Influence of Different Pretreatments on the Acoustic Properties of Dawn Redwood (*Metasequoia glyptostroboides* Hu et Cheng)

Yafeng Wu, Tingou Sha, Zijian Zhao, Zhengbin He,* and Songlin Yi *

To modify the acoustic properties of dawn redwood (*Metasequoia glyptostroboides* Hu et Cheng), thermal, ultrasonic, and combined thermal-ultrasound treatments were employed in this work. The changes in the logarithmic decrement (δ), specific Young's modulus (E'/ρ), and extractives content were examined. The results showed that thermal and ultrasonic treatments were both essential for a decrease in the logarithmic decrement (δ) and an increase in the specific Young's modulus (E'/ρ) of dawn redwood (*Metasequoia glyptostroboides* Hu et Cheng). A superposition effect on decreasing of the logarithmic decrement (δ) was discovered after thermal-ultrasound combined treatment. The amounts of extractives, extracted by 95 °C distilled water, 1% NaOH solution, and benzene-ethanol solution, decreased after thermal and ultrasonic treatments. Moreover, there was a linear correlation between logarithmic decrement (δ) and extractives, in which extractives from 1% NaOH solution and 95 °C distilled water had a significant effect. Finally, dawn redwood samples treated with ultrasonic power at 340 W for 9 min at a thermal temperature of 200 °C were chosen as the optimal method in this research.

Keywords: Thermal treatment; Ultrasound treatment; Thermal-ultrasound combined treatment; Logarithmic decrement (δ); Extractives

*Contact information: Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing 100083, China; *Corresponding authors: hzbbjfu@126.com, ysonglin@126.com*

INTRODUCTION

Many musical instruments are made of wood because of its physical and mechanical properties (Brancheriau *et al*. 2006). Specific Young's modulus (E'/ρ) is an acoustical parameter that is preferred to be high in the wood with excellent acoustic quality (Roohnia *et al*. 2015). The logarithmic decrement (δ) is another important acoustical parameter, and it is preferred to be small in the wood with excellent acoustic quality (Roohnia *et al*. 2015). Good instruments require wood with excellent acoustic properties, and the extractives content in wood is a key factor affecting its acoustic quality (Se Golpayegani *et al*. 2012). Extractives can diminish the logarithmic decrement (δ) in some tropical Leguminosae, but they can increase δ in sapwood of *Thuja plicata* (Brémaud *et al*. 2011). Another report has shown that mulberry wood (*Morus alba*) extracted by water has a lower logarithmic decrement (δ) (Roohnia *et al*. 2011), which is an important gauge of acoustic properties (Se Golpayegani *et al*. 2012). Impregnation of spruce wood with extractives of muirapiranga diminish the value of δ in spruce wood (Minato *et al*. 2010). Thus, the effect of extractives on δ is highly dependent on species. It is necessary to find alternative methods for modulating the extractives content in wood and to find the influence of extractives on acoustic properties in different wood species.

Prior research has shown that both thermal treatment and ultrasonic pre-treatment can change the content of extractives in wood. Heat treatment causes a chemical change in pine (*Pinus pinaster*): most of the original extractives disappear and are replaced by new compounds, such as anhydrosugars and phenolic compounds. This process causes wood to degrade, resulting in small mass losses (Esteves *et al*. 2011). And thermal treatment is beneficial to wood dimensional stability, which is a benefit for musical instruments (Nguila Inari *et al*. 2007). The ultrasound procedure mechanically disrupts cell walls, and to release their content while heating the liquid, which increases extractives diffusion (He *et al*. 2012, 2013, 2014). However, there has been nearly no research about the influence of thermal and ultrasonic treatments on the acoustic properties of wood.

This study was designed to improve the acoustic performance of dawn redwood (*Metasequoia glyptostroboides* Hu et Cheng) using thermal and ultrasonic treatments, as well as a thermal-ultrasound combined treatment. Ultrasound treatment was performed prior to the wood drying process, and thermal treatment was applied when the moisture content was reduced to ≤ 10% by conventional drying. Simultaneously, the relationship between extraction content and the change of the logarithmic decrement (δ) was determined.

EXPERIMENTAL

Materials

Four hundred and fifty tangential pieces of dawn redwood sapwood (*Metasequoia glyptostroboides* Hu et Cheng) were obtained from the Guangxi province in China. Specimen size was 3 mm (tangential) × 50 mm (radial) × 230 mm (longitudinal).

