimens were first placed them into  $-20$  °C refrigerator for 2 h, and then transferred to  $50$  °C oven for another 2 h according to CNS15200-7-4. The cycle number was recorded if the sample film cracked. If the films were intact after the cycling test, gloss retention of film was measured.

The lightfastness of films finished on wood was carried out with a Paint Coating Fade Meter (SUGA TEST INSTRUMENTS Co., Tokyo, Japan), the light source was mercury light (H400-F) and chamber temperature was at  $32 \pm 4$  °C. After 100 h exposure, the changes in color of the specimens were measured with nine points on the radial section using a spectrophotometer (CM-3600d, Minolta, Osaka, Japan) fitted with a D65 light source with a measuring angle of  $10^\circ$  and a test-window diameter of 8 mm. The tristimulus values X, Y, and Z of all specimens were obtained directly from the colormeter.

The brightness ( $L^*$ ), redness-greenness ( $a^*$ ), and yellowness-blueness ( $b^*$ ) color parameters were then computed according to the Commission internationale de l'éclairage (CIE) 1976  $L^*a^*b^*$  color system, followed by calculating the brightness difference ( $\Delta L^*$ ), color difference ( $\Delta E^*$ ) and yellowness difference ( $\Delta YI$ , calculated by ASTM E313) directly from the Minolta Managed Content Services (MCS) software system (version of 3.1, Newport Beach, CA, USA).

#### 2.4. Soil Block Test for Decay Resistance of Heat-Treated Woods

The soil block test was performed, with partial reference to the AWPA E14-94 standard. The samples were cut into a size of 200 mm (L)  $\times$  20 mm (R)  $\times$  20 mm (T) with duplicates of 5. The test samples were buried upright with 200 mm length of the samples in the ground and each sample was installed 50 mm apart. The testing site was located in National Chung Hsing University, Taichung, Taiwan. The surface layer ca. 100 mm of the soil is humus and underlayer is yellow-brown color soil. The experiment was performed for 50 days and the weight loss, brightness difference ( $\Delta L^*$ ) and color difference ( $\Delta E^*$ ) of the test samples were assessed.

### 3. Results and Discussion

#### 3.1. The Normal Shear Strength

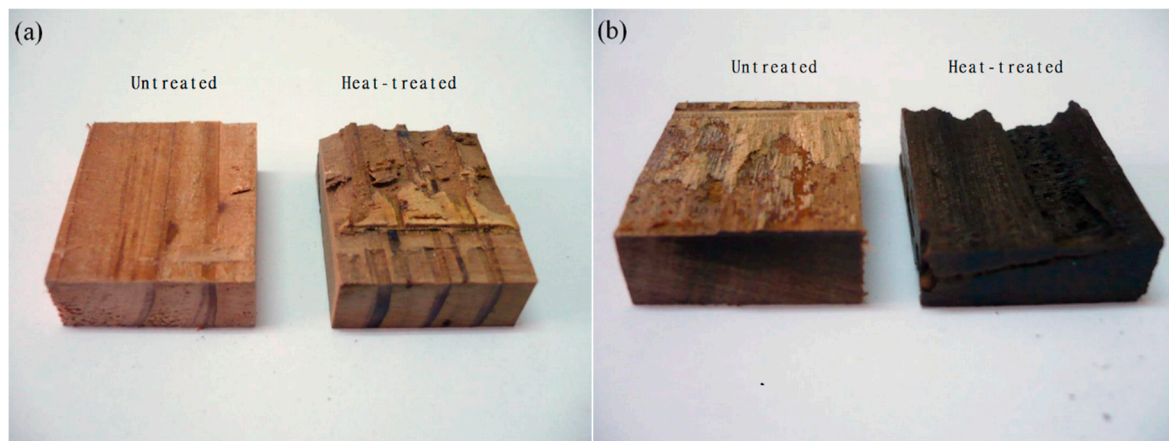
The normal shear strength of heat-treated and untreated *C. japonica* and *A. confusa* wood with UF and PVAc adhesives are listed in Table 1. For UF adhesive, the shear strength of heat-treated *C. japonica* and *A. confusa* woods were 7.66 and 13.98 MPa, respectively, slightly lower than those of untreated woods at 7.73 and 19.50 MPa, respectively. The results may be due to preferential degradation of the less-ordered molecules of amorphous cellulose and hemi-cellulose with heat-treatment, and the increase of the crystallinity of cellulose as well as the affecting of wettability of UF adhesive on the heat-treated wood surface [13,25]. It also may be caused by the extractives of wood migrating to the surface with higher temperature heat treatment, which affected the wettability of the UF adhesive [20,26,27]. In addition, the decomposition products during the heat-treated processing (such as acidic components including acetic acid and formic acid) decrease the pH value on the wood surface, which accelerate the curing of the UF adhesive and further reduce the gluing ability of wood [20,28]. The wood failure of heat-treated *C. japonica* was 90% and was higher than the untreated one at 40%. The appearance of wood failure occurred in the wood itself and not in the interface of the glue layer, as shown in Figure 3. This result was due to the degradation of hemi-cellulose and cellulose of wood during the heat-treated processing and the decrease of the hardness as well as the brittle surface of heat-treated wood [29,30]. Similar results were also obtained for heat-treated *A. confusa* wood with wood failure of 100% and untreated wood of 80%.

