

Effect of Artificial Weathering on the Properties of Industrial-Scale Thermally Modified Wood

Dong Xing,^{a,b} Siqun Wang,^b and Jian Li^{a,*}

Thermally modified wood is widely used in cladding, decking, and other construction projects that are meant for outdoor exposure. The purpose of this study was to investigate changes in the color, microstructure, and chemical composition of heat-treated, *Larix* spp. wood that was exposed to artificial weathering. In this study, accelerated weathering tests (UV and moisture) were conducted over a period of 3000 h. Photodegradation of both heat-treated and untreated wood was evaluated in terms of color, microstructure, and chemical changes that were characterized using scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy. Ultra-violet radiation caused the degradation of lignin and extractives of wood, resulting in an immediate color change of the wood. The SEM observation of the heat-treated wood showed deformations and cracks in both treated and untreated samples. Irradiation resulted in a pronounced reduction in the absorption intensity and broadening of the FTIR spectra. It was found that the industrial heat-treatment of wood products resulted in more color stability than untreated wood during the early stages of weathering. Thermal modification was found, however, was ineffective in improving the UV resistance wood over long-term photodegradation conditions.

Keywords: Heat-treated wood; Artificial weathering; Photodegradation; UV resistance; FTIR

Contact information: a: Key Laboratory of Bio-based Material Science and Technology, Northeast Forestry University, Harbin, Heilong Jiang province, China 150040; b: Center for Renewable Carbon, University of Tennessee, Knoxville, TN, USA 37996; *Corresponding author: nefulijian@163.com

INTRODUCTION

The use of heat-treated wood as an industrial product used for both indoor and outdoor applications is on the upswing. This highly desirable modification to wood maximizes its dimensional stability, durability, and attractive dark color (Nuopponen *et al.* 2003; Icel *et al.* 2015). Heat treatment process elements, such as duration of treatment, temperature of treatment, type of heating atmosphere, pressure, and catalysts vary (Shi *et al.* 2007). With the development of the manufacturing industry and controlling systems, thermal modifications to wood have resulted in several processes at the industrial level, such as Finland's Thermowood® (or Premium Wood), the Retification® process (Retiwood, New Option Wood, France), France's Le-Bois Perdure®, the Plato® process (Netherlands), and Oil-heat treatment (OHT®, Germany). Applications for heat-treated wood include furniture, parquetry, cladding, joinery, decorations, shutters, decking, and many others. Increased awareness of the existence and usefulness of wood products that do not contain any toxic preservatives has boosted the popularity of heat-treated wood in recent years.

Surface photodegradation of wood products, which is caused by the combined effects of ultraviolet (UV) and shorter wavelengths of visible radiation, heat, moisture,

atmospheric pollutants, and microorganisms, has been extensively studied (Chaouch *et al.* 2010; Tomak *et al.* 2014). Chemical analysis of wood surfaces indicates that irradiation causes the degradation of hemicellulose, lignin, and the depolymerisation of cellulose (Forsthuber *et al.* 2014). Photochemical reactions on wood surfaces include the complex degradation of extractives, the reduction of the methoxyl content of lignin, the dissociation of carbon-carbon bonds, and the generation of carbonyl-based chromophoric groups (Decker 2005). In most outdoor conditions, the day-night cycle of ultraviolet radiation and humidity poses many challenges, swiftly inducing photodegradation and depolymerisation of wood components (extractives, lignin, cellulose, and hemicellulose). Among the constituent wood polymers, lignin is the most sensitive to light and has a structure that is vulnerable to the absorption of ultraviolet/visible light because of the chromophoric groups. This leads to the breakage of weak chemical bonds and the subsequent fading, darkening, and cracking of wood products.

Of all exterior environmental factors, light contributes most to the weathering of wood above ground (Pandey and Pitman 2003). The precise pathways and mechanisms involved in complex photochemical reactions of wood are not yet clear (Abu-Sharkh and Hamid 2004). Heat-treated wood shows better color stability in the first stage of exposure to UV radiation and moisture than does untreated wood, which is probably attributed to the thermal modification of lignin-cellulose formation and the modified chromophoric lignin structure (Ayadi *et al.* 2003; Colom *et al.* 2003; Peng *et al.* 2015). A number of studies have been carried out on the wettability (Huang *et al.* 2012) and mechanical (Yildiz *et al.* 2013), physical (Podgorski *et al.* 1996), and chemical changes (Pizzo *et al.* 2015) to which heat-treated wood is susceptible, as a result of artificial or natural weathering (Rosu *et al.* 2010; Saha *et al.* 2013). Despite the tremendous utility of heat-treated wood in many circumstances, research into the weathering performance of industry-scale heat-treated wood products, with biomass gas as a shield atmosphere, has been scarce.