The samples were then ground to powder with a wood grinder (60 to 80 μm) for extraction. The initial moisture content ranged from 50±5% to 60±5%.

Methods

1. The dawn redwood samples were divided into 30 groups. Ten pieces in each group.
2. Six groups were treated at temperatures of 120, 140, 160, 180, 200, and 220 °C in water vapor for 30 min after the wood moisture was reduced to ≤ 10% by conventional drying.
3. Sixteen groups were treated by ultrasound for 3, 6, 9, and 12 min at ultrasound powers of 160, 220, 280, and 340 W. Ultrasonic medium was water, and ultrasonic frequency was 20 kHz in this study. And the ultrasonic device was SB-400DTY ultrasonic frequency sweep cleaning machine (Power: 0-400 w; Frequency: 20-40 KHz; Duty cycle: 2h; Nonfocused).
4. Seven groups were treated by both thermal and ultrasound treatments using the conditions that resulted in the best acoustic properties, which were chosen from the former 22 groups. The samples were subjected to ultrasonic treatment for 9 min at 160, 220, 280, or 340 W, treated by the conventional wood drying process, and then thermal-treated at 200 °C . Finally, the samples that underwent ultrasonic treatment for 9 minutes at 160 W were heated at 140, 160, and 180 °C (Table 1).
5. The control group was treated with conventional wood drying to reduce the wood moisture to ≤10%.

Table 1. Thermal-ultrasound Combined Treatment Groups

Group	Ultrasound powers	Time	Heat temperature	Time
1	160 W	9 min	140 °C	30 min
2	160 W		160 °C	
3	160 W		180 °C	
4	160 W		200 °C	
5	220 W		200 °C	
6	280 W		200 °C	
7	340 W		200 °C	

Measurement of the Vibrational Properties

Logarithmic decrement, (δ), an important parameter impacting the acoustic quality of wood, was used to find the damping ratio of an underdamped system in the time domain. The logarithmic decrement (δ) is the natural log of the ratio of the amplitudes of any two successive peaks (Roohnia *et al*. 2011), as determined by Eq. 1,

$$\delta = \frac{1}{n}\ln\frac{x(t)}{x(\mathrm{t+nT})} \tag{1}$$

where $x(t)$ is the amplitude at time t, and $x(t + nT)$ is the amplitude of the peak n periods away, where n is any integral number of successive, positive peaks. The logarithmic decrement (δ) was measured by the mechanical properties for thin wood composites test system (cantilever beam vibration tester).

Specific Young's modulus (E'/ρ) is a materials property consisting of the elastic Young's modulus per mass density of a material. Young's modulus E' was measured by cantilever beam vibration tester in the study. And the density (ρ) measurement error is estimated to be 0.05 to 0.1%.

The cantilever beam vibration tester is an apparatus that measures vibrational properties of small and thin samples of wood or composite panels. The apparatus applies a known displacement to a cantilever beam, then releases it into its natural first mode of transverse vibration, thus making it possible to calculate the logarithmic decrement (δ) and specific Young's modulus (E'/ρ) by recording vibrational tip displacements decrement in each vibration period (Hunt *et al*. 2013). The test was repeated three times and calculated average for the final data. And relative error did not exceed 10%.

Extraction of the Samples

The wood powder was extracted by 95 °C distilled water, 1% NaOH solution, and benzene-ethanol (2:1) solution (TAPPI T207 cm-99, 1999).

RESULTS AND DISCUSSION

Acoustic Properties of Samples

The wood treatment processes reduced the logarithmic decrement (δ) (Tables 2 and 3), and the pretreatment increased the specific Young's modulus (E'/ρ) (Tables 3 and 4). An LSD multi-comparison test was used to categorize the value of δ in treatment, and the test was analyzed by SPSS. There were significant differences between the untreated groups, ultrasonic treated groups, and thermal-ultrasound combined treated groups. The thermal-ultrasound combined treatment had the greatest impact on reducing the logarithmic decrement (δ). An LSD multi-comparison test was used to categorize the specific Young's modulus (E'/ρ) in treatment. There were significant differences between the untreated groups and the other treated groups. Though there were indistinctive differences between thermal treated groups and ultrasonic treated groups, the thermal-ultrasound combined treatment improved the specific Young's modulus most in the study.