**Table 1.** Normal shear strength of untreated and treated Japanese cedar (*Cryptomeria japonica* D. Don) and Formosa acacia (*Acacia confusa* Merr.(Leguminosae)) wood with urea-formaldehyde resin (UF) and polyvinyl acetate (PVAc) adhesives.

Wood		Shear Strength (MPa)	
		UF	PVAc
<i>C. japonica</i>	Untreated	7.73 $\pm$ 0.35 (40) <sup>2</sup>	8.25 $\pm$ 0.30 (90)
	Heat-treated <sup>1</sup>	7.66 $\pm$ 0.33 (90)	7.43 $\pm$ 0.33 (100)
<i>A. confusa</i>	Untreated	19.50 $\pm$ 0.22 (80)	15.39 $\pm$ 0.31 (20)
	Heat-treated	13.98 $\pm$ 0.30 (100)	11.39 $\pm$ 1.05 (40)

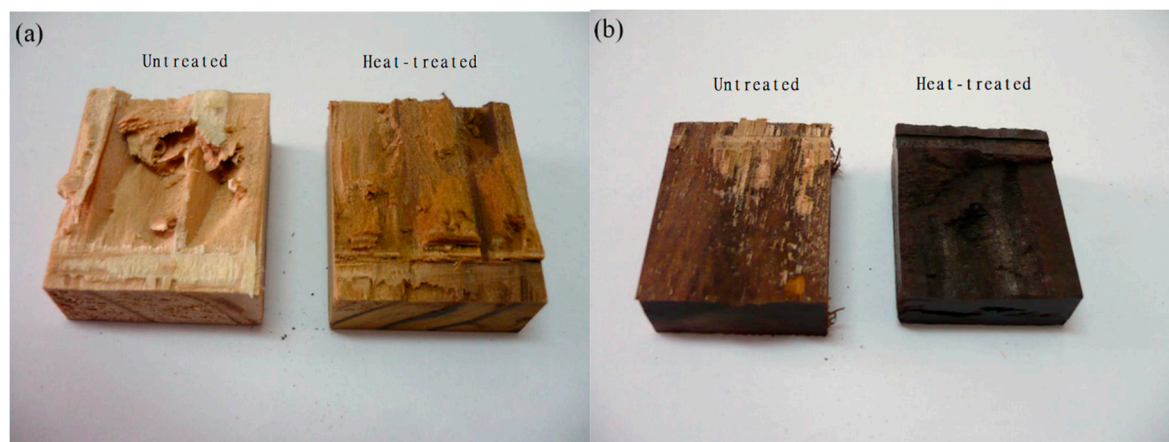
<sup>1</sup> Heat-treated conditions are heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and holding time of 2 h for *C. japonica* and 3 h for *A. confusa*. <sup>2</sup> represents wood failure (%).





**Figure 3.** Appearance of untreated and heat-treated Japanese cedar (*Cryptomeria japonica* D. Don) (a) and Formosa acacia (*Acacia confusa* Merr.(Leguminosae)) (b) wood with urea-formaldehyde resin (UF) adhesive after the shear strength test.

For the PVAc adhesive, the similar results of adhesion performances were as the UF adhesive. The shear strength of heat-treated *C. japonica* and *A. confusa* wood was 7.43 and 11.39 MPa, which was lower than that of untreated wood at 8.25 and 15.39 MPa, respectively. However, the wood failure of heat-treated *C. japonica* and *A. confusa* wood was 100 and 40% and was higher than that of untreated ones at 90 and 20%, respectively. The appearances of untreated and heat-treated *C. japonica* (a) and *A. confusa* (b) wood with PVAc adhesives after normal shear strength test are as shown in Figure 4.