The aim of this study was to investigate the changes in the microstructure, chemical composition, and surface aesthetics of industrial-scale heat-treated wood after artificial weathering exposure over the following time periods: 24, 72, 120, 360, 720, 960, 1440, and 3000 h. The color stability, surface microstructure, and chemical composition of the wood were evaluated. Results of this research on a softwood variety (*Larix*) could provide a reliable performance indicator for heat-treated wood in outdoor conditions.

EXPERIMENTAL

Materials

Larix gmelinii (Rupr.) Kuzen is a fast-growing softwood species that is found across northern and eastern China. In this study, a 15-year-old *Larix gmelinii* tree was selected from a location in the Xiangfang District, Harbin, Heilongjiang Province of China. *Larix* spp. is one of the most commonly used species for furniture, decoration, and outdoor facilities in China because of its low price and extractives composition that make it resistant to exterior conditions; however, modification is often needed to compensate for its poor dimensional stability, weak durability, and aesthetic appearance.

All samples were taken from one log and cut into dimensions of 2000 × 100 × 20 mm in the longitudinal, tangential, and radial directions, respectively. The 12 specimens were initially conditioned at 103 °C for 48 h before heat treatment, and were then sealed in 12 plastic bags.

Methods

Heat treatment

In this study, the wood samples were heat-treated using the industrial method with biomass gas as both a shield environment and a heat-transfer medium. After the wood sawdust was ignited in the bottom of a chamber, biomass gas formed from the combustion and was then injected into the upper chamber for the heat-treatment process. The exhaust biomass gases from the heat treatment were passed through a non-thermal plasma air purifier.

Table 1. Heat Treatment Process

Sample No.	Species	Temp(°C)	Heating rate(°C/h)	Holding time(h)	Atoms	Number of samples
H0	<i>Larix spp.</i>	-	-	-	-	3
H1	<i>Larix spp.</i>	170	15	6	Biomass gas	3
H2	<i>Larix spp.</i>	190	15	6	Biomass gas	3
H3	<i>Larix spp.</i>	210	15	6	Biomass gas	3

The lumber pieces that were prepared for the thermal treatment were enclosed in the sealed chamber and treated from 170 to 210 °C for 6 h, respectively. Each heat treatment was repeated three times. The thermal treatment process is shown in Table 1. The treatment temperature was controlled to within ± 1.0 °C with 10 detective thermocouples distributed around the chamber. Then, all of the specimens were conditioned at an ambient temperature and relative humidity of $65 \pm 1.0\%$ until the artificial weathering test began.

Artificial weathering

Artificial weathering tests were conducted at the Key Laboratory of Bio-Based Material Science and Technology, Northeast Forestry University, Harbin, Heilong Jiang, China. The heat-treated and the untreated samples were exposed to cycles of ultraviolet light and moisture under controlled conditions in an Accelerated Weathering Tester (Model QUV/spray with Solar Eye Irradiance Control, Q-lab Corporation, Cleveland, OH, USA), which simulates dew and rain by condensing humidity. The tester can reproduce the damage that may occur to wood over months or years of outdoor conditions. The artificial cycle included 8 h of irradiation using the lamp UVA-340 light $0.77 \text{ W/m}^2/\text{nm}$ at 50 ± 3.0 °C black-panel temperatures, followed by 4 h of condensation (dew) at 40 ± 3.0 °C. Nine heat-treated and 3 untreated specimens were fixed on the specimen holder and the irradiation was interrupted after 20, 72, 120, 192, 360, 720, 1188, 1440, 2200, and 3000 h of exposure, respectively. Then, the 12 specimens were removed for the evaluation of changes in chemical and physical structure before and after artificial weathering.

Color measurements

Measurements of the surface color of the specimens were performed with a CM-2300 d spectrophotometer (D5003908, Konica Minolta Sensing, Inc., Japan) for different periods of artificial weathering exposure; the spectrophotometer was equipped with an integrating sphere according to the color system, CIE $L^*a^*b^*$ system (CIELAB) (International Commission on Illumination). Measurements were made over an 8 mm

diameter spot with 10 different tests on the tangential surfaces of the 12 specimens before and after weathering. The equipment was calibrated before each color measurement was recorded.

