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Nondestructive Bending Strength Evaluation of Woodceramics Made from Woody Part of Broussonetia Kazinoki Sieb.*1

- Effect of Resin Impregnation Ratio -

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ABSTRACT

Nondestructive evaluation (NDE) technique method using a resonance frequency mode was carried out for woodceramics made by different phenol resin impregnation ratios (40, 50, 60, 70%) for *Broussonetia Kazinoki* Sieb. Dynamic modulus of elasticity increased with increasing resin impregnation ratios. There was a close relationship 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. Therefore, the dynamic modulus of elasticity using resonance frequency mode is useful as a nondestructive evaluation method for predicting the MOR of woodceramics made by different impregnation ratios.

Keywords : nondestructive evaluation (NDE), resin impregnation ratio, woodceramics of Broussonetia Kazinoki Sieb, resonance frequency, MOE, MOR

1. INTRODUCTION

Nondestructive evaluation (NDE) techniques have been extensively used for sorting or grading of wood products. There are examples include visual grading and machine stress rating (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, 1990; Byeon & Hong, 1997). Park and Byeon (2006)

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reported that dynamic MOE by resonance frequency using flexural vibration and bending strength and creep performances of a three-ply laminated wood 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. Gerhards (1974) showed that the stress wave speed are affected by such as moisture, temperature, grain angle and knot. A longitudinal stress wave and transverse vibration methods were developed for the estimation of modulus of the elasticity for lumber (Ross & Pellerin, 1991; Ross *et al*., 1991, 1994).

The applications of stress wave signals by impact for log have been reported by several researchers (Aratake *et al*., 1992; Ross *et al*., 1997; Jang, 2000; Park, 2003). Ross *et al*. (1997) and Jang (2000) found that relationship between the MOE of the logs and the lumber obtained from the logs is high. Another stress wave application approaches have been accomplished in degraded wood (Ross *et al*., 1994, 1997). Ross *et al.* (1994) found that the stress wave evaluation technique is effective to detect the presence of wet wood in red oak lumber. Ross *et al*. (1997) also found that the stress wave characteristics have a good coincidence with compressive strength values of biologically degraded wood. The stress wave was also used by Cha (1996) for the development of glulam from Korean small diameter log.

Basic relationship between ultrasonic transmission and wood property was studied (Jang, 2000; Kang & Lee, 2000; Lee *et al*., 2003; Son & Lee, 2008). The ultrasonic was also used to evaluate the property of laminated wood (Hong *et al*., 2001) and to assess wooden ancient buildings (Lee *et al*., 2001).

The NDE of wood using the ultrasonic has been used to detect non-visible defects such as honeycomb or closed surface checks (Anderson *et al*., 1997; Fuller, 1995). Most NDE technique applications focus on sorting and grading the lumber and log.

However, There was few researches in the application of stress wave for NDE of a woodceramics material. It is not suitable method to use impact hammer to evaluate the strength property because of its brittle property.

Therefore, NDE technique using the resonance frequency by free vibration mode was applied to woodceramics produced by different resin impregnation ratios, and the relationship between the resonance frequency parameter and static bending strength properties has been analysed.

2. MATERIALS and METHODS

2.1. Board Manufacture

Particle from woody part of paper mulberry (*Broussonetia Kazinoki* Sieb.) was made from a mill. The particle was screened by 40 mesh sieve and dried to below 8 percent moisture content and then mixed 10 percent powder PF resin (KNB-100PL, Kolon Chemical Co., Ltd).

A board measuring 260 × 260 × 11 mm and a density of 0.6 g/cm^3 was made by hot-pressing and molding at temperature of 190°C. The pressing pressure was 50 kgf/cm^2 → 30 kgf/cm^2 → 20 kgf/cm^2 and pressing time was 6 minutes → 5 minutes → 4 minutes.