**Figure 4.** Appearances of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) (a) and Formosa acacia (*Acacia confusa*) (b) wood with polyvinyl acetate (PVAc) adhesive after the normal shear strength test.

### 3.2. The Finishing Performances

The appearance, adhesion and impact resistance of untreated and heat-treated *C. japonica* and *A. confusa* wood after PU and NC lacquer finishing are shown in Table 2, respectively. The result showed that the heated wood had a more even and darker color than the untreated wood. The adhesion of both PU and NC lacquer films of heat-treated and untreated *C. japonica* and *A. confusa* was grade 10, showing excellent adhesion. The striking height was the same of 10 cm for PU finished untreated and heat-treated *C. japonica*. However, it was 40 and 35 cm for untreated and heat-treated *A. confusa*, respectively, highlighting that the impact resistance of heat-treated *A. confusa* was slightly inferior to that of untreated wood. This may be due to the generation of a hydrophobic surface after heat treatment, resulting in a decrease of wettability for coatings. In addition, the NC lacquer finished on

untreated or heat-treated *C. japonica* and *A. confusa* wood had the same values of 5 cm. In summary, the adhesion and impact resistance of heat-treated wood is similar to those of untreated wood for PU and NC lacquer finishing.

**Table 2.** Adhesion and impact resistance of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) (a) and Formosa acacia (*Acacia confusa*) wood finished with polyurethane (PU) and nitrocellulose lacquer (NC) coatings.

Wood		PU		NC	
		Adhesion (Grade)	Impact Resistance (cm)	Adhesion (Grade)	Impact Resistance (cm)
<i>C. japonica</i>	Untreated	10	10	10	5
	Heat-treated <sup>1</sup>	10	10	10	5
<i>A. confusa</i>	Untreated	10	40	10	30
	Heat-treated	10	35	10	30

<sup>1</sup> Heat-treated conditions are heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and the holding time of 2 h for *C. japonica* and 3 h for *A. confusa*.

The hot and cold cycling test and gloss retention of untreated and heat-treated *C. japonica* and *A. confusa* woods finished with PU and NC lacquer coatings are shown in Table 3. The results indicated that all samples were intact after 20 cycles of the hot and cold cycling test. However, the gloss retention of both heat-treated woods was higher than that of the untreated woods for both PU and NC lacquer finishing. Because the dimension stability of wood could be improved after heat-treatment, the gloss lowering of film derived from wood swelling and shrinkage during the hot and cold cycling test could be reduced.

**Table 3.** Cycling test and gloss retention of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) and Formosa acacia (*Acacia confusa*) wood finished with polyurethane (PU) and nitrocellulose lacquer (NC) coatings.

Wood		PU		NC	
		Cycling Test (Cycles)	Gloss Retention (%)	Cycling Test (cycles)	Gloss Retention (%)
<i>C. japonica</i>	Untreated	>20	93	>20	93
	Heat-treated <sup>1</sup>	>20	96	>20	100
<i>A. confusa</i>	Untreated	>20	90	>20	95
	Heat-treated	>20	100	>20	98

<sup>1</sup> Heat-treated conditions are heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and holding time of 2 h for *C. japonica* and 3 h for *A. confusa*.

The lightfastness of films finished on wood was carried out on a Paint Coating Fade Meter with 100 h exposure; the brightness difference ( $\Delta L^*$ ), color difference ( $\Delta E^*$ ) and yellowness difference ( $\Delta YI$ ) are listed in Tables 4 and 5. The light induced degradation of wood is mainly due to the photochemical radical reactions occurring in lignin and the generation of chromophoric groups. These structures are responsible for the wood color changes. For both PU and NC lacquer finishing, the  $\Delta E^*$  and  $\Delta YI$  values of heat-treated woods after UV-light irradiation were lower than those of untreated woods. During the heat-treatment of wood, the mainly thermal degradation occurs in hemicellulose and cellulose and the relative content of lignin increased in the heat-treated wood. The best photostability of heat-treated *C. japonica* and *A. confusa* woods' color could be partially explained by the increase of lignin stability by condensation during the heat-treatment [31]. Furthermore, the  $\Delta L^*$  values of heat-treated wood were higher than those of untreated woods, meaning the heat-treated woods possessed a brighter surface.

