Nondestructive Evaluation of Strength Performance for Heat-Treated Wood Using Impact Hammer & Transducer[*1]

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ABSTRACT

Nondestructive evaluation (NDE) technique method using a resonance frequency mode was carried out for heat-treated wood under different conditions. The effect of heat treatment on the bending strength and NDE technique using the resonance frequency by impact hammer and force transducer mode for *Korean paulownia, Pinus densiflora, Lidiodendron tulipifera* and *Betula costata* were measured. The heat treatment temperature has been investigated at 175°C and 200°C, respectively.

There were a close relationship of dynamic modulus of elasticity and static bending modulus of elasticity to MOR. In all conditions, It was found that there were a high correlation at 1% level between dynamic modulus of elasticity and MOR, and static modulus of elasticity and MOR. However, the result indicated that correlation coefficient is higher in dynamic modulus of elasticity to MOR than that in static modulus of elasticity to MOR. Therefore, the dynamic modulus of elasticity using resonance frequency by impact hammer mode is more useful as a nondestructive evaluation method for predicting the MOR of heat-treated wood under different temperature and species conditions.

Keywords : nondestructive evaluation(NDE), heat treatment, impact hammer, MOE, MOR

1. INTRODUCTION

Recently, the "ThermoWood" is manufactured to make high value and to accept consumers preference in Europe. These heat treatment improve the dimensional stability of wood, increase its resistance to micro-organisms, darken its color, and modify its hardness (Kocaefe *et al*., 2008). Also, Byeon *et al* (2012) and Kocaefe (2008 & 2010) found effect of heat treatment on the bending strength of wood which decreased due to the reduction of density after heat treatment.

Nondestructive evaluation (NDE) techniques have been extensively used for sorting or grading of wood products. Examples include visual grading and machine stress rated (MSR) of lumber. Dynamic modulus of elasticity (MOE_d)

and ultrasonic techniques also have been used for the same purpose. There are two methods to measure dynamic MOE_d using a resonance frequency and the velocity of acoustic propagation. The resonance frequency can be achieved by a free vibration and/or the fast Fourier transform (FFT) analyzer of impact hammer signals. The dynamic MOE_d method using the resonance frequency has been extensively used for the characterization of wood for musical instruments (Sobue *et al.*, 1984; Hong, 1985; Byeon & Hong, 1997). Park and Byeon(2006) reported that dynamic MOE by resonance frequency using flexural vibration and comparison with bending strength and creep performances of 3-ply woods had a high correlation coefficient of 0.811~0.947. The MOE_d method by impact hammer has been developed as a simple and efficient method. Gehards (1974) showed that the stress wave speed are affected by such as moisture and temperature, grain angle, knot. A longitudinal stress wave and transverse vibration methods were developed for the estimation of modulus of the elasticity for lumber (Ross & Pellerin, 1991).

Therefore, NDE technique using the resonance frequency by impact hammer mode was applied to heat-treated wood (*Korean paulownia, Pinus densiflora, Lidiodendron tulipifera* and *Betula costata*) under different temperature conditions and the relationship between the resonance frequency parameter and static bending strength properties was analysed.

2. MATERIALS and METHODS

2.1. Material

The species of *Korean paulownia, Pinus densiflora, Lidiodendron tulipifera* and *Betula costata* were used in the dry ingredients. Specimens of each species were made from edge
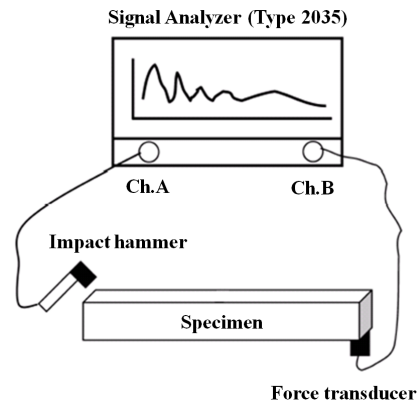

Fig. 1. Schematic diagram of impact hammer vibration mode.

grain 20 mm (R) × 10 mm (T) × 100 mm (L) and flat grain 10 mm (R) × 20 mm (T) × 100 mm (L) and processed 8 each.

The humidification of specimens was treated over 1 week in the constant temperature and humidity room (20°C ± 1°C, 65% ± 5%), and heated for 6 hours at 120°C in dry oven. The heat treatment of specimens treated at the heating rate 10°C/min heating conditions in the vacuum sintering furnace (KOVACO KSF-100 Type). At this time, maintained for 30 minutes in the maximum temperature of 175°C and 200°C. After heat treatment, the humidification of treated samples were treated again over 1 week in the constant temperature and humidity room (20°C ± 1°C, 65% ± 2%). After that, bending strength and hardness test of specimen was conducted.