Table 2. One-Way ANOVA for Effects of Treatment on Logarithmic Decrement (δ)

	Sum of Squares	*df*	Mean Square	*F*	*p* value
Between Groups	.001	3	.000	38.132	.000
Within Groups	.000	28	.000		
Total	.001	31			

Table 3. LSD Multi-Comparison Test for Effects on Logarithmic Decrement (δ)

(I) Group	(J) Group	Mean Difference (I-J)	SD	*p* value	95% Confidence Interval	
					Lower Limit	Upper Limit
1	2	.0038703*	.0015279	.017	.000740	.007000
	3	.0073949*	.0013595	.000	.004610	.010180
	4	.0138942*	.0014911	.000	.010840	.016949
2	1	-.0038703*	.0015279	.017	-.007000	-.000740
	3	.0035245*	.0010344	.002	.001406	.005643
	4	.0100239*	.0012022	.000	.007561	.012486
3	1	-.0073949*	.0013595	.000	-.010180	-.004610
	2	-.0035245*	.0010344	.002	-.005643	-.001406
	4	.0064993*	.0009792	.000	.004494	.008505
4	1	-.0138942*	.0014911	.000	-.016949	-.010840
	2	-.0100239*	.0012022	.000	-.012486	-.007561
	3	-.0064993*	.0009792	.000	-.008505	-.004494
*not significant at the 5% level						

1, Untreated groups; 2, Thermal treated groups; 3, Ultrasonic treated groups; 4, Thermal-ultrasound combined treated groups

Table 4. One-Way ANOVA for Effects of Treatment on specific Young's Modulus

	Sum of Squares	*df*	Mean Square	*F*	*p* value
Between Groups	343.684	3	114.561	26.103	.000
Within Groups	122.886	28	4.389		
Total	466.571	31			

The logarithmic decrement (δ) decreased when the thermal treatment temperature was varied from 120 °C to 220 °C (Fig. 1). The change in δ was related to the extractives chemical composition (Matsunaga *et al*. 2000). Normally, wood species used for European musical instruments possess low δ values (Takunori *et al*. 2012). The specific Young's modulus (E'/ρ) increased when the thermal treatment temperature was varied from 120 °C to 220 °C (Fig. 3). Thermal treatment causes the degradation of hemicelluloses and thermal cracking reaction in cellulose when the temperature is higher than 165 °C (Boonstra and Tjeerdsma 2006). And the logarithmic decrement (δ) and the specific Young's modulus (E'/ρ) both reached their extreme points at 200 °C. Therefore, heat treatment at 200 °C was judged to be the most appropriate condition for modifying the acoustic properties of dawn redwood in this research.

Table 5. LSD Multi-Comparison Test for Effects on specific Young's modulus

(I) Group	(J) Group	Mean Difference (I-J)	SD	*p* value	95% Confidence Interval	
					Lower Limit	Upper Limit
1	2	-7.3818306*	.0015279	.000	-10.416237	-4.347424
	3	-5.7330683*	.0013595	.000	-8.432951	-3.033185
	4	-11.9386994*	.0014911	.000	-14.899977	-8.977422
2	1	7.3818306*	.0015279	.000	4.347424	10.416237
	3	1.6487623*	.0010344	.111	-.405541	3.703065
	4	-4.5568688*	.0012022	.001	-6.944327	-2.169410
3	1	5.7330683*	.0013595	.000	3.033185	8.432951
	2	-1.6487623*	.0010344	.111	-3.703065	.405541
	4	-6.2056311*	.0009792	.000	-8.150291	-4.260971
4	1	11.9386994*	.0014911	.000	8.977422	14.899977
	2	4.5568688*	.0012022	.001	2.169410	6.944327
	3	6.2056311*	.0009792	.000	4.260971	8.150291
*not significant at the 5% level						

1, Untreated groups; 2, Thermal treated groups; 3, Ultrasonic treated groups; 4, Thermal-ultrasound combined treated groups

The logarithmic decrement (δ) of the ultrasonic treatment groups decreased with increasing treatment time when the treatment time was less than 9 min, while it increased with the treatment time after 9 min. Moreover, the value of δ was reduced with increasing ultrasound power at the same treatment time. Wood extractives influence the logarithmic decrement (δ) (Matsunaga *et al*. 2000). Ultrasound waves were used to extract resins, steroids, and other compounds from the wood samples, which caused the decrease in δ. In this experiment, higher ultrasound power was more effective in releasing extractives. And amorphous regions of wood cellulose was damaged by ultrasound; thus the specific Young's modulus (E'/ρ) increased with increasing treatment time when the treatment time was less than 9 min (Tang and Liang 2000). However, lengthy ultrasound treatment damages the crystal structure of wood, which has a negative effect on its acoustic properties (Tang and Liang 2000). This effect explains why the δ value increased and the E'/ρ value decreased after the 9 min treatment. Therefore, ultrasonic treatment at 340 W for 9 min was the optimal choice in this study.

