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Changes in The Dynamic and Static MOE of Furfuryl Alcohol–Treated Wood

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To assess changes in the mechanical properties of wood treated with furfuryl alcohol, the static modulus of elasticity, the dynamic modulus of elasticity and some physical properties of pine and larch wood were estimated before and after furfuryl alcohol treatment. The possibility of reducing floor noise by using furfuryl alcohol–treated wood was also evaluated.

In comparison to untreated specimens, furfuryl alcohol–treated wood exhibited a color change from yellow to slightly brown, and swelling and water absorption ratios were significantly reduced. Furthermore, the specific gravity, static MOE and dynamic MOE were enhanced while the natural frequency was reduced. The correlation coefficient between the dynamic modulus of elasticity and the static modulus of elasticity for furfuryl alcohol–treated specimens and for control specimens were 0.90 and 0.92, respectively. The dynamic MOE to specific gravity ratio (dMOE/r) and the static MOE to density ratio (sMOE/r) both decreased as a result of furfuryl alcohol treatment. The furfuryl alcohol–treated wood could contribute to a decrease in noise if used as flooring material.

Key words: furfuryl alcohol treatment, static MOE, dynamic MOE, color change, water absorption

INTRODUCTION

Wood is a hygroscopic material in that its dimensions change in humid environments and it is vulnerable to mold and other infestations. To overcome these disadvantages, several wood modification techniques have emerged, including heating, surface densification, chemical bulking of cell walls, polymer impregnation, and chemical alteration of cell composition, among other methods (Hills, 2006).

Furfurylation is a specific type of impregnation modification that uses furfuryl alcohol. When wood is treated with furfuryl alcohol, polymerization occurs, the basic chemistry of which has been established (Chuang *et al.*, 1984; Gonza´lez *et al*. 1992; Gonza´lez *et al.*, 2002; Maciel *et al.*, 1982). Polymerization reduces equilibrium moisture content and increases dimensional stability and biological durability (Hills, 2006; Nordstierna *et al.*, 2008; Lande *et al.*, 2004, Esteves *et al.*, 2011). Furfurylation modification causes several positive changes in the mechanical properties of wood. Esteves *et al.* (2011) suggested that density and hardness increase significantly in furfuryl alcohol–treated Pinus pinaster wood. However, they also found that the MOE of furfuryl alcohol–treated wood was similar to that of untreated wood and the MOR increased slightly. Epmeier *et al.* (2004) reported similar results. In contrast, the impact bending strength of wood is decreased when treated with furfuryl alcohol (Lande *et al.*, 2004).

Furfurylation darkens the color of the wood, which could allow furfuryl–treated softwood to replace tropical hardwood. Furthermore, because of its dimensional stability, furfurylated softwood could be used as flooring material. Several studies concerning the reduction of floor noise have recently emerged. Norimoto *et al.* (1992) demonstrated that quality sounding boards for pianos have a low internal friction to dynamic MOE ratio (Q–1/E’), and that this value is strongly correlated with the dynamic MOE to density ratio (E’/r). These results suggest that either the static or dynamic MOE to density ratio could be used to estimate floor noise levels. Other studies have found that static MOE and dynamic MOE are highly correlated. Lee & Huang (1997) studied the adoption of resonance frequency by transverse vibration method and density to estimate the dynamic modulus of elasticity (dMOE) and Park and Byeon (2006) reported that the correlation coefficient between static bending strength and the dynamic modulus measured by resonant frequency ranged from 0.811 to 0.947 in laminated timber. Cho (2000) found that the correlation coefficient between static MOE and dynamic MOE by the strength variation of Japanese cedar was 0.82.

The purpose of this study was to assess the property changes related to furfurylation of wood. We also evaluated the possibility of reducing floor noise by using furfurylated wood, given the changes in density, static MOE and dynamic MOE. The study was limited to small specimens. In addition, a curing temperature of 130 was adopted for furfuryl alcohol treatment, as determined by pre–experiments.

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MATERIALS AND METHODS

Sample specimen

Defect–free, straight–grained pine wood (*Pinus densiflora* S. et Z.) and larch wood (*Larix kaemferi* carr) test specimens were prepared through sawing and planing. The test specimens were cut from timber which was first oven–dried at 60°C and thereafter conditioned to stable moisture content (MC). Test specimens measured nominally 20 (h)×20 (w)×320 (l) mm^3 at 13% MC. Before impregnation, all specimens were oven dried for 48 hours at 103±1°C. Then, initial and final oven–dried weights and sizes of the specimens were measured. For static and dynamic MOE estimation, the same specimen was analyzed both before and after treatment. Finally, Brinell hardness was estimated for the control and treated specimens.