2.3. Dynamic MOE Measurement by an Impact Hammer

The measurement was performed by impacting the top end of a specimen with an impact hammer (Type 8203, B & K), as shown in Fig. 1. An force transducer (Type 4372V, B & K) was set at the bottom end plane to receive the

excitation and transmit it to a signal analyzer unit (Type 2035, B & K). Each specimen was tapped twice with a hammer and an averaged frequency was obtained from the frequency domain system. Resonance frequency and dynamic MOE were calculated using Equations [1] and [2], respectively.

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

where f_0: value at frequency counter timer, α: value according to vibration type-8.2,

h: thickness of specimen (cm), l: length of specimen (cm).

$$MOE_d = 48\pi^2 \rho l^4 f^2 / m^4 h^2 \qquad (2)$$

where ρ: density (g/cm^3), m: value according

Table 1. The properties of each species according to the heat treatment

temperature	Species	Density (g/cm^3)	Resonance frequency (Hz)	MOR (MPa)	MOEs (GPa)	MOEd (GPa)
Solid	Korean Paulownia	0.299 (0.023)	4,276 (160)	42.43 (1.37)	5.62 (0.81)	4.73 (0.38)
	Pinus densiflora	0.546 (0.034)	4,625 (279)	85.85 (5.98)	9.34 (1.77)	10.08 (1.20)
	Lidiodend-ron tulipifera	0.548 (0.039)	4,061 (240)	81.34 (10.09)	10.39 (2.41)	7.80 (1.12)
	Betula costata	0.694 (0.023)	4,748 (160)	121.13 (10.19)	12.30 (3.08)	13.78 (1.07)
175°C	Korean Paulownia	0.222 (0.013)	4,594 (202)	25.77 (3.82)	4.60 (0.65)	4.19 (0.49)
	Pinus densiflora	0.497 (0.021)	5,042 (223)	85.65 (10.00)	11.73 (1.58)	11.46 (1.12)
	Lidiodend-ron tulipifera	0.440 (0.023)	4,427 (394)	57.13 (7.55)	7.85 (2.13)	8.47 (1.79)
	Betula costata	0.648 (0.037)	5,067 (261)	98.20 (15.88)	15.67 (0.90)	15.62 (2.13)
200°C	Korean Paulownia	0.194 (0.011)	4,095 (295)	14.21 (2.74)	3.22 (0.73)	2.87 (0.42)
	Pinus densiflora	0.452 (0.031)	4,622 (273)	64.68 (12.35)	9.38 (1.67)	9.30 (1.67)
	Lidiodend-ron tulipifera	0.374 (0.045)	3,779 (420)	32.73 (15.68)	5.13 (2.40)	5.31 (1.71)
	Betula costata	0.571 (0.021)	4,352 (307)	65.17 (13.33)	12.02 (2.89)	11.63 (1.94)

Parenthesis is standard deviation, mean value was calculated from 10 replications.
MOE : modulus of elasticity, MOR : modulus of rupture.

to basic vibration-4.73, h: thickness of specimen (cm), l: length of specimen (cm).

After resonance frequency measurement, bending strength property test for the same specimen was performed by a three point loading method (concentrated load at midspan and supported at its ends) in a universal testing machine (UTM, Taeshin accuracy machine, TSU-2). The span was 80 mm, and the cross-head speed was set at 0.6 mm/min. The static modulus of elasticity (MOEs) and modulus of rupture (MOR) were calculated from the test result.

3. RESULTS and DISCUSSION

3.1. Strength Properties of each species according to the heat treatment

Table 1 shows the average values of density, resonance frequency, modulus of rupture (MOR), static modulus of elasticity (MOEs) and the dynamic modulus of elasticity (MOEd) for four species after heat treatment. Before and after heat treatment, *Betula costata* showed highest dynamic modulus of elasticity followed by *Pinus densiflora, Lidiodendron tulipifera* and *Korean paulownia*, respectively.

The density of heat-treated wood is almost proportional to the dynamic modulus of elasticity. Density of heat-treated wood at the high temperature is lower than that at the low temperature. The density of heat-treated wood at the higher temperature was low since hemicellulose was more degraded at the 200°C more than at 175°C. Esteves *et al* (2007) reported that wood density decrease because of the removal of wood components by heat treatment and moisture desorption. And Kocaefe *et al* (2008) reported that decreasing density of the heat-treated wood was caused by decomposition of hemicelluloses, ramification of lignin, and
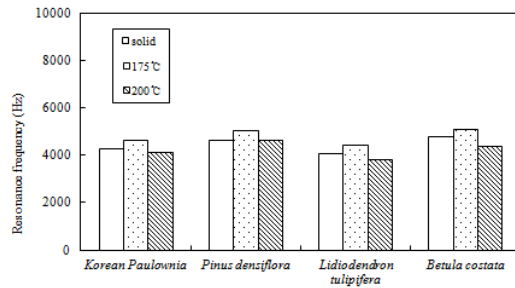

Fig. 2. Resonance frequency of heat-treated woods.

crystallization of cellulose.