This may be due to the producing of more Stab lignin and less chromophoric groups of heat-treated wood after UV-light exposure. In addition, the  $\Delta E^*$  and  $\Delta YI$  values of both heat-treated and untreated woods finished with PU were lower than those with NC lacquer, showing that the PU finished wood had superior lightfastness.

**Table 4.** Lightfastness of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) and Formosa acacia (*Acacia confusa*) wood finished with polyurethane (PU) coating.

Wood		Brightness Difference ( $\Delta L^*$ )	Color Difference ( $\Delta E^*$ )	Yellowness Difference ( $\Delta YI$ )
<i>C. japonica</i>	Untreated	$-6.17 \pm 0.19$	$32.61 \pm 0.57$	$15.25 \pm 0.24$
	Heat-treated <sup>1</sup>	$-0.47 \pm 0.97$	$18.68 \pm 2.63$	$3.28 \pm 0.87$
<i>A. confusa</i>	Untreated	$-5.27 \pm 2.24$	$11.22 \pm 2.26$	$0.89 \pm 0.09$
	Heat-treated	$-0.25 \pm 0.23$	$1.70 \pm 0.66$	$0.07 \pm 0.15$

<sup>1</sup> Heat-treated conditions are heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and the holding time of 2 h for *C. japonica* and 3 h for *A. confusa*.

**Table 5.** Lightfastness of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) and Formosa acacia (*Acacia confusa*) wood finished with nitrocellulose lacquer (NC) coating.

Wood		Brightness Difference ( $\Delta L^*$ )	Color Difference ( $\Delta E^*$ )	Yellowness Difference ( $\Delta YI$ )
<i>C. japonica</i>	Untreated	$-8.28 \pm 0.87$	$63.63 \pm 1.67$	$23.42 \pm 1.00$
	Heat-treated <sup>1</sup>	$4.56 \pm 0.63$	$28.22 \pm 4.14$	$4.23 \pm 0.15$
<i>A. confusa</i>	Untreated	$-8.10 \pm 0.81$	$11.04 \pm 0.62$	$5.46 \pm 1.15$
	Heat-treated	$1.69 \pm 0.69$	$7.98 \pm 1.29$	$3.02 \pm 2.81$

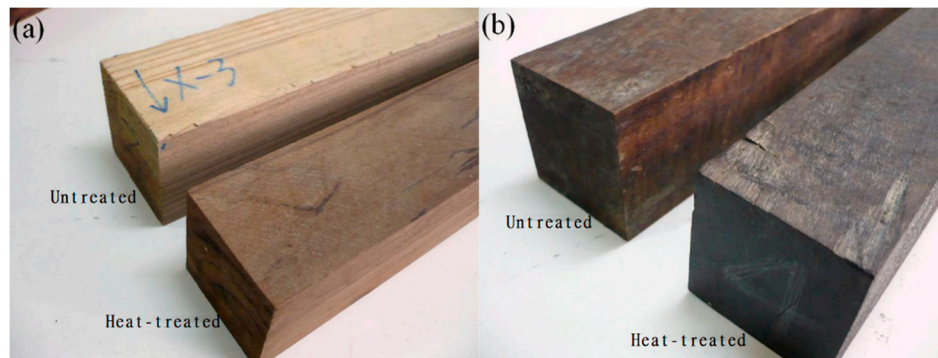
<sup>1</sup> Heat-treated conditions are heating rates of 10 °C/h, temperature of 190 °C, wood thickness of 50 mm, and the holding time of 2 h for *C. japonica* and 3 h for *A. confusa*.