The three coordinates of CIELAB represent the lightness of the color, its position between red/magenta and green, and its position between yellow and blue, respectively. The color difference (ΔE) related a measurement to a known L^* , a^* , or b^* value that was calculated as a function of the artificial weathering time according to the following equations,

$$\Delta L_t^* = L_t^* - L_0^* \quad (1)$$

$$\Delta a_t^* = a_t^* - a_0^* \quad (2)$$

$$\Delta b_t^* = b_t^* - b_0^* \quad (3)$$

$$\Delta E = \sqrt{(\Delta L_t^*)^2 + (\Delta a_t^*)^2 + (\Delta b_t^*)^2} \quad (4)$$

where, L_0^* , a_0^* , and b_0^* represent the test values of specimens before artificial irradiation and L_t^* , a_t^* , and b_t^* denote the test values of specimens exposed to t hours of weathering.

Scanning electron microscopy (SEM) analysis

Scanning electron microscopy analysis was used to examine surface details before and after 3000 h of artificial weathering. The surface of specimens were split for the dimensions of $8 \times 8 \times 2$ mm and all blocks were sputter-coated (BAL-TEC SCD 005, Germany) with a gold layer for 140 sec and were mounted on standard aluminum stubs with electrically conductive paste. The specimens were scanned using an FEI Quanta 200 scanning electron microscope (Hillsboro, OR) at a 10-kV accelerating voltage. The temperature conditions were approximately 20 °C and the column vacuum stood at 0.83 torr.

Fourier transform infrared (FTIR) spectroscopy

The surfaces of the specimens were cut and ground. After grinding, specimens were dried at 105 °C for 24 h before pellet preparation. Approximately 2.3 ± 0.1 mg of the specimen was mixed with 250 ± 2 mg of the mixture, and this was used for preparing KBr pellets. The specimens were analyzed using FTIR (USA Nicolet Company Magna-IR 560 E.S.P) spectroscopy at a resolution of 4 cm^{-1} and 40 scans between wavenumbers of 4000 and 400 cm^{-1} . Measurements were performed on four replicates per specimen.

RESULTS AND DISCUSSION

Visual Observation

The color and visual changes observed during different exposure periods for both the control and heat-treated specimens are shown in Fig. 1. It was observed that the surfaces of all of the samples faded and became lighter immediately after the short-term artificial weathering. The light-induced photodegradation markedly reduced the integrity of both the heat-treated and untreated wood surfaces.

The color changes in the untreated specimens were much greater than those of the wood heat-treated for 360 h, showing that they resisted UV radiation better than the heat-treated samples. However, the surface color differences between the heat-treated and untreated samples became insignificant with long-term weathering exposure, which

accords with previous studies (Huang *et al.* 2013). With regards to the moisture spray section of artificial cycles, water stains were seen on the samples after 72 h of artificial weathering. The water stains on all of the samples became larger with increased artificial time because of the uptake and release of water. However, it was difficult to analyze these phenomena by visual observation alone. Further investigations were performed and are presented below.



Fig. 1. The visual observation of heat-treated and untreated *Larix* spp. surfaces during different artificial weathering periods

Microstructure Analysis using SEM

Microstructural changes in the wood surface properties were characterized using SEM. Figure 2 shows the SEM microstructure on the tangential surfaces of both the controls and the heat-treated wood samples before and after artificial weathering for 3000 h. In Fig. 2a, the untreated sample has intact cell walls and some easy-to-recognize damage caused by splitting; however, the heat treatment had only a slight effect on the cell wall structure (Figs. 2b-d); a previous heat treatment study yielded similar results (Yildiz *et al.* 2013), with cracks between the S1 and S2 layers, visible changes in the pits, and abrupt transitions between earlywood and latewood.

