EFFECT OF COATING THICKNESS ON SOUND ABSORPTION PROPERTY OF FOUR WOOD SPECIES COMMONLY USED FOR PIANO SOUNDBOARDS

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Abstract. Effects of polyurethane (PU) coating thicknesses (0.15, 0.30, 0.45, and 0.60 mm) on sound absorption coefficients of four wood species were investigated using the standing wave ratio method with an input sound vibration frequency range set between 125 and 4000 Hz. Wood species of four specific gravity (SG) levels were Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla*. Experimental results indicated that PU coating can significantly increase sound absorption coefficients of higher SG species such as Sitka spruce and *Picea brachytyla* in all tested frequency levels, but this significant increase was not observed in lower SG species such as Korean and European spruces when tested in the frequency range from 800 to 2000 Hz. Effects of coating thickness on sound absorption coefficients of four evaluated species were found to interact with wood SG values and input sound vibration frequency ranges. Specifically, coating 0.30-mm-thick PU on Korean and European spruces tends to result in significantly lower sound absorption coefficients among the ones coated with four evaluated thicknesses when tested at the frequency less than 800 Hz, but PU coating thickness resulting in lower sound absorption coefficients on Sitka spruce and *Picea brachytyla* was 0.15 mm. Sitka spruce and *Picea brachytyla* coated with 0.30- and 0.6-mm-thick PU had lower sound absorption coefficients when tested at the frequency ranging from 1000 to 2000 Hz. When tested at the frequency greater than 2500 Hz, sound absorption coefficients of four coated species increased as coating thickness increased from 0.30 to 0.60 mm with an increment of 0.15 mm, but these four species coated with three thicker PU had significantly lower sound absorption coefficients than the ones coated with 0.15-mm-thick PU. The uncoated higher SG species tended to have lower sound absorption coefficients than

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uncoated lower SG ones when tested in the frequency ranging from 500 to 4000 Hz, but the differences were not found when tested under the frequency less than 400 Hz. Coating four species with different thicknesses of PU could alter their SG effects on their sound absorption coefficients.

Keywords: Piano soundboard, spruce wood, coating thicknesses, specific gravity, sound absorption coefficient.

INTRODUCTION

Piano is one of the string instruments vibrating air and producing extremely weak sound. The role of a piano soundboard is to act like a microphone and greatly increase the volume of this weak sound (Miu 1981; Jin 2008). Acoustical performances of a piano, such as volume control and pronunciation persistence, are mainly influenced by the sound absorption performance of soundboards. Therefore, soundboards are one of the most important acoustical components in piano construction, and its sound absorption performance needs to be evaluated and understood. The sound absorption coefficient is a physical quantity (Bucur et al 1999; Zou 2007; Guan et al 2009) describing the sound absorption performance of a material at different frequencies. There are two typical methods by which sound can be absorbed by a sound absorbent or acoustic material. The first one is that sound is absorbed by a porous material, whereas the second one is that sound is absorbed by setting the material into damped vibration as a diaphragm; therefore, the more the damping, the greater the absorption of sound (Chrisler 1940).

A wood material used for piano soundboards needs to have a lower sound absorption coefficient to reflect the acoustic energy produced by the string vibration as much as possible. The *Picea* wood, commonly used for piano soundboards because of its poorer sound absorption performance, is a natural polymer material with the advantages of simple color, natural texture, and easy processing. However, *Picea* wood has some defects such as discoloration and poor dimensional stability, which might need surface finishing treatment. But, the surface finishing treatment if performed improperly can easily impair the sound quality of a piano (Yan et al 2018).

Currently, some piano manufacturers still keep their soundboards uncoated to maintain their original acoustic quality. Consequently, wood defects such as shrinkage, expansion, and cracking can significantly affect the sound quality of piano products (Cai and Li 2011). Most of the piano manufacturers have started their coating operation through applying polyurethane (PU) varnish on soundboards to prolong the service life of piano soundboards and meanwhile maintain their surface beauty (Luo et al 2009). However, coating soundboards can result in altering their sound absorption performance in terms of their sound absorption coefficients.

Suzuki (1986) investigated the vibration and sound radiation properties of Steinway piano soundboards. Liu et al (2001) and Shen et al (2005) studied the effects of *Picea* genera wood growth rings on its sound vibration properties. Ma (2005) and Wu et al (2019a, 2019b) analyzed the effects of the anatomical structure of wood as a porous material on its acoustic vibration properties. Shen et al (2001) investigated the effects of *Picea* genera wood densities on their longitudinal and radial loss tangents. Wang et al (2015) investigated the specific gravity (SG) and

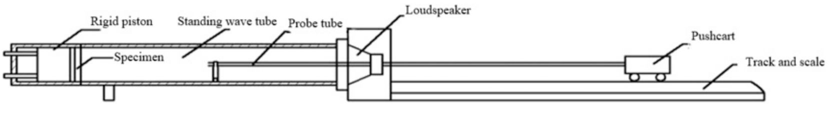

Figure 1. Illustration of the instrument setup for measuring the sound absorption coefficient of wood materials evaluated in this study.