### 3.3. Decay Resistance Performances

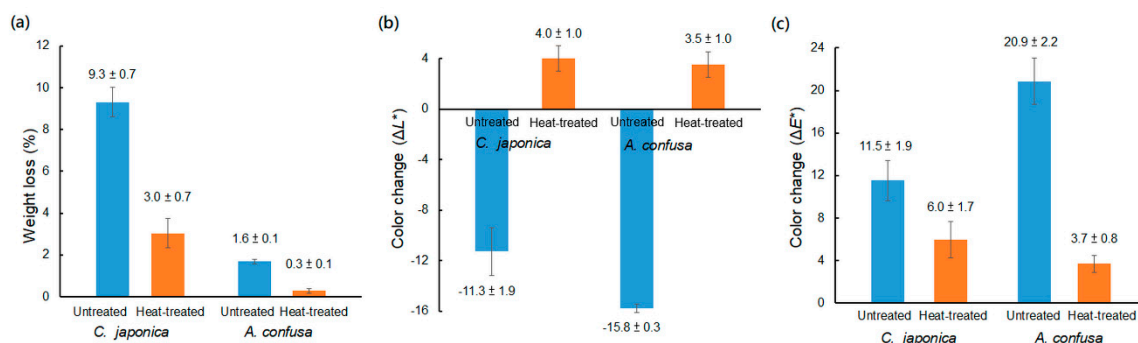
The appearances of untreated and heat-treated wood after a 50-day soil block decay resistance test is shown in Figure 5. The untreated woods showed an uneven color on the surface; there were several dark spots in the untreated *A. confusa*. However, the heat-treated wood had a uniform color after the decay resistance test. The weight loss and color changes of untreated and heat-treated *C. japonica* and *A. confusa* wood after the resistance test are drawn in Figure 6. The weight loss of untreated *C. japonica* and *A. confusa* were 9.3 and 1.6%, while that of the heat-treated woods were 3.0 and 0.3%, respectively. In a study by Vidholdová and Reinprecht [32], 21 tropical woods were attacked intentionally for six weeks by brown-rot fungus, resulting in 0.08% to 6.48% weight loss of the wood. However, our results showed higher values (1.6% and 9.3%). This phenomenon can be explained by multiple factors in our soil block test—moisture vibration changes, water flow, temperature cycles, and microorganisms. Nonetheless, the medium difference shows that the brown-rot fungus is a key factor in the decay. The results showed that the heat-treated wood had superior decay resistance properties due to the increase of hydrophobicity and decrease of water absorbency [17,25]. There also was a decrease in OH group content, which affected enzyme recognition blocking of the fungi [33], and reduced the hemicellulose content of the wood, therefore cutting down on the main nutritive source for the fungi [3,14,34]. In addition, the extractives of wood and pyrolysis products such as acidic or phenolic compounds, which have fungicidal efficiency, are deposited on the wood surface, suppressing the growth of fungi [20,27,33,35]. The color changes on  $\Delta L^*$  of untreated *C. japonica* and *A. confusa* were  $-11.3$  and  $-15.8$  after the 50-day block decay test, meaning a darkening color was observed on the untreated wood surface; the  $\Delta L^*$  was 4.0 and 3.5, respectively for the heat-treated wood, indicating a slight bright color obtained after the decay test. The  $\Delta E^*$  of the untreated woods



were 11.5 and 20.9, which was greater than the values of 5.9–0.5 from a previous study [32]. The  $\Delta E^*$  values of heat-treated wood were also lower than that of the untreated wood. The best photostability of heat-treated wood color could be partially explained by the increase of lignin stability by condensation during the heat-treatment, restricting light from attacking the lignin. In addition, the phenol content increased after heating and the antioxidant compounds can limit degradation caused by oxygen and radicals [31].



**Figure 5.** Appearances of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) (a) and Formosa acacia (*Acacia confusa*) (b) wood after the 50-day decay resistance test.



**Figure 6.** Weight loss (a) and color changes (b,c) of untreated and heat-treated Japanese cedar (*Cryptomeria japonica*) and Formosa acacia (*Acacia confusa*) wood after the 50-day decay resistance test.

#### 4. Conclusions

The results showed that the normal shear strength of heat-treated *C. japonica* and *A. confusa* with UF and PVAc adhesives was lower than that of untreated wood (the decrease is around 99% to 72%), but the wood failure of heat-treated wood was higher than that of the untreated one. Furthermore, the adhesion and impact resistance of heat-treated *C. japonica* and *A. confusa* finished with PU and NC coatings showed no difference with untreated wood. The finished heat-treated wood also showed superior durability and had better gloss retention and lightfastness than those of the untreated wood. The heat-treated wood also had better decay-resistance than untreated wood, ascertained by a soil block test. The weight loss of heat-treated *C. japonica* and *A. confusa* were 3.0% and 0.3%, respectively. Both values of mass decrease were only 32% and 19% compared to the untreated wood.

**Author Contributions:** Conceptualization, C.-W.C. and K.-T.L.; methodology, W.-L.K. and C.-W.C.; formal analysis, W.-L.K., C.-W.C. and K.-T.L.; investigation, W.-L.K.; data curation, C.-W.C. and W.-L.K.; writing—original draft preparation, K.-T.L.; writing—review and editing, C.-W.C. and K.T. Lu; supervision, K.-T.L.; project administration, K.-T.L.

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