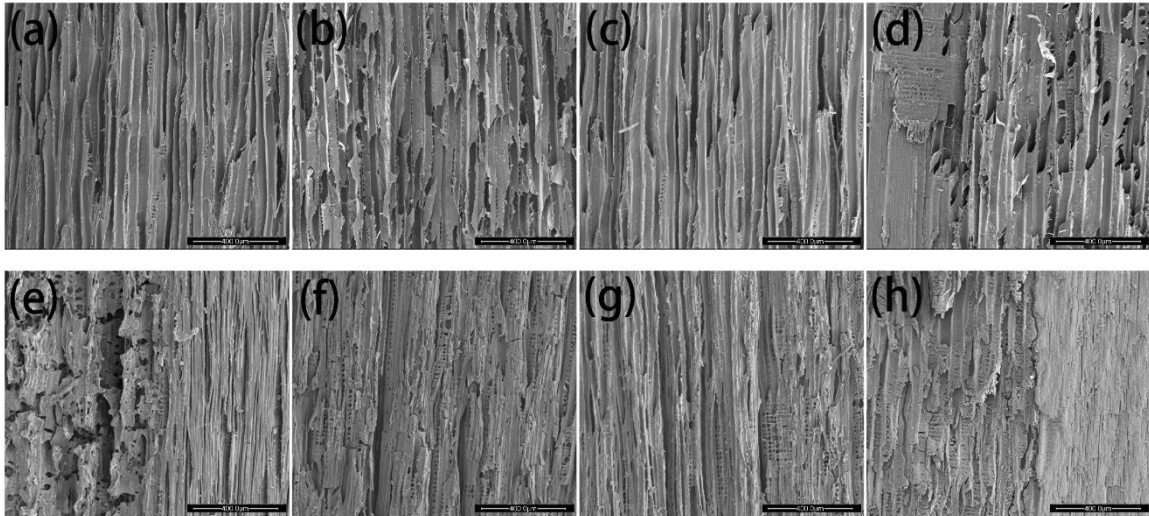


Fig. 2. SEM images of *Larix* spp. specimens before and after 3000 h of artificial weathering: (a-d) H0 to H3 before weathering; (e-h) H0 to H3 after weathering

The untreated wood surfaces became brittle and rough after 3000 h of artificial weathering (including UV treatment and moisture spray). In Fig. 2e, there are several apparent erosions of tracheids and partial disintegration of pits in the untreated specimen after weathering, findings that agreed with previous studies of wood surface deterioration after exposure to sunlight or UV light (Srinivas and Pandey 2012).

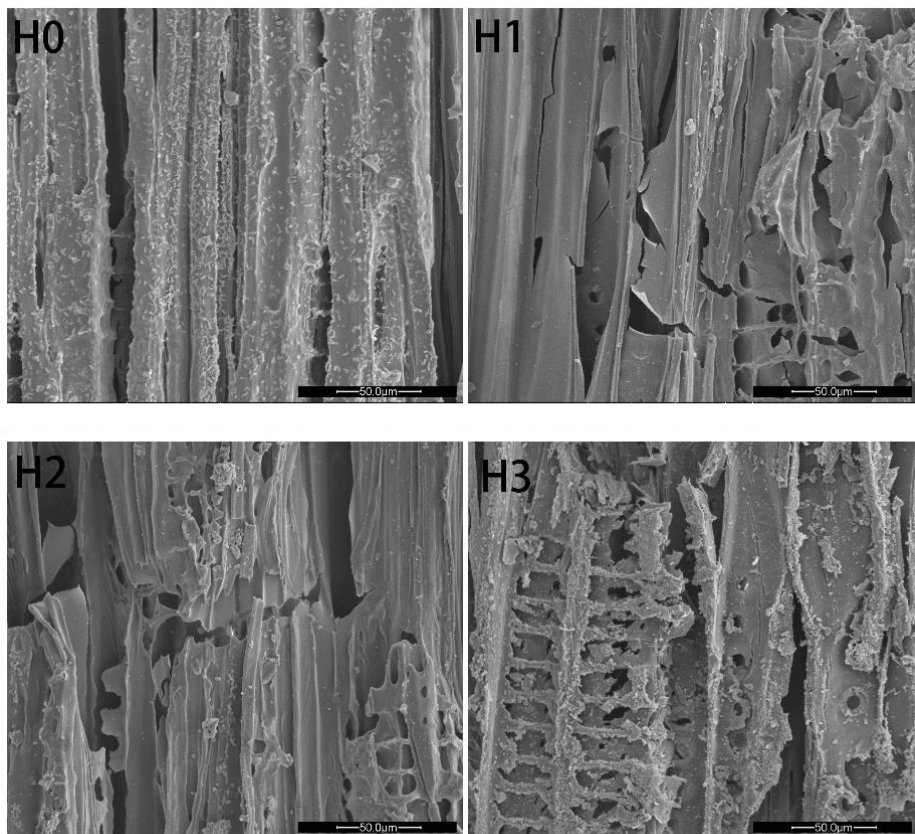


Fig. 3. Microorganism observation of *Larix* spp. specimens after 3000 h of artificial weathering

The SEM micrographs of the heat-treated wood displayed different types of degradation behaviors, as shown in Figs. 2f-h. A large number of distinctive cracks formed in the heat-treated specimens after exposure to fluorescent UV lamps. Distortion and crinkling of the cell walls occurred in the longitudinal direction, resulting in the delamination of the cell walls (Xing and Li 2014). This shows that the lignin binding of the cellulose microfibrils in the cell wall layers was partially degraded during the weathering process. Furthermore, the pits of three of the heat-treated specimens were heavily damaged. Most of the cracks on the pits formed transverse to the cell axis. Longitudinal fractures were scarcely observable in the untreated specimen.