3.2. Resonance Frequency

Table 1 and Fig. 2 shows the resonance frequency value of each species after heat treatment. The highest values of resonance frequency were shown at heat treatment temperature of 175°C for all species. Heat treatment resulted that the values of MOEd was 175°C > solid wood > 200°C.

The dynamic MOE decreased due to the reduction of density after heat treatment of 200°C. In this study, the heat treatment of specimens treated at the heating rate 10°C/min heating conditions, and maintained for 30 minutes in the maximum temperature of 175°C and 200°C.

3.3. Dynamic MOE for all Species According to the Heat Treatment

Table 1 and Fig. 3 shows the dynamic modulus of elasticity (MOEd) value of each species after heat treatment. Before and after heat treatment, the MOEd was measured lower at the 200°C than 175°C.

The MOEd of heat-treated *Betula costata, Lidiodendron tulipifera, Pinus densiflora* and *Korean paulownia* decreased at temperature of 200°C more than those at 175°C. This deterio-
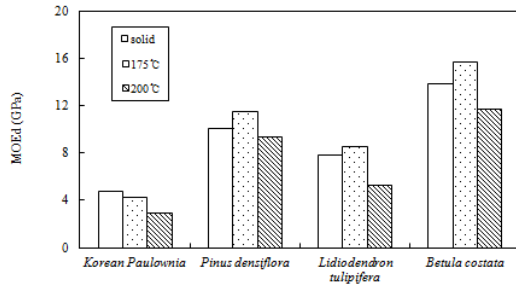
Fig. 3. Dynamic modulus of elasticity of heat-treated woods.

ration might be explained as due to hemi-cellulose degradation. Kocaefe *et al* (2010) reported that there is a significant change in hardness due to heat treatment. The hardness of heat-treated jack pine generally were deteriorated at temperatures higher than 200°C compared to those of untreated jack pine.

3.4. Relationships Between Density, MOEs, MOEd and MOR for all Species After Heat Treatment.

Least squares regression analysis method has been used in the field of wood properties, because mechanical properties of wood are linearly related (Bodig & Jayne, 1982; Bucur, 1995). Regression parameters are presented in Table 2. Fig. 4~6 show relationships between density, static MOEs, dynamic MOEd and MOR.

The correlation coefficients for density-MOR, density-static MOE, density-dynamic MOE for heat treated woods were 0.929, 0.854, 0.935 at the 175°C and 0.875, 0.843, 0.928 at the 200°C. The results showed that correlation coefficient of density to MOEd of heat treated woods was much higher than the others. Hong

Table 2. Summary of regression parameters for relationships between density, MOR, RF, MOEs, and MOEd for species after heat treatment

| Temperature	Parameter	Regression model	Correlation coefficient *r*
175°C	Density vs. MOR	y = 1814.x - 139.5	r = 0.929**
	Density vs. MOEs	y = 16444x + 24181	r = 0.854**
	Density vs. MOEd	y = 278267x - 24447	r = 0.957**
	MOEs vs. MOR	y = 0.007x - 87.47	r = 0.768**
	MOEd vs. MOR	y = 0.0062x + 54.337	r = 0.927**
	MOEs vs. MOEd	y = 0.1325x + 11517	r = 0.727**
200°C	Density vs. MOR	y = 1570.x - 173.9	r = 0.875**
	Density vs. MOEs	y = 23033x + 12301	r = 0.843**
	Density vs. MOEd	y = 252121x - 26133	r = 0.933**
	MOEs vs. MOR	y = 0.004x - 32.64	r = 0.708**
	MOEd vs. MOR	y = 0.0062x – 8.4875	r = 0.932**
	MOEs vs. MOEd	y = 0.2302x + 9952	r = 0.820**
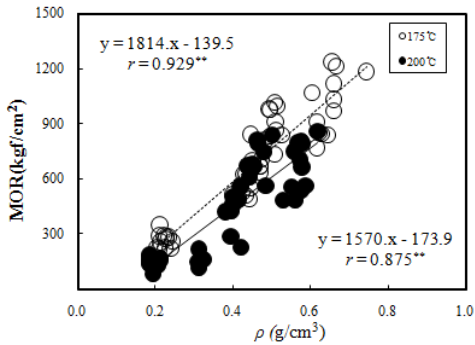
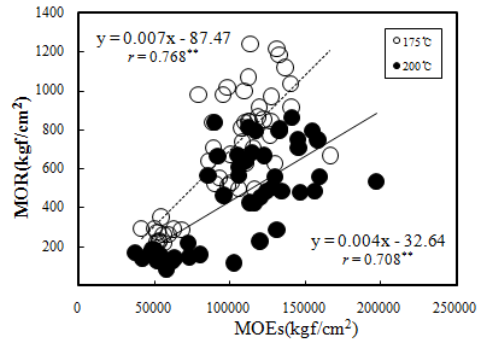Fig. 4. Relation of density to bending MOR of heat-treated woods.