Figures 1 and 2 show that for thermal-ultrasound combined treatment groups, logarithmic decrement (δ) was lower at higher temperature at the ultrasonic power of 340 W. The logarithmic decrement (δ) was lower with increasing ultrasonic power and a heat treatment temperature of 200 °C.

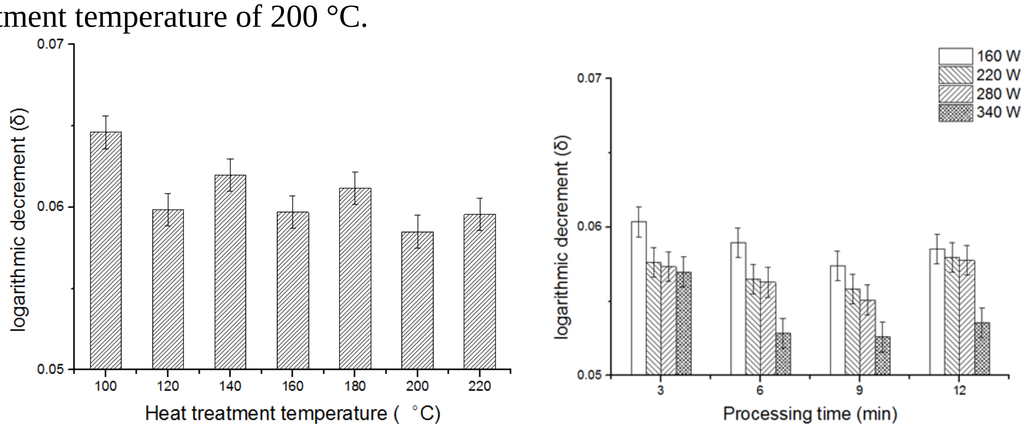

Fig. 1. Effect of thermal and ultrasonic treatment on logarithmic decrement (δ)

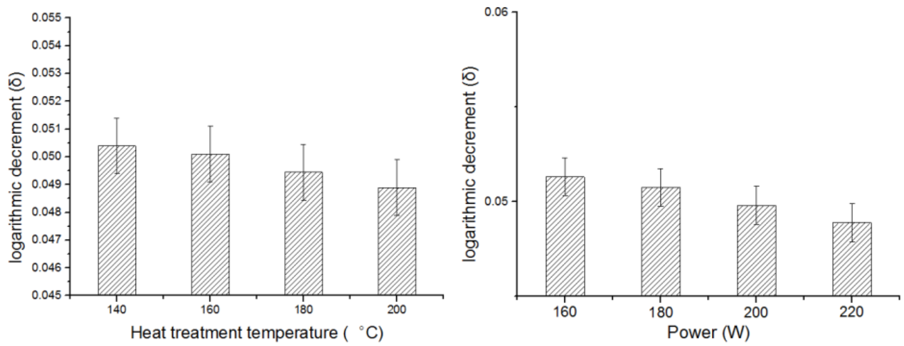

Fig. 2. Effect of thermal-ultrasound combined treatment on logarithmic decrement (δ)

Figures 3 and 4 show that for thermal-ultrasound combined treatment groups, specific Young's modulus (E'/ρ) was higher at higher temperature at the ultrasonic power of 340 W.