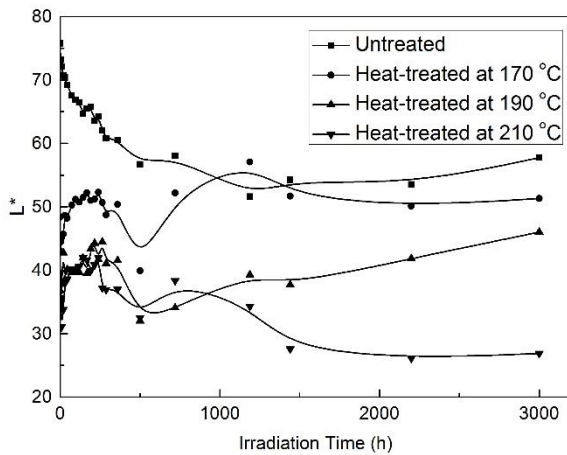
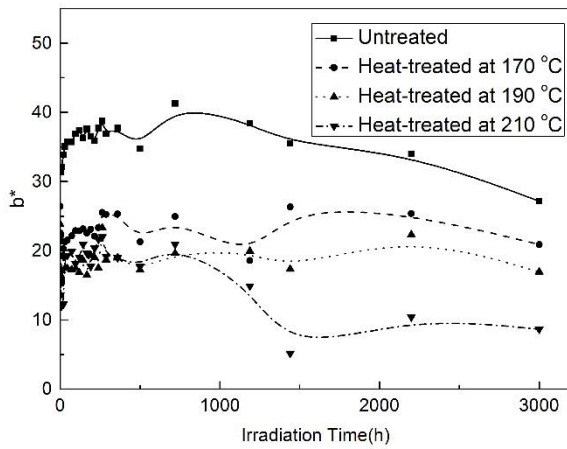
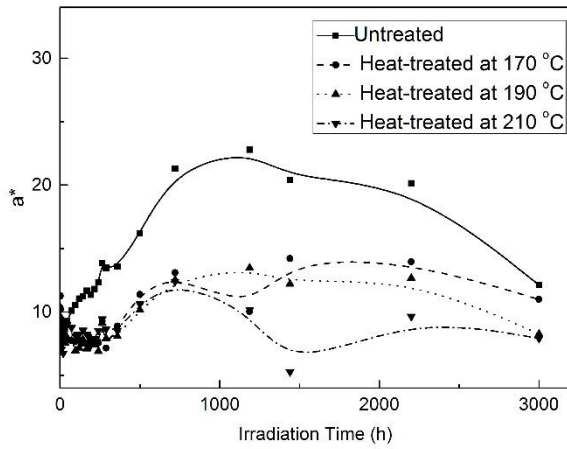
Bacterial and fungal spore infection could be clearly seen after artificial exposure, as shown in Fig. 3. Several different types of biodegradation were observed in both untreated and heat-treated wood. For the different intensity of heat treatment, different degradation products were formed, which is attributable to the different bacterial and fungal processes. Bacterial particles were found on the untreated specimens, while clusters of cocci bacterial particles were seen on three heat-treated specimens. The hydrolysis of polysaccharides and lignin produced by the heat treatment formed glucose and disaccharide, which are easy for microorganisms to consume. The pits of the wood heat-treated at 210 °C were severely deteriorated and had formed several cracks. In addition, the moisture spray had created relatively welcoming conditions for microorganisms. Previous studies have revealed that different types of fungal and bacterial attacks occur in both softwoods and hardwoods, depending mainly on the chemical components of the cell walls and on their structural features (Huang *et al.* 2013). The UV radiation, the water spray treatment, and the microorganism attack all caused the degradation and cracks in the cell walls, and causing increased hydrophilicity of the heat-treated samples shown in Fig. 1. This degradation consequently contributed to the color changes, water stains, and cracks in the cell walls during weathering.

Color Changes in the Wood Specimens

Figure 4 shows the curves of the lightness (L^*), redness (a^*), yellowness (b^*), and the total color differences between the heat-treated and untreated *Larix* spp. wood as a function of the artificial moisture and UV light radiation exposure time. An immediate increase in the a^* value of the untreated specimens demonstrated that the irradiation made the wood surface redder, while the a^* value of the heat-treated specimens showed better stability with up to 500 h of artificial weathering. After 500 h of exposure, the color parameters of all samples turn to be relatively stable. After 1500 h of exposure, the a^* value of all of the specimens tended to decrease gradually with increasing irradiation time. After 3000 h of irradiation, the surfaces of both the untreated and the heat-treated specimens had similar a^* values.