Fig. 5. Relation of bending MOEs to MOR of heat-treated woods.

(1985) reported that the correlation coefficient values of density versus dynamic MOEd relationship for normal wood and compression wood in *Pinus densiflora* were very high values of 0.896 and 0.688. Ross & Pellerin (1991) reported that close correlation between MOEd and MOEs for clear solid wood by stress wave mode.

Correlation coefficients for static MOE - MOR, dynamic MOE - MOR for heat treated woods were 0.708, 0.927 at the 175°C and 0.708, 0.932 at the 200°C. The correlation coefficient of dynamic MOE and MOR of heat-treated woods was much higher than the static MOE and MOR.

3.5. Relationship Between Density and Mechanical Properties

Regression parameters are presented in shows the relation of density to MOR of heat treated woods. The correlation coefficients for the regression bending density to MOR were 0.929 at the 175°C and 0.875 at the 200°C. Both correlation coefficients were very high and significant at the 1% level, and there were a similar correlations between 175°C and 200°C.

3.6. Relationship Between Static MOE and Mechanical Properties

Fig. 5 shows the relation of bending MOEs to MOR of heat treated woods. The correlation coefficients for the regression bending MOEs to MOR were 0.768 at the 175°C and 0.708 at the 200°C. Both were significant at the 1% level, and there were a similar correlations between 175°C and 200°C. Byeon *et al* (2005) reported that a high correlation coefficient between bending MOE and MOR of finger-jointed wood were similar to this results (significant at the 1% level). And Nakai (1984) also reported that solid Japanese cedar showed a high correlation coefficient (0.69~0.78) between bending MOE and MOR.

3.7. Relationship Between Dynamic MOE and Mechanical Properties

Fig. 6 shows the relation of bending MOEd to MOR of heat treated woods. The correlation coefficients for the regression bending MOEd to MOR were 0.927 at the 175°C and 0.932 at the 200°C. Both were significant at the 1% level, and there were a similar correlations between 175°C and 200°C. The correlation coefficient was higher in dynamic modulus of elasticity to
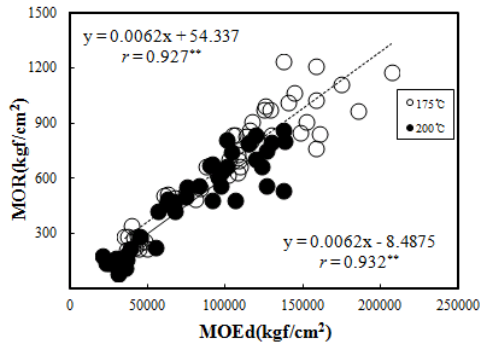
Fig. 6. Relation of bending MOEd to MOR of heat treated woods.

MOR than those in static modulus of elasticity to MOR and density to MOR. Therefore, the dynamic modulus of elasticity using impact hammer mode is more useful as a non-destructive evaluation method for predicting the MOR.

4. CONCLUSIONS

Nondestructive testing method using resonance frequency by impact hammer and force transducer mode was carried for heat-treated wood.

The MOR of heat-treated *Betula costata, Lidiodendron tulipifera, Pinus densiflora* and *Korean paulownia* decreased at temperature of 200°C more than those at 175°C.

After heat treatment, the dynamic MOE was lower at 200°C than that at 175°C.

Also, close correlations were found between dynamic modulus of elasticity and static bending modulus of elasticity and between dynamic modulus of elasticity and MOR and between static bending modulus of elasticity and MOR. And, a high correlation and 1% level of significance were observed in all conditions between bending MOE and MOR.

The correlation coefficient is higher in dynamic modulus of elasticity to MOR than those

in static modulus of elasticity to MOR and in density to MOR.

Therefore, the dynamic modulus of elasticity using resonance frequency by impact hammer and force transducer mode is useful as a non-destructive evaluation method for predicting the MOR of heat-treated wood.

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