Impregnation

All samples went through the same impregnation procedure. The samples were placed in an autoclave and vacuum (76 cmHg.V) was applied for 30 minutes. The furfuryl alcohol was then moved into the treatment chamber and pressure (1.38 MPa) was applied for 2 hours. After the samples were removed from the autoclave, they were wiped clean of excess liquid and cured at 130°C for 2 hours.

Color measurement

Specimen color was measured using a spectrophotometer (CR–400/410, KONICA MINOLTA) with a D65 light source. In this color space, color is defined by its Cartesian chromatic coordinates. The CIE L*a*b* color parameters (L*, a*, b*) were used to express color change. From the L*, a*, and b* values obtained, the total color difference (ΔE) was calculated using following formula:

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2}$$

where ΔL, Δa and Δb are the changes between before and after treatment values.

Dimensional stability

Water absorption and radial and tangential direction swelling ratios were measured after soaking the oven–dried samples in distilled water for 8 weeks. The cross–sectional and longitudinal dimensions and volume (v) of the saturated specimens were then determined, after which all specimens were oven–dried to a constant weight.

Dynamic modulus of elasticity

The dynamic modulus of elasticity was determined by the free–free suspended beam technique, in which a pick–up accelerometer (B & K) is fastened to the center of the specimen and the specimen is struck lightly on one end with an impulse hammer (Type 8203, B & K). The impact causes the specimen to vibrate and the signal produced by the accelerometer is then transformed by an FFT analyzer (Type 3065, B & K) and processed using computer software, generating the estimated resonant frequency (f_0). From the f_0, the resonant frequency (f) was corrected to eliminate the influence of shear deflection (Kataoka and Ono, 1975). The dynamic modulus of elasticity (dMOE) was calculated using the following formula.

$$f = f_0 (1 + \alpha h^2/L^2)$$

where

f = resonant frequency
f_0 = estimated resonant frequency
L = length of the specimen
a = a constant (4.73 for the fundamental mode of vibration)

$$dMOE = 48\pi^2 \rho l4f^2/m^4h^2$$

where

dMOE = dynamic modulus of elasticity
ρ = density of the specimens
h = thickness
m = a constant (4.73 for the fundamental mode of vibration)

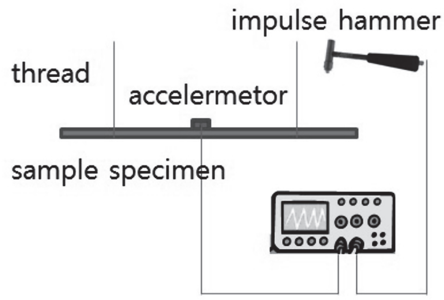

Fig. 1. Schematic diagram for the dynamic MOE measuring apparatus.

Static modulus of elasticity in bending

Static three–point bending tests were performed using a universal testing machine (AGS–1000G, Shimadzu Corporation). Both untreated and furfural alcohol treated–specimens were loaded in the radial direction for the bending tests. The span (L) was 28 cm and the cross head was advanced at 10 mm/min. The proportional limit, ultimate load, and deflection were obtained from load–deflection curves, and the static MOE were calculated.

Brinell hardness

A steel ball was forced against the longitudinal–radial surface of control and furfural alcohol–treated wood by a Brinell hardness tester at 500 N/mm^2. The indentation load, indentation depth and indentation surface area were evaluated, and the Brinell hardness (HB) was determined using the following formula.

$$H_B = 2P/(\pi D)(D-((D^2-d^2)^{1/2}))$$

where

P = load,
D = diameter of the steel ball,
d = diameter of the indentation

RESULTS AND DISCUSSION

Physical properties

Furfuryl alcohol treatment caused several positive changes in the physical properties of pine and larch wood. We found that the average weight percentage gain (WPG) was 35.58% for pine and 33.88% for larch specimens after impregnation with furfuryl alcohol (Table 1). Treatment with furfuryl alcohol significantly reduced swelling and water absorption compared to untreated specimens. The water absorption (WA) values of untreated specimens were found to be 68.94% for Larch and 119.74% for pine after a 48–hour immersion period in distilled water. After impregnation, the water absorption values decreased to 22.63% for larch and 39.88% for pine compare to untreated, respectively. Other studies have found similar results. However, furfuryl alcohol treatment caused the specimens to change color from yellow to slightly brown. The total color difference (ΔE) was 53.72 for Larch and 48.36 for Pine, respectively.