Yellow and blue, the opponent colors, were represented by the b^* value. An increase in the b^* value indicated a tendency of the wood to become yellowish, while a decrease in the b^* value meant that the surface tended towards being bluish. As shown in Fig. 4, the slightly increased b^* value in all of the specimens, with up to 192 h of weathering, indicated that the surfaces of both the untreated and the heat-treated specimens were becoming yellowish in color. The fluctuating b^* value indicated that there were complex chemical reactions taking place because of the exposure to UV radiation and high moisture. From 1440 h to 3000 h of exposure time, the b^* value remained at an almost constant level. After 3000 h of artificial weathering, both the untreated and the heat-treated

Larix spp. wood exhibited a slightly blue color compared with the sample before weathering, respectively.



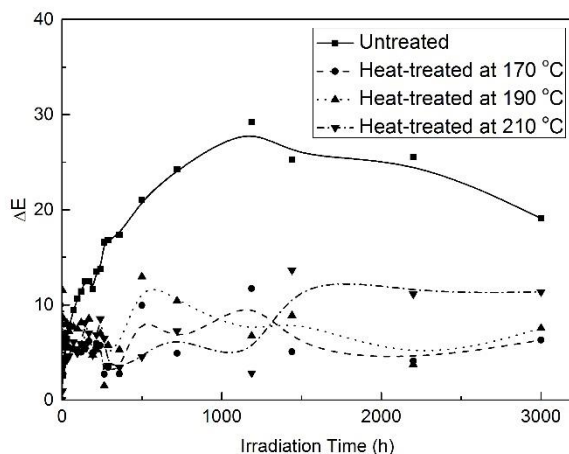


Fig. 4. The CIELAB parameters (L^* , a^* , b^* , and ΔE) of both untreated and heat-treated *Larix* spp. during artificial weathering

The lightness of color (L^*) of a wood surface is strongly affected by the heat treatment process, and the value of L^* in this study followed the intensity of heat treatment in a linear fashion. The L^* values of both the untreated and the heat-treated specimens displayed different tendencies during artificial weathering. For the untreated specimens, the L^* value significantly decreased up to 1000 h, then it increased slightly when the exposure time was extended. On the contrary, the L^* value of the heat-treated specimens increased notably up to 360 h, followed by a slight fluctuation of the curve from 360 h to 1188 h. Then, the L^* value remained nearly constant thereafter up to 3000 h of weathering. Darkening of the surface of the untreated specimens was mainly attributed to the transportation and degradation of extractives subjected to UV radiation and moisture. During the heat treatment process, most extractives are removed and degraded; therefore, the heat treatment completely changes the photochromic behavior of the wood products (Stark and Matuana 2007). Thus, the lightness changes of the heat-treated specimens during the artificial weathering process are mainly attributed to lignin photo-degradation. After 1440 h of weathering, changes in the L^* value of all of the specimens were not obvious; meanwhile, the untreated wood surface's color turned gray, which showed the similar tendency of color change that was observed in all of the heat-treated specimens (H1 and H2). While for the H3 sample, the degradation products was generated during heat treatment, which caused water stain and darker surfaces after weathering. However, the ΔE of the untreated *Larix* spp. wood was more sensitive at an earlier stage than that of the heat-treated specimens. From the beginning of the treatment to 1440 h of exposure, the ΔE of the untreated *Larix* spp. wood was much greater than that of the heat-treated samples. From that point on, the entire specimens' ΔE values remained relatively constant up to 3000 h. This result indicates the better color stability of heat-treated *Larix* spp. exposed to UV radiation and moisture spray, which is in accordance with previous research (Yildiz *et al.* 2013).

Thermal modification, which is a mild pyrolysis, also profoundly changes the components of the wood cell wall (Del Menezzi *et al.* 2008), for example, the degradation of hemicellulose, evaporation of extractives, and the recondensation of lignin (Saim *et al.* 2009; Salca and Hiziroglu 2014). The removal of extractives and the modification of the lignin are mostly attributed to the behavior of photodegradation. Heat treatment has been

found to be effective against both weathering and fungal decay in previous research using short-term artificial weathering (Shi *et al.* 2007; Rosu *et al.* 2010).

Chemical Analysis with FTIR Spectroscopy

In this study, the results of the FTIR analysis of artificial weathering on both untreated and heat-treated *Larix* spp. specimens are presented in order to investigate the changes in the chemical components of the specimens following artificial weathering. The characteristic bands of FTIR absorption in the regions from 400 to 4000 cm^{-1} for both untreated and heat-treated wood are summarized in Table 2. The FTIR spectra of specimens before and after 3000 h of weathering, between the spectral regions of 2000 to 500 cm^{-1} , are shown in Fig. 5. Differences because of heat treatment, UV radiation exposure, and moisture spray were taken into consideration in the spectra.