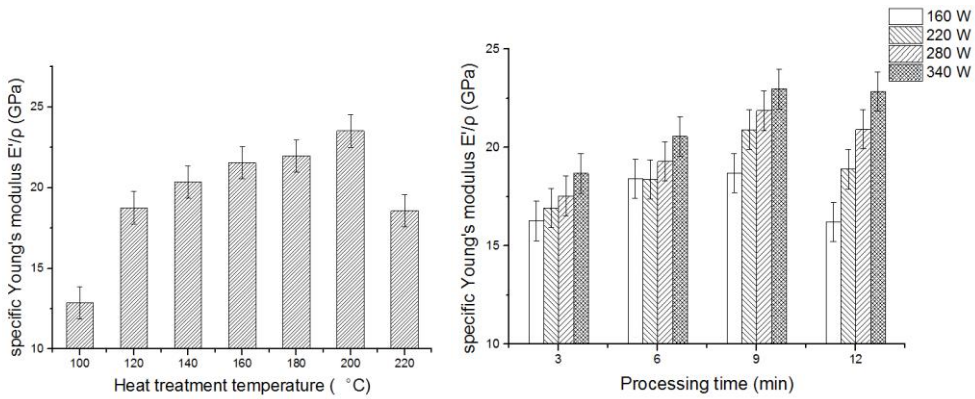

Fig. 3. Effect of thermal and ultrasonic treatment on specific Young's modulus (E'/ρ)

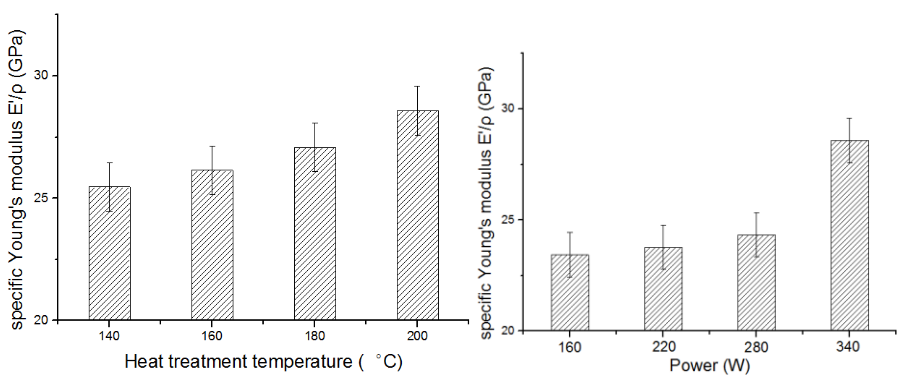

Fig. 4. Effect of thermal-ultrasound combined treatment on specific Young's modulus (E'/ρ)

The specific Young's modulus (E'/ρ) was higher with increasing ultrasonic power and a heat treatment temperature of 200 °C (Figs. 3 and 4). Thus, the best acoustic properties were obtained in the treatment conditions where ultrasonic power was 340 W and thermal temperature was 200 °C in this study.

Amount of Extractives

The extractives content decreased as heat treatment temperature increased, reaching its minimum at 200 °C (Fig. 5). Extractives content of ultrasonic treatment groups decreased as the ultrasonic power and processing time were increased (Figs. 6 and 7). However, the extractives content of thermal-ultrasound combined treatment groups decreased as ultrasonic power and heat treatment temperature was increased (Figs. 8 and 9). The extractives released at 95 °C by distilled water included pigment, tannin, alkaloid, amylum, and pectin, whereas the extractives produced by 1% NaOH solution were primarily protein, amino acid, lignin, and hemicelluloses. However, more resin, wax, and fat are released by extraction with a benzene-ethanol solution (Zhang *et al*. 2009). Wood extractives decreased by 26.91%, 9.12%, and 11.35% after the thermal, ultrasound, and thermal-ultrasound treatments, respectively (Fig. 10). Therefore, thermal treatment was helpful in removing or changing pigment, tannin, alkaloid, amylum, and pectin. Compared with no treatment, the benzene-ethanol solution decreased wood extractives by 66.68% after ultrasonic treatment. The influence of thermal treatment was inferior to ultrasonic treatment on modulating the extractives extracted by 1% NaOH. The extractives content of all samples decreased. Moreover, thermal-ultrasound combined treated groups had the best improvements in acoustic properties in this study.

