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Nondestructive Bending Strength Evaluation of Ceramics Made from *Miscanthus sinensis* var. *purpurascens* Particle Boards[1]

- Effect of Resin Impregnation Ratio -

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ABSTRACT

Nondestructive evaluation (NDE) method by using a resonance frequency mode was carried out for ceramics made from particle boards with different phenol resin impregnation ratios (30, 40, 50, 60%) at carbonizing temperature of 800℃. The material for ceramics was *Miscanthus sinensi*s var. *purpurascens* board. Dynamic modulus of elasticity increased with increasing impregnation ratio. There was a close relationship of dynamic modulus of elasticity and static bending modulus of elasticity to modulus of rupture (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 free vibration mode is more useful as a nondestructive evaluation method for predicting the MOR of ceramics made from *Miscanthus sinensi*s var. *purpurascens* particle boards by different phenol resin impregnation ratios.

Keywords : Nondestructive evaluation (NDE), ㅈarbonizing temperature, *Miscanthus sinensi*s var. *purpurascens*, Resonance frequency, MOR

1. INTRODUCTION

These days, low-carbon, clean fuels and energy-efficient technologies have been discussed worldwide. *Miscanthus sinensis* var. *purpurascens* particle boards have been considered as one of the viable strategies for achieving sustainable development for low-carbon green growth. Woodceramics are new porous carbon materials obtained by carbonizing wood or woody material impregnated with thermosetting resin such as phenol resin in a vacuum furnace. During the carbonizing process, thermosetting resin changes into glassy carbon, which has superior corrosion resistance and mechanical strength (Okabe *et al.* 1996).

Nondestructive evaluation (NDE) techniques have been extensively used for sorting or grad-

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Table 1. Characteristics of phenol-formaldehyde resin used in this study

Items \ Resin types	Powder resin (Novolak type)	Liquid resin (Resol type)
Solid content (%)	99	51~53
Melting point (°C)	80~95	
Specific gravity	-	1.06
Gelation time (sec.)	80~120	80~95
Plate flow (mm)	30~35	
Viscosity (cps)	-	45~65

ing 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. Basic relationship between ultrasonic transmission and wood property was studied (Kang & Lee, 2000; Lee *et al*., 2003; Son & Lee, 2008). 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).

Therefore, NDE technique using the resonance frequency by free vibration mode was applied to ceramics made by different phenol resin impregnation ratios (30, 40, 50, 60%) and the relationship between the resonance frequency parameter and static bending strength properties were analysed.

2. MATERIALS and METHODS

2.1. Material

The raw material of *Miscanthus sinensis var. purpurascens* for ceramic board was provided from Rural Development Administration National Institute of Crop Science Bio-energy Crop Center in Muan county, Jeollanam province, Korea. The height and stem diameter of this materials were approximately 400 cm and 9.6 mm Respectively. Growth characteristics such as height and stem diameter of this materials were two times greater than those of normal Miscanthus.

2.2. Board Manufacture

Particles from part of *Miscanthus sinensis var. purpurascens* were made by a mill. The particles were screened with 10～20 mesh sieve and dried to below 7 percent moisture content and then mixed 10 percent PF resin powder (KNB-100PL, Kolon Chemical Co., Ltd). Table

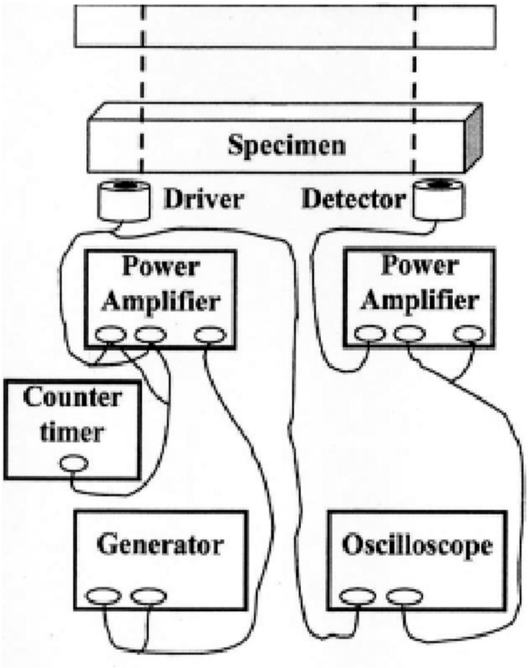

Fig. 1. Schematic diagram of magnetic driver vibration mode.