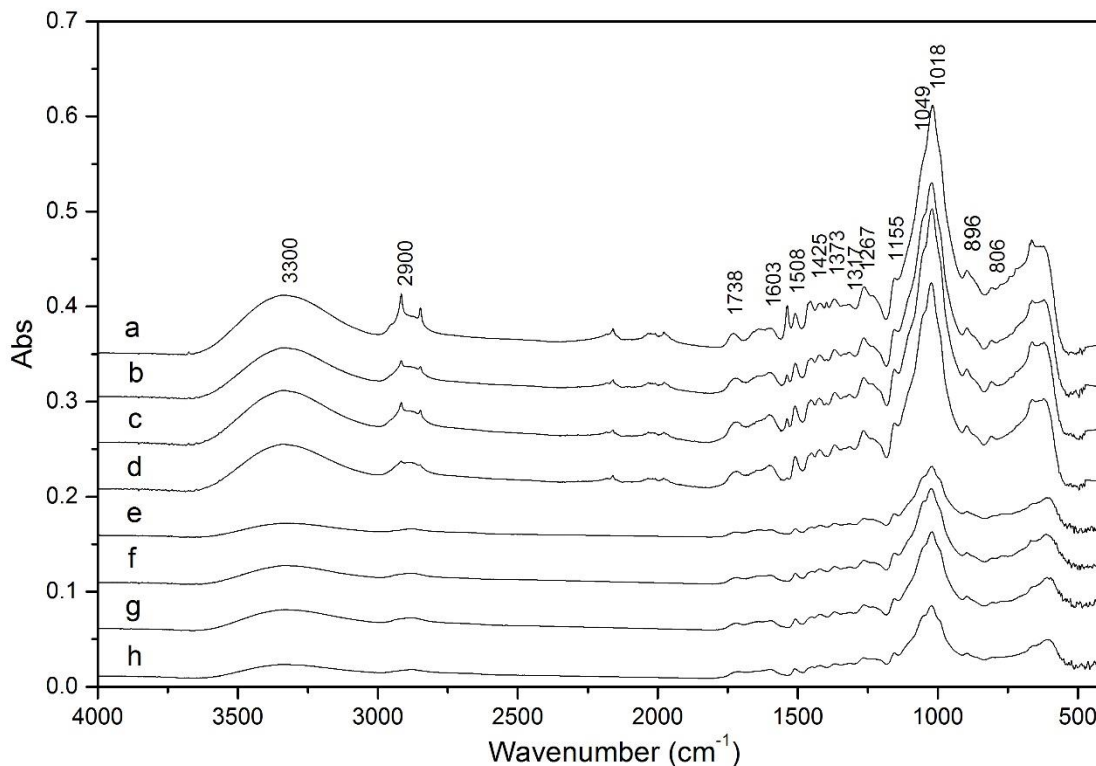


Fig. 5. FTIR spectra of *Larix* spp. before and after 3000 h of artificial weathering: (a) H0 before weathering; (b) H1 before weathering; (c) H2 before weathering; (d) H3 before weathering; (e) H0 after weathering; (f) H1 after weathering; (g) H2 after weathering; (h) H3 after weathering.

In Fig. 5, the curves (a-d) show the FTIR spectra of the specimens before artificial weathering. The FTIR spectrum differences between heat-treated and untreated wood have been well investigated in previous research (Montaruli *et al.* 2009; Srinivas and Pandey 2012). In this study, heat treatment caused complicated reactions, such as degradation of hemicellulose (Li *et al.* 2015), evaporation and degradation of extractives, and recondensation and crosslinking of lignin, which led to the total deviations in curves a through d. The surface chemical components of both heat-treated and untreated specimens were fundamentally modified by high temperature pyrolysis. Figure 5 shows the FTIR spectra (curves e to h) of the specimens after 3000 h of artificial weathering. It is clear from

the results of the FTIR analysis that artificial weathering had a prominent effect on the functional groups of the heat-treated wood surface.