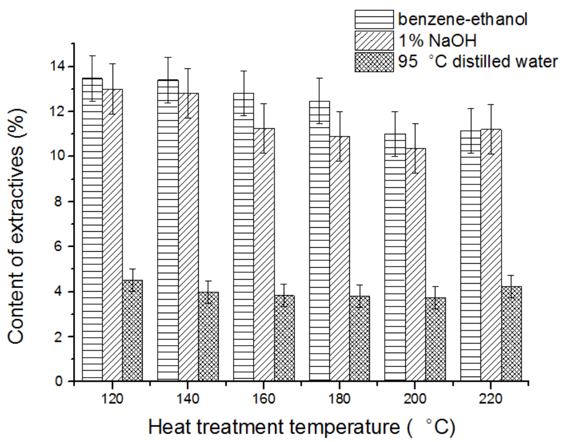

Fig. 5. Effect of temperature on extractives content

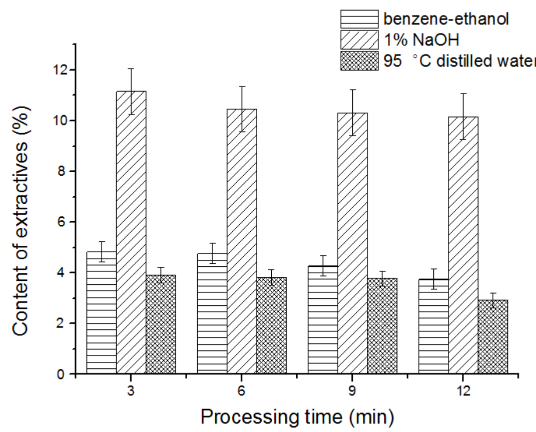

Fig. 6. Effect of time on extractives content

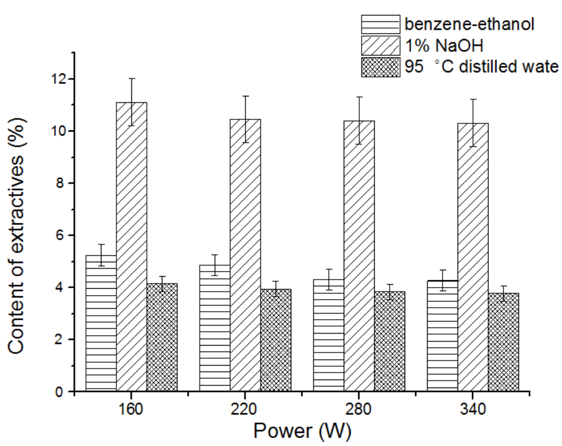

Fig. 7. Effect of ultrasonic power on extractives content

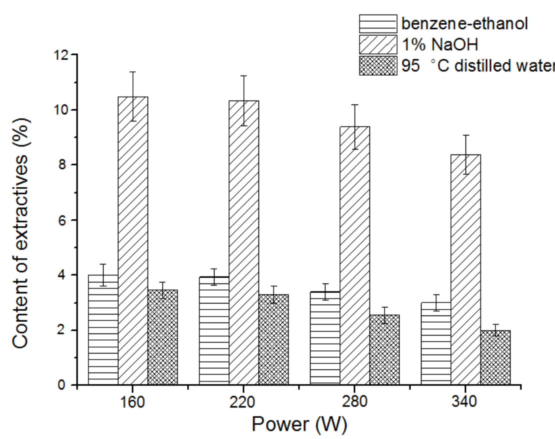

Fig. 8. Effect of different power on extractives content of combined treatment groups

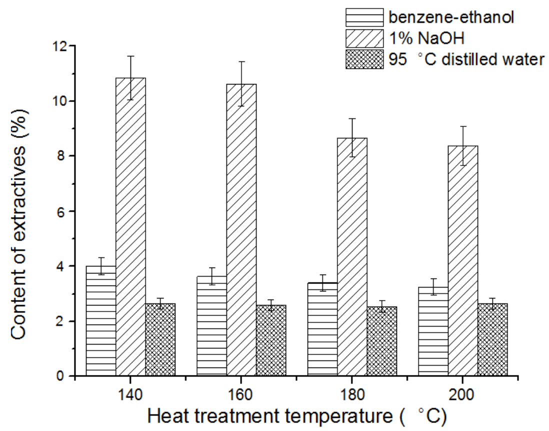

Fig. 9. Effect of different temperatures on extractives content of combined treatment groups