2.2. Resin Impregnation and Carbonization

The board was cut into sample measuring 120 × 120 × 11 mm which were then impregnated at controlled resin impregnation ratios of 40, 50, 60 and 70 percent in a decompression impregnation apparatus filled with liquified PF resin (KPD-L777, Kolon Chemical Co., Ltd) at 1 atmosphere. The impregnated specimens were

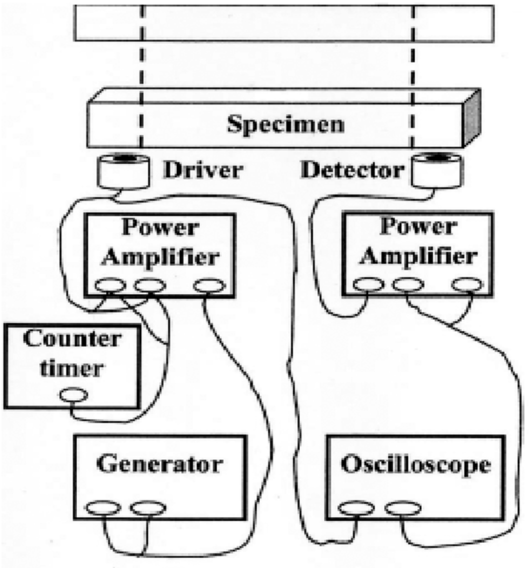

Fig. 1. Schematic diagrams of vibration techniques: magnetic driver.

dried and cured at 60°C for 8 hours, then at 100 and 135°C for 10 hours, respectively.

Woodceramics boards were made in a vacuum sintering furnace (KOVAC KSF-200V). Samples from the board were treated with varying resin impregnation ratios while a carbonizing temperature of 600°C, heating rate of 4°C/min, and maintaining time of 2 hours.

2.3. Resonance Mode and Bending Test

Vibration was induced via a small steel plate attached to the bottom end of the specimens and suspended by two threads at the magnetic driver as shown in Fig. 1. The vibration was received at a small steel plate attached to the other end. The test was made both ends free. The test apparatus was consisted of a sine generator (B & K, 1023), universal counter timer (GSP, 5001), and oscilloscope (HP, 1,740 A). The value of the frequency counter timer was recorded when the relative amplitude indicated the highest value on the oscilloscope. Resonance frequency (f) and dynamic modulus of elasticity (MOE_d) was calculated by the following equations:

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

where f_0: value at frequency counter timer, α: value according to vibration type-8.2, h: thickness of specimen, l: length of specimen.

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

where ρ: density, m: value according to basic vibration-4.73, h: thickness of specimen, l: length of specimen.

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. Dynamic Elastic Properties According to Resin Impregnation Ratio

3.1.1. Resonance Frequency

The mean values of resonance frequency according to different resin impregnation ratios were shown in Table 1 and Fig. 2. The mean values of resonance frequency were 1,949, 2,349, 2,348, 2,318 Hz for 40, 50, 60, 70% of

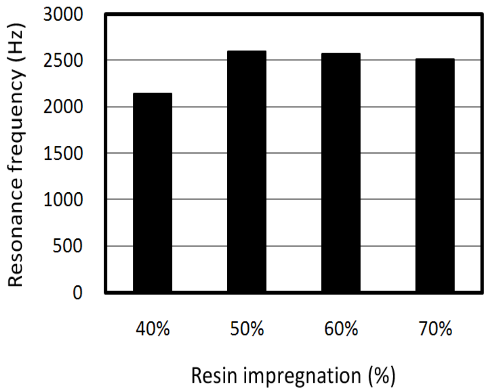

Fig. 2. Resonance frequency according to different resin impregnation ratios at carbonizing temperature of 600°C.

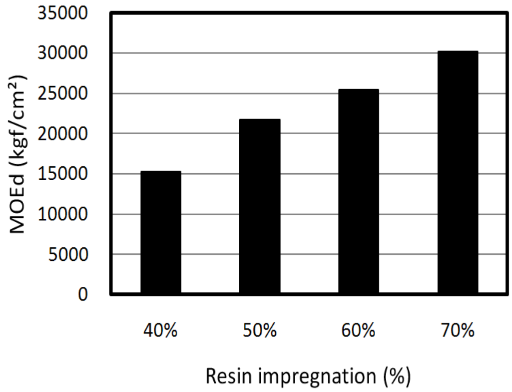

Fig. 3. Dynamic MOE according to different resin impregnation ratios at carbonizing temperature of 600°C.