1 shows the characteristics of phenol-formaldehyde resin used in this test.

A board 260 × 260 × 11 mm and 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 3 min → 2 min → 1 min.

2.3. Resin Impregnation and Carbonization

The board was cut into sample measuring 120 × 120 × 14 mm which were then impregnated at controlled resin impregnation ratios of 30 ± 2%, 40 ± 2%, 50 ± 2%, and 60 ± 2% in a decompression impregnation apparatus filled with liquified PF resin (KPD-L777, Kolon Chemical Co., Ltd) at 1 atmosphere. The thickness of resin impregnated board increased from 11 mm to 14 mm after impregnation of PF resin.

The impregnated specimens were dried and cured at 60°C for 1 hours, then at 100°C and 135°C for 8 hours, respectively. Ceramics boards were made in a vacuum carbonization furnace (KOVAC KSF-200V). Samples from the board were treated with various resin impregnation ratios while a carbonizing temperature of 800°C, heating rate of 4°C/min, and duration of 2 hours remained constant.

2.4. Resonance Mode and Bending Test

The resonance frequency was first measured by a free transverse vibration at both ends system apparatus which was composed of sine generator (B&K, 1023), universal counter timer (GSP, 5001), and oscilloscope (HP, 1740A). The value at frequency counter timer was measured when the relative amplitude value was highest in oscilloscope. Dynamic modulus of elasticity (MOE$_d$) was calculated by the following equations:

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

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^2), m: value according to basic vibration-4.73, h: thickness of specimen (cm), l: $_1$ length of specimen (cm).

After resonance frequency measurement, bending strength property test for the same specimen was performed by a three point loading

Table 2. The physical and mechanical properties of ceramics made at different resin impregnation ratios at carbonizing temperature of 800°C

Impregnation ratio (%)	Temperature (°C)	Density (g/cm^3)	Resonance frequency		MOE$_d$		MOE$_s$ (GPa)	MOR (MPa)
			(Hz)	p-value	(GPa)	p-value		
30	800	0.56 (0.03)	2728 a[1] (198)	0.001	1.36 a (0.27)	0.004	1.21 (0.31)	2.76 (0.83)
40		0.62 (0.05)	2985 b (128)		1.70 b (0.27)		1.63 (0.34)	3.25 (0.75)
50		0.63 (0.03)	3045 b (189)		1.71 b (0.31)		1.66 (0.39)	3.30 (0.97)
60		0.65 (0.03)	3326 b (137)		1.95 b (0.33)		1.82 (0.41)	3.74 (0.95)

Notes ; MOE: modulus of elasticity, MOR: modulus of rupture, Mean value from 10 replications.

[1] Mean followed by the same letter within the same column are not significantly different ($P < 0.05$) according to Duncan's new multiple range test ($n = 2$)

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 (MOE$_S$) 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

Table 2 shows the average values of density, resonance frequency, modulus of rupture (MOR), static modulus of elasticity (MOE$_S$) and the dynamic modulus of elasticity (MOE$_d$) for ceramics made from *Miscanthus sinensis* var. *purpurascen* board by different phenol resin impregnation ratios (30, 40, 50, 60%) at carbonizing temperature of 800°C.