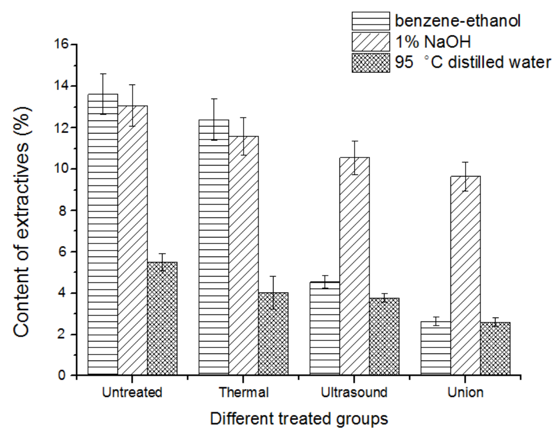

Fig. 10. Extractives content of different groups

Relationship between Logarithmic Decrement (*δ*) and Extractives

Figure 11 shows the relationship between the extractives generated by the three different solutions and the corresponding logarithmic decrement (*δ*). The linear correlation coefficient was 0.646 between the amount of extractives in the 1% NaOH solution and the value of *δ*. The linear correlation coefficient was 0.748 between the amount of extractives in 95 °C distilled water and *δ*. The linear correlation coefficient was 0.811 between amount of extractives in the benzene-ethanol solution and *δ*. Smaller amounts of extractives in 1% NaOH solution or 95 °C distilled water showed strong influence on δ. The results also illustrate that pigment, tannin, and amino acid extracted by 1% NaOH solution and 95 °C distilled water influenced the transmission of sound waves. Particles in an impure medium lead to scattering, which causes additional energy consumption. As a result, the logarithmic decrement (*δ*) increases, and the acoustic properties are unsatisfactory (Noguchi *et al.* 2012). These extractives were eliminated through ultrasound processing or changed in thermal treatment. The value of *δ* then decreased, and the acoustic properties were modified.

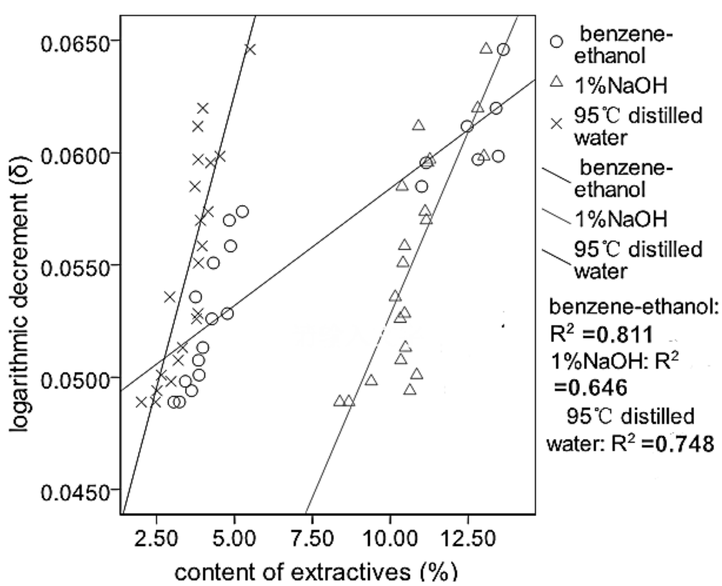

Fig. 11. Relationship between logarithmic decrement (δ) and extractives

CONCLUSIONS

1. Thermal and ultrasonic treatments were both essential for the decreasing logarithmic decrement and increasing specific Young's modulus (E'/ρ) of the wood samples.
2. Treatment with an ultrasonic power of 340 W for 9 min at a temperature of 200 °C was the optimal method used in this study.
3. A synergistic effect occurred after the thermal-ultrasound combined treatment. The combined treatment led to decreased extractives released by 95 °C distilled water, 1% NaOH solution, and benzene-ethanol solution. The decrease in extractives content affected logarithmic decrement (δ).
4. There was a linear correlation between logarithmic decrement (δ) and extractives, smaller amount of extractives in 1% NaOH solution or 95 °C distilled water show strong influence on logarithmic decrement (δ).
5. Changing the extracted chemical materials from the extractive solution was conducive for studying the modification of acoustic properties of wood.

ACKNOWLEDGMENTS

This paper was supported by "The national science foundation of China-Study on the moisture migration mechanism during ultrasonic-assisted wood vacuum superheated steam drying (31270604)."

REFERENCES CITED

Boonstra, M. J., and Tjeerdsma, B. (2006). "Chemical analysis of heat treated softwoods," *Holz Roh. Werkst.* 64(3), 204-211. DOI: 10.1007/s00107-005-0078-4

Brancheriau, L., Baillères, H., Détienne, P., Gril, J., and Kronland, R. (2006). "Key signal and wood anatomy parameters related to the acoustic quality of wood for xylophone-type percussion instruments," *J. Wood Sci.* 52(3), 270-273. DOI: 10.1007/s10086-005-0755-2

Bre´maud, I., Amusant, N., Minato, K., Gril, J., and Thibaut, B. (2011). "Effect of extractives on vibrational properties of African Padauk (*Pterocarpus soyauxii* Taub.)," *Wood Sci. Technol.* 45(2), 461-472. DOI 10.1007/s00226-010-0337-3.