Table 1. The properties of woodceramics made with different impregnation ratios at carbonizing temperature of 600℃

Impregnation ratio(%)	Density (g/cm^2)	Resonance frequency (Hz)	MOEd (kgf/cm^2)	MOEs (kgf/cm^2)	MOR (kgf/cm^2)
40	0.52 (0.024)	1,949 (177)	15,280 (3,231)	12,150 (2,622)	32 (7)
50	0.55 (0.020)	2,349 (60)	21,698 (2,387)	16,786 (4,408)	46 (10)
60	0.60 (0.011)	2,348 (89)	25,402 (1,945)	21,546 (6,111)	51 (9)
70	0.66 (0.016)	2,318 (136)	30,223 (3,207)	23,877 (8,229)	55 (18)

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

resin impregnation ratio, respectively. Resonance frequency increased with increasing resin impregnation ratio. The density also increased with increasing resin impregnation ratio. Some of the studies show different results, Hong (1995) reported that resonance frequency of normal wood in *Pinus densiflora* increased, whereas that of compression wood decreased, with increasing density.

3.1.2. Dynamic Modulus of Elasticity

The mean values of dynamic modulus of elasticity according to resin impregnation ratio were shown in Table 1 and Fig. 3. The mean values of dynamic modulus of elasticity were 12,150, 16,786, 21,546, 23,877 kgf/cm^2 for 40, 50, 60, 70% of resin impregnation ratio, respectively. Both density and dynamic modulus of elasticity also increased with increasing resin impregnation ratio. Byeon (2004) reported that woodceramics made from particle-board impregnated with phenol resin from three species of *Pinus densiflora, Pinus koraiensis* and *Larixleptolepis* had a similar result. Byeon (2010) also reported that static modulus of elasticity to woodceramics made by *Broussonetia Kazinoki* increased with increasing resin impregnation ratio.

Table 2. Summary of regression parameters for relationships between density, MOR, MOE_d, and MOEs for woodceramics produced by different resin impregnation ratio

Parameter	Regression model	Coefficientof determination R^2	Correlation coefficient r
Density vs. MOEs	y = 94897x - 36430	0.669	0.818
Density vs. RF	y = 2171x + 971	0.348	0.590
Density vs. MOEd	y = 99546x - 35069	0.849	0.921
Density vs. MOR	y = 178.0x - 57.75	0.428	0.654
MOEs vs. MOEd	y = 0.948x - 2796	0.768	0.876
MOEs vs. MOR	y = 0.0021x + 7.028	0.776	0.881
RF vs. MOEd	y = 6E + 06x - 4E + 09	0.875	0.935
RF vs. MOR	y = 0.046x - 58.34	0.412	0.642
RF vs. MOEs	y = 18.11x - 21575	0.340	0.583
MOEd vs. MOR	y = 0.002x - 0.079	0.632	0.795

RF: Resonance frequency; MOEs: static modulus of elasticity; MOEd: dynamic modulus of elasticity; MOR: modulus of rupture

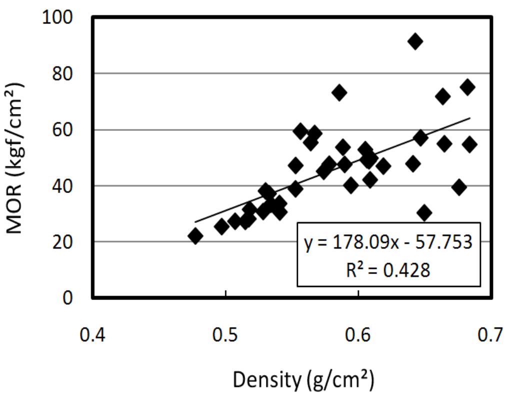

Fig. 4. Relationship between density and MOR according to percentage of resin impregnation at carbonizing temperature of 600°C.

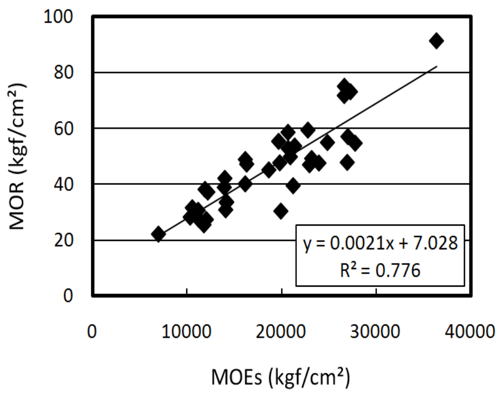

Fig. 5. Relationship between MOEs and MOR according to percentage of resin impregnation at carbonizing temperature of 600°C.