3.1.1. Resonance Frequency

The mean values of resonance frequency according to different resin impregnation ratios were shown in Table 2 and Fig. 2. The mean values of resonance frequency were 2,728, 2,985, 3,045, 3,326 Hz for 30%, 40%, 50%, 60% of resin impregnation ratio, respectively. Resonance frequency increased with increasing resin impregnation ratio. The density also increased with increasing resin impregnation ratio. 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 MOE$_d$ according to resin impregnation ratio ere shown in Table 2 and Fig. 3. The mean values of dynamic MOE were 1.36, 1.70, 1.71, 1.95 GPa for 30%, 40%, 50%, 60% of resin impregnation ratio, respectively. Both density and dynamic modulus of elasticity also increased with increasing resin impre-

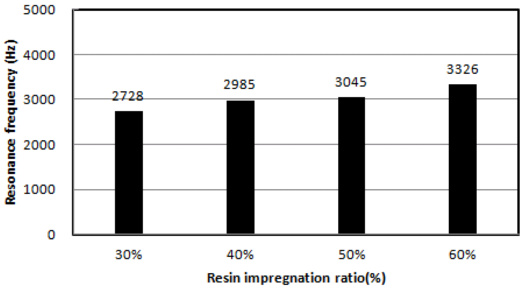

Fig. 2. Resonance frequency according to different resin impregnation ratios at carbonizing temperature of 800°C.

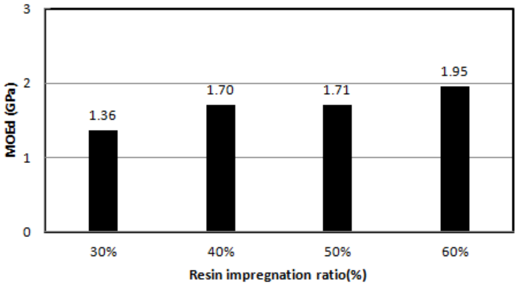

Fig. 3. Dynamic modulus of elasticity according to different resin impregnation ratios at carbonizing temperature of 800°C.

gnation ratio. Byeon (2004) reported that wood-ccearaics had been made from particle board of impregnated with phenol resin from three kinds of species, *Pinus densifora, Pinus koraiensis* and *Larixleptolepis* had a similar tendency. Byeon (2011) also reported that MOE_s to ceramics made by *Broussonetia Kazinoki* increased with increasing resin impregnation ratio.

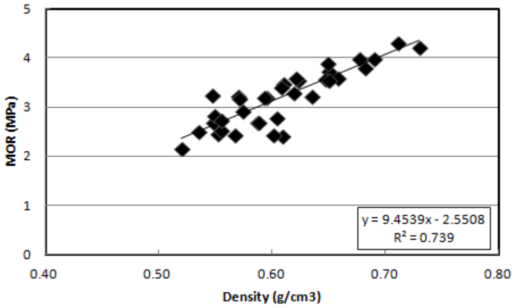

Fig. 4. Relationship between MOR and density according to resin impregnation ratios at carbonizing temperature of 800°C.

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 3 show relationships between density, static MOE_s, dynamic MOE_d and MOR.

The correlation coefficients for density-static MOE, density-resonance frequency, density-dynamic MOE_d, density-MOR (Fig. 4) for ceramics produced by different resin impregnation ratios were 0.808, 0.765, 0.898 and 0.860, respectively. The correlation coefficient of density versus dynamic MOE_d in the ceramics made by different impregnation ratio was much higher than the others. 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 ceramics were analyzed. The regression coefficient shows that correlation coefficient between bending MOE_s and MOR for ceramics produced by different impregnation ratio was high value of 0.757 (Table 3 and Fig. 5). It is considered to be caused by the uniform quality of ceramics inner or outer. Whereas, wood-

Table 3. Summary of regression parameters for relationships between density, MOR, MOE, RF and MOEd for Ceramics produced at different resin impregnation ratios

Parameter	Regression model	Correlation coefficient *r*	p-value
Density vs. MOEs	y = 6.2277x − 2.2406	0.808^{**}	0.000
Density vs. RF	y = 3175.9x + 1011.2	0.765^{**}	0.000
Density vs. MOEd	y = 5.8705x − 1.927	0.898^{**}	0.000
Density vs. MOR	y = 9.4539x − 2.5508	0.860^{**}	0.000
MOEs vs. MOEd	y = 0.9535x − 0.02	0.808^{**}	0.000
MOEs vs. MOR	y = 1.2416x + 1.2777	0.870^{**}	0.000
RF vs. MOEd	y = 0.0014x − 2.3626	0.863^{**}	0.000
RF vs. MOR	y = 0.0019x - 224898	0.723^{**}	0.000
RF vs. MOEs	y = 0.0013x − 2.3078	0.688^{**}	0.000
MOEd vs. MOR	y = 1.4881x + 0.7532	0.884^{**}	0.000