Esteves, B., Videira, R., and Pereira, H. (2011). "Chemistry and ecotoxicity of heat-treated pine wood extractives," *Wood Sci. Technol.* 45(4), 661-676. DOI: 10.1007/s00226-010-0356-0

He, Z. B., Yang, F., Yi, S. L., and Gao, J. M. (2012). "Effect of ultrasound pretreatment on vacuum drying of Chinese catalpa wood," *Dry. Technol.* 30(15), 1750-1755. DOI:10.1080/07373937.2012.713420

He, Z. B., Yang, F., Peng, Y. Q., and Yi, S. L. (2013). "Ultrasound-assisted vacuum drying of wood: Effects on drying time and product quality," *BioResources* 8(1), 855-863. DOI: 10.15376/biores.8.1.855-863.

He, Z. B., Zhao, Z. J., Yang, F., and Yi, S. L. (2014). "Effect of ultrasound pretreatment on wood prior to vacuum drying," *Maderas Cienc. Tecnol.* 16(4), 395-402. DOI: 10.4067/S0718-221X2014005000031.

Hunt, John F., Zhang, H. J., Guo, Z. R., and Fu, F. (2013). "Cantilever beam static and dynamic response comparison with mid-point bending for thin MDF composite panels," *BioResources* 8(1), 115-129. DOI: 10.15376/biores.8.1.115-129.

Matsunaga, M., Sakai, K., Kamitakahara, H., Minato, K., and Nakatsubo, F. (2000). "Vibrational property changes of spruce wood by impregnation with water-soluble extractives of pernambuco (*Guilandina echinata* Spreng.) II: Structural analysis of extractive components," *J. Wood Sci.* 46(3), 253-257. DOI: 10.1007/BF00776458.

Minato, K., Konaka, Y., Bremaud, I., Suzuki, S., and Obataya, E. (2010). "Extractives of muirapiranga (*Brosimun* sp.) and its effects on the vibrational properties of wood," *J. Wood Sci.* 56(1), 41-46. DOI: 10.1007/s10086-009-1051-3.

Nguila Inari, G., Petrissans, M., and Gerardin, P. (2007). "Chemical reactivity of heat-treated wood," *Wood Sci. Technol.* 41(2), 157-168. DOI: 10.1007/s00226-006-0092-7.

Noguchi, T., Obataya, E., and Ando, K. (2012). "Effects of aging on the vibrational properties of wood," *J. Cult. Herit.* 13(3), S21-S25. DOI: 10.1016/j.culher.2012.02.008.

Roohnia, M., Hashemi-Dizaji, S.-F., Brancheriau, L., Tajdini, A., Hemmasi, A.-H., and Manouchehri, N. (2011). "Effect of soaking process in water on the acoustical quality of wood for traditional musical instruments," *BioResources* 6(2), 2055-2065. DOI: 10.15376/biores.6.2.2055-2065.

Roohnia, M., Kohantorabi, M., and Tajdini, A. (2015). "Maple wood extraction for a better acoustical performance," *Eur. J. Wood Prod*. 73(1), 139-142. DOI 10.1007/s00107-014-0871-z.

Se Golpayegani, A., Brémaud, I., Gril, J., Thevenon, M.-F., Arnould, O., and Pourtahmasi, K. (2012). "Effect of extractions on dynamic mechanical properties of white mulberry (*Morus alba*)," *J. Wood Sci.* 58(2), 153-162. DOI: 10.1007/s10086-011-1225-7.

Tang, A. M., and Liang, W. Z. (2000). "Studies on the structure changes of fast-growing wood fiber treated by ultrasonic wave," *Technic. Acoust.* 19(2), 78-85. DOI: 10.3969/j.issn.1000-3630.2000.02.008.

Zhang, Z. F., Peng, W. X., and Li, K. F. (2009). "Influence of extraction technology on *Eucalyptus urophydis* wood shrinkage," *Journal of Central South University of Forestry and Technology* 29(4), 165-168. DOI: 10.14067/j.cnki.1673923x.2009.04.033.

Article submitted: September 8, 2015; Peer review completed: December 18, 2015; Revised version received: January 20, 2016; Accepted: January 22, 2016: Published: February 1, 2016.
DOI: 10.15376/biores.11.1.2734-2743