3.2. Relationship Between Density and Mechanical Properties

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. Figs. 4∼6 show relationships between density, static MOEs, dynamic MOE_d and MOR.

The correlation coefficients between density and static MOE, density and resonance frequency, density and dynamic MOE_d, density and MOR (Fig. 4) for woodceramics produced

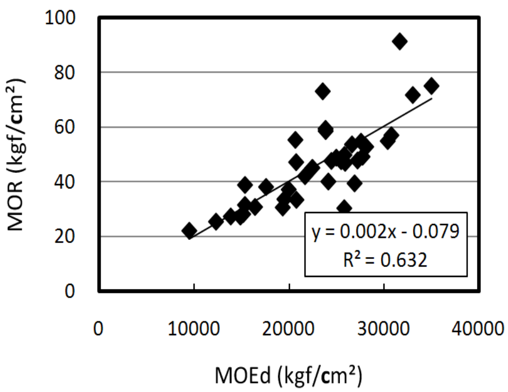

Fig. 6. Relationship between MOEd and MOR according to percentage of resin impregnation at carbonizing temperature of 600°C.

by different resin impregnation ratios were 0.818, 0.590, 0.921 and 0.654, respectively. The correlation coefficient of density versus dynamic MOE_d in the woodceramics made by different impregnation ratio was much higher than the others. Some of the studies show different results, Hong (1995) reported that the correlation coefficient values of density versus dynamic MOE_d relationship for normal wood and compression wood in *Pinus densiflora* were very high values of 0.896 and 0.688.

3.3. Relationship between Static MOEs and Mechanical Properties

Relationship between static MOE and MOR for woodceramics were analyzed. The regression coefficient shows that correlation coefficient between bending MOEs and MOR for woodceramics produced by different impregnation ratio was high value of 0.881 (Table 2 and Fig. 5). It is considered to be caused by the uniform quality of woodceramics inner or outer. Woodceramics, on the other hand, produced from different carbonizing temperatures with three kinds of species (*Pinus densifora, Pinus koraiensis, Larix leptolepis*) had a higher density in outside than those in inside, and were a low correlation coefficient between static MOE and MOR (Byeon, 2004).

3.4. Relationship between MOE_d and Mechanical Properties

Relationships between MOE_d and MOEs, MOR for woodceramics were analyzed (Table 2 and Fig. 6). In this research, the correlation coefficients between dynamic MOE_d versus MOR and static MOEs versus MOR of woodceramics were high 0.795 and 0.881, respectively. And close correlations were found in MOE_d and MOEs for woodceramics produced by different impregnation ratios. Generally, close correlation MOE_d and MOEs for clear solid wood was reported by stress wave mode (Ross & Pellerin, 1991). Some of the studies show different results, Byeon (2004) reported that the correlation coefficient of static MOE and MOR for the woodceramics produced by different carbonizing temperatures was lower value of 0.425.

3.5. Predicting MOR of Woodceramics

Both dynamic MOE_d and static MOEs were correlated to MOR for woodceramics and the results were written in Table 2. The results showed that high correlation coefficients were existed in the dynamic MOE_d and MOR, static MOEs and MOR. On the othe hand, the correlation coefficient between density and MOR was not high.

Therefore, both the dynamic MOE_d and static MOEs are probably a good strength predictor for woodceramics produced by different resin impregnation ratio.

4. CONCLUSIONS

Nondestructive testing method using resonance frequency by flexural free vibration mode was carried out for woodceramics produced by impregnation ratios of 40, 50, 60 and 70%.

Both resonance frequency and dynamic modulus of elasticity increased with increasing resin impregnation ratios.

There was a close relationship between density and dynamic modulus of elasticity.

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.

Therefore, the dynamic modulus of elasticity using resonance frequency mode is useful as a nondestructive evaluation method for predicting the MOR of woodceramics produced by different impregnation ratios.

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