Mechanical properties

The density was higher and the Brinell hardness greater for the furfuryl alcohol–treated wood than for the control wood. The Brinell hardness of the control and treated woods were 1.78 MPa and 4.91 MPa for pine and 1.50 MPa and 2.12 MPa for larch, respectively (Table 2). It is suggest that the treatment cause the wood to stiffen.

At the same conditions, the frequency of vibration is proportional to the material elasticity and is inversely proportional to the mass of the material. In this study, furfuryl alcohol treatment decreased the resonant frequency, which was proportional to weight gain by furfuryl alcohol treatment (Figure 2). Here, the R value was 0.46, and was only slightly correlated. Although resonant frequency decreased, the dynamic MOE increased as a result of treatment. The strain of the dynamic MOE is relatively smaller than that of the static MOE, such that the value of the dynamic MOE may be influenced more by surface area than by the inner area of the vibrating body. Therefore, it is considered that surface stiffness produced by the furfural alcohol treatment caused the dynamic MOE enhancement.

As a result of furfuryl alcohol treatment, the static modulus of elasticity (sMOE) also increased. The static MOE of wood before and after the treatment was 7727 MPa and 8009 MPa for pine and 8978 MPa and 9997 MPa for larch, respectively. These results estimated that was polymerization occurred inside the wood by furfuryl alcohol treated.

The relationship between the dynamic and static MOE of untreated and furfuryl alcohol–treated specimens are shown in Figure 3 and 4, respectively. Figures show that the dynamic MOE was highly correlated with the static MOE. The correlation coefficient was 0.92 for untreated specimens and 0.90 for furfuryl alcohol–treated specimens.

Figures 5 and 6 show the dynamic and static MOE changes according to specific gravity. The dynamic MOE to specific gravity ratio (dMOE/r) and the static MOE to

Table 1. Weight percent gains (WPG), total color changes (ΔE), thickness and width swelling, and water absorption (WA) of untreated and furfuryl alcohol–treated (FA) wood

Species	Treatment	g	ΔE	Radial direction Swelling (%)	Tangential direction Swelling (%)	WA (%)
Pine	untreated	–	–	8.38	5.3	119.74
	FA	0.52	48.36	2.04	2.8	39.88
Larch	untreated	–	–	6.48	5.91	68.94
	FA	0.34	53.72	1.22	3.64	22.63

Table 2. Specific gravity (r), natural frequency (f_0), resonant frequency (f), hardness (H_B), static modulus of elasticity (sMOE) and dynamic modulus of elasticity (dMOE) of untreated and furfuryl alcohol–treated (FA) wood

Species	Treatment	r	f_0	f	H_B(MPa)	sMOE(MPa)	dMOE(MPa)	dMOE/r	sMOE /r
Pine	untreated	0.53	784.55	809.11	1.78	7727.2	8877.5	16770.9	14579.2
	(STDEV)	(0.03)	(46.84)	(47.68)	(0.52)	(1365.38)	(1341.82)	(2082.08)	(2158.03)
	FA	0.67	770.50	796.93	4.91	8009.3	9845.9	14818.2	12075.0
	(STDEV)	(0.03)	(41.29)	(42.11)	(2.54)	(1058.37)	(1167.20)	(1658.12)	(1573.07)
Larch	untreated	0.52	883.40	899.30	1.50	8978.5	10652.1	20613.2	17648.2
	(STDEV)	(0.03)	(39.64)	(40.46)	(0.43)	(637.31)	(636.55)	(1719.82)	(1766.66)
	FA	0.67	825.50	840.94	2.12	9997.4	11700.9	17344.2	14836.6
	(STDEV)	(0.03)	(24.53)	(25.05)	(0.68)	(564.42)	(1003.27)	(1073.05)	(652.38)

*STDEV: standard deviation

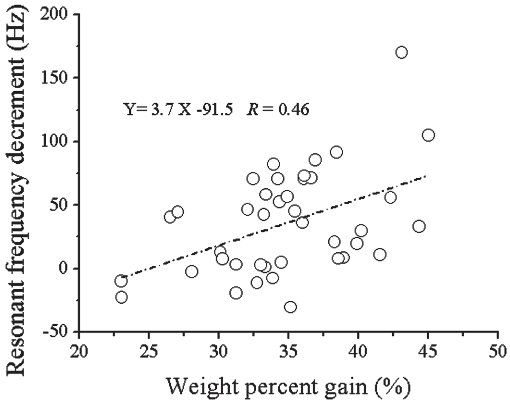

Fig. 2. The relationship between weight percent gain and resonant frequency decrement due to furfuryl alcohol treatment.