In Table 2, most of the major peak changes were observed at the wave numbers of 3336, 2900, 1738, 1603, 1508, 1425, 1373, 1317, 1267, 1155, 1049, 1018, 896, and 806 cm^{-1} . The absorption intensity of both untreated and heat-treated specimens obviously decreased at 3336 cm^{-1} (OH-stretching and intra-molecular hydrogen bonds of alcohols, phenols, and acids), as well as at 2900 cm^{-1} (C-H bonds in cellulose) after 3000 h of artificial weathering (Gelbrich *et al.* 2012; Shi *et al.* 2012). The decrease in band intensity at 1738 cm^{-1} (C=O of esters, ketones, aldehydes, and acids) was because of deacetylation and degradation of the hemicelluloses (Huang *et al.* 2013). The absorption peak assigned to lignin at around 1603 cm^{-1} and 1508 cm^{-1} slightly changed compared with that of the untreated specimens. Most of the characteristic band intensity of lignin significantly decreased.

Table 2. FTIR Absorbances of Heat-Treated and Untreated *Larix* spp.

Wavenumber (cm^{-1})	Functionality	Vibrating type
3336	O-H of alcohols, phenols and acids	O-H stretching vibrations
2900	CH_2 , CH- and CH_3	C-H stretching vibrations
1738	C=O of esters, ketones, aldehydes, and acids	C=O stretching
1603	Aromatic ring(syringyl lignin)	Benzene ring stretching vibrations
1508	Aromatic ring(guaiacyl lignin)	Benzene ring stretching vibrations
1425	C-H and Aromatic ring	Benzene skeletal combined with C-H deformations
1373	C-H(cellulose and hemicellulose)	C-H bending vibrations
1317	O-H (cellulose and hemicellulose)	bending vibrations in the plane
1267	CO-OR(hemicellulose acyloxy); Aromatic ring ether(lignin)	CO-OR stretching vibrations
1155	Carbohydrate C-O-C	C-O-C vibrations
1049	C-O, C-H(Primary alcohol, guaiacyl)	C-O valence vibration
1018	C-O-C	C-O deformation
896	anti-symmetric out-of-phase stretching in pyranose ring	stretching in pyranose ring
806	C-H	Mannan vibrations and C-H out of plane bending vibration in lignin

The absorption intensities of both the heat-treated and untreated specimens rapidly decreased during artificial weathering, which indicates a serious degradation of the lignin of the cell wall by UV irradiation (Emmanuel *et al.* 2015). The absorption peaks at around 1425 cm^{-1} , 1373 cm^{-1} , and 1317 cm^{-1} that were assigned to cellulose showed no discernible difference in the spectra of heat-treated versus untreated specimens (Bui *et al.* 2015), which demonstrates similarity in the degradation of cellulose after long-term artificial weathering.

The decrease of peaks at around 1267 cm^{-1} (CO-OR of hemicellulose and lignin), 1155 cm^{-1} (antisymmetric bridge oxygen stretching or C=O and C=C stretching and CH₂ rocking), and 1049 cm^{-1} (asymmetric in-plane ring stretching) were mainly responsible for the modification of cellulose and hemicellulose by light irradiation. The peaks of heat-treated and untreated specimens at 896 cm^{-1} (anti-symmetric out-of-phase stretching in the pyranose ring) were related to cellulose and hemicellulose (Vongsvivut *et al.* 2015), and the changes of the peaks at around 806 cm^{-1} were mainly responsible for the benzene ring seen in softwood as a result of delignification.

Heat treatment profoundly affected the components of wood cell wall, starting with deacetylation and followed by mild depolymerization catalyzed by the released acetic acid. These reactions were strongly dependent on the temperature and the duration of the heat treatment process. For the specimens exposed to long-term artificial weathering (UV radiation and water spray), the chemical components of both the heat-treated and the untreated specimens were greatly changed and became similar. These results indicate that the heat treatment provided limited improvement to the wood's capacity to resist long-term UV light exposure.

CONCLUSIONS

1. Both heat-treated and untreated *Larix* spp. wood was strongly affected even by a short period of artificial weathering by means of UV radiation and moisture spray. The pronounced surface changes which took place attributed to weathering were investigated both by visual observation and by microscopic and chemical component analysis.
2. Whitening and photodegradation of both the heat-treated and the untreated wood surface could be observed after gradual UV exposure. Small cracks, penetration of pits, and microorganism attacks on the cell walls of the heat-treated wood were readily observed.
3. The pronounced color changes of the wood surface, measured using a colorimeter, were mainly attributed to the removal of extractives and the modification of lignin.
4. Heat-treated wood presented better color stability after exposure to UV radiation and moisture contact in the early stages. For long-term outdoor use of heat-treated wood products, heat treatment is not sufficient to improve wood's resistance to photodegradation.
5. The differences in photodegradation behavior during artificial weathering between heat-treated and untreated wood were mainly caused by the higher ratio of lignin condensation and the lower ratio of extractives because of their removal during the heat treatment.

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