Parenthesis is standard deviation, MOE: modulus of elasticity, MOR: modulus of rupture, RF: resonance frequency, Mean value from 10 replications.

ceramics 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, had a low correlation coefficient between static MOE and MOR (Byeon, 2004).

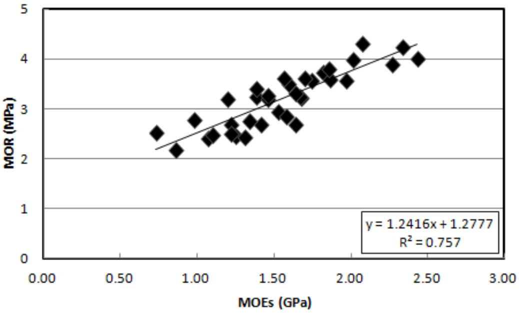

Fig. 5. Relationship between MOR and MOEs according to resin impregnation ratios at carbonizing temperature of 800°C.

3.4. Relationship between MOEd and Mechanical Properties

Relationships between $\mathrm{MOE_d}$ and $\mathrm{MOE_s}$, MOR for ceramics were analyzed (Table 3 and Fig. 6). The correlation coefficient between dynamic $\mathrm{MOE_d}$ to MOR and static $\mathrm{MOE_s}$ to MOR for ceramics were high values of 0.884 and 0.870. And close correlations were found in $\mathrm{MOE_d}$ and $\mathrm{MOE_s}$ for ceramics produced by different impregnation ratios. Generally, close correlation $\mathrm{MOE_d}$ and $\mathrm{MOE_s}$ for clear solid wood was reported by stress wave mode (Ross & Pellerin, 1991). However, 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 Ceramics

The correlation coefficient was higher in dynamic modulus of elasticity to MOR than those in static modulus of elasticity to MOR and density to MOR. Therefore, the dynamic modulus

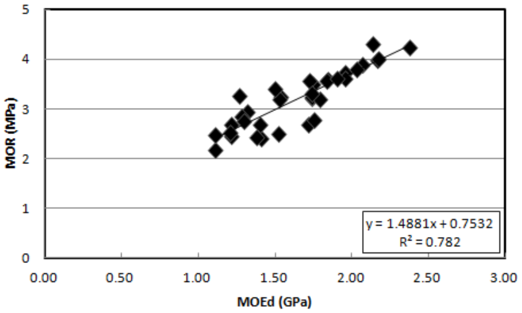

Fig. 6. Relationship between MOR and MOEd according to resin impregnation ratios at carbonizing temperature of 800°C.

of elasticity using resonance frequency by free vibration mode is more useful as a nondestructive evaluation method for predicting the MOR.

4. CONCLUSIONS

Nondestructive evaluation method by using a resonance frequency mode was carried out for ceramics made from particle boards with different phenol resin impregnation ratios (30, 40, 50, 60%) at carbonizing temperature of 800°C. The material for ceramics was *Miscanthus sinensi*s var. *purpurascens* board.

The resonance frequency and dynamic modulus of elasticity increased with increasing phenol resin impregnation ratio. There were close relationships among density vs modulus of rupture (MOR) and static modulus of elasticity vs MOR and dynamic modulus of elasticity vs MOR. However, the result indicated that correlation coefficient is highest in dynamic modulus of elasticity to MOR. Therefore, the dynamic modulus of elasticity using resonance frequency by free vibration mode is most useful as a nondestructive evaluation method for predicting the MOR of ceramics made from *Miscanthus sinensi*s var. *purpurascens* particle boards by different phenol resin impregnation ratios.

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