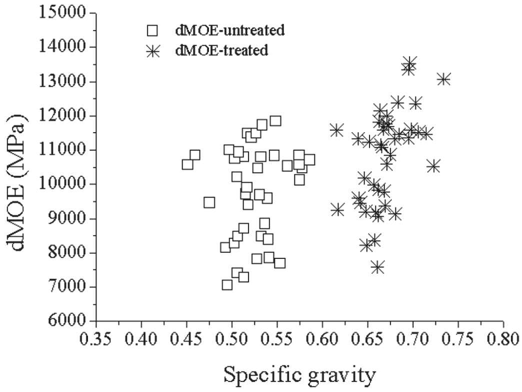

Fig. 5. The relationship between the dynamic modulus of elasticity (dMOE) and specific gravity for untreated and furfuryl alcohol–treated pine and larch wood.

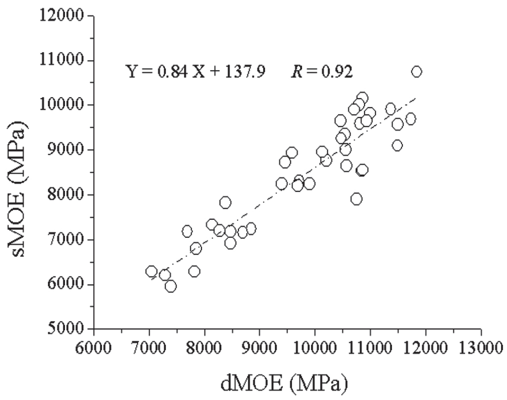

Fig. 3. The relationship between the static modulus of elasticity (sMOE) and the dynamic modulus of elasticity (dMOE) of untreated wood specimens.

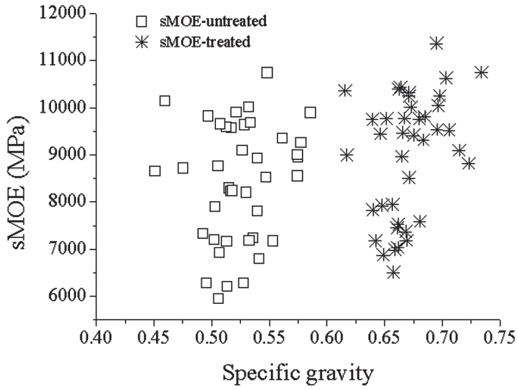

Fig. 6. The relationship between the static modulus of elasticity (sMOE) and specific gravity for untreated and furfuryl alcohol–treated pine and larch wood.

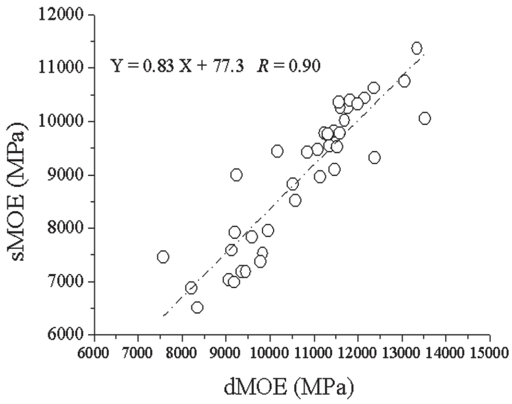

Fig. 4. The relationship between the static modulus of elasticity (sMOE) and the dynamic modulus of elasticity (dMOE) of furfuryl alcohol–treated specimens.

specific gravity ratio (sMOE/r) decreased in furfurylated specimens (Table 2). Norimoto (1992) suggested that higher dMOE/r or sMOE/r ratios are preferred for quality sounding boards for pianos. Therefore, we conclude that the low dMOE/r and sMOE/r values associated with furfuryl–treated wood could contribute to a decrease in noise if used as flooring materials.

CONCLUSIONS

Pine and larch wood specimens were treated with 70% furfural alcohol and cured at a temperature of 130 . We analyzed the changes in physical and mechanical properties, as well as the relationship between the static and dynamic modulus of elasticity. Our study obtained the following results:

Furfuryl alcohol treatment affected the physical and mechanical properties of wood. The color of the specimens changed from yellow to slightly brown. Swelling and water absorption were reduced significantly, and although the natural frequency decreased, the density, hardness, static modulus of elasticity and dynamic modulus of elasticity were all enhanced.

The dynamic modulus of elasticity was highly correlated with the static modulus of elasticity both of furfuryl alcohol–treated specimens and control specimens.

The dynamic MOE to specific gravity ratio (dMOE/r) and the static MOE to specific gravity ratio (sMOE/r) were decreased as a result of furfuryl alcohol treatment. The furfuryl alcohol–treated wood could contribute to a decrease in noise if used as flooring material.

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