Table 1. Mean values of sound absorption coefficients for each combination of input sound vibration frequency (125-2000 Hz) by wood specific gravity (SG) by coating thickness and mean comparisons of the sound absorption coefficient for coating thickness within each combination of frequency by SG.

	SG									
	0.39					0.42				
	Thickness (mm)[a]									
Frequency (Hz)	0	0.15	0.30	0.45	0.60	0	0.15	0.30	0.45	0.60
125	0.083 (7.2)C	0.146 (3.1)B	0.139 (3.5)B	0.139 (9.4)B	0.191 (2.1)A	0.117 (6.0)D	0.132 (15.8)C	0.138 (5.8)C	0.191 (1.6)A	0.168 (9.4)B
160	0.074 (11.3)C	0.133 (3.7)B	0.132 (5.2)B	0.131 (3.6)B	0.165 (2.8)A	0.103 (9.4)C	0.125 (5.6)B	0.122 (4.1)B	0.153 (2.8)A	0.152 (4.6)A
200	0.022 (12.0)D	0.112 (12.5)B	0.101 (6.9)C	0.128 (2.8)A	0.133 (2.7)A	0.017 (15.6)C	0.104 (2.5)B	0.097 (4.7)B	0.114 (2.3)A	0.114 (3.0)A
250	0.015 (6.7)C	0.096 (2.1)B	0.098 (3.1)B	0.118 (2.2)A	0.116 (3.5)A	0.009 (11.1)C	0.096 (3.8)A	0.088 (4.1)B	0.099 (3.6)A	0.103 (4.2)A
315	0.016 (14.1)D	0.084 (3.1)B	0.072 (9.1)C	0.094 (4.9)A	0.089 (4.9)AB	0.014 (18.9)C	0.082 (3.7)A	0.072 (4.2)B	0.076 (5.7)AB	0.083 (5.3)A
400	0.018 (14.9)D	0.078 (1.3)AB	0.061 (13.3)C	0.083 (5.5)A	0.072 (3.7)B	0.018 (14.7)C	0.068 (8.9)AB	0.062 (7.4)B	0.065 (6.7)B	0.074 (3.6)A
500	0.026 (10.2)D	0.062 (1.6)B	0.054 (3.8)C	0.076 (5.3)A	0.070 (1.4)A	0.028 (9.4)C	0.062 (7.4)B	0.057 (6.1)B	0.064 (5.6)AB	0.072 (6.4)A
630	0.025 (10.6)D	0.049 (5.4)B	0.041 (6.5)C	0.064 (5.6)A	0.068 (5.3)A	0.030 (15.3)D	0.045 (9.7)C	0.045 (6.8)C	0.055 (4.8)B	0.065 (4.1)A
800	0.032 (8.9)B	0.039 (6.8)B	0.035 (7.6)B	0.059 (4.5)A	0.056 (7.8)A	0.040 (6.6)B	0.034 (7.8)B	0.039 (5.1)B	0.057 (4.6)A	0.051 (10.4)A
1000	0.050 (4.0)A	0.040 (2.5)B	0.031 (11.6)C	0.045 (5.9)AB	0.047 (2.5)AB	0.055 (4.8)A	0.039 (14.3)B	0.040 (6.6)B	0.058 (6.2)A	0.054 (6.7)A
1250	0.057 (6.1)A	0.044 (7.9)B	0.035 (15.1)C	0.042 (6.0)B	0.045 (11.1)B	0.054 (13.9)A	0.044 (18.6)B	0.045 (10.4)B	0.045 (3.8)B	0.050 (9.2)AB
1600	0.059 (6.1)B	0.080 (3.3)A	0.055 (9.4)B	0.061 (4.3)B	0.062 (7.0)B	0.058 (4.6)B	0.092 (3.5)A	0.056 (10.9)B	0.056 (9.9)B	0.055 (11.4)B
2000	0.068 (14.0)AB	0.075 (1.3)A	0.049 (8.9)C	0.061 (10.0)B	0.062 (4.3)B	0.061 (4.3)B	0.077 (3.4)A	0.053 (11.5)C	0.056 (4.7)BC	0.062 (8.5)B

	SG									
	0.44					0.51				
	Thickness (mm)[a]									
Frequency (Hz)	0	0.15	0.30	0.45	0.60	0	0.15	0.30	0.45	0.60
125	0.106 (14.5)D	0.124 (4.9)C	0.136 (3.1)B	0.146 (9.0)A	0.139 (4.5)AB	0.108 (11.8)E	0.139 (5.0)C	0.148 (8.8)B	0.130 (7.6)D	0.158 (5.5)A
160	0.092 (5.0)C	0.123 (4.3)B	0.126 (6.1)B	0.137 (3.2)A	0.128 (5.5)B	0.095 (7.4)C	0.128 (6.1)B	0.139 (3.1)A	0.124 (5.8)B	0.142 (4.4)A
200	0.024 (18.2)C	0.094 (3.8)B	0.106 (5.4)A	0.108 (4.2)A	0.107 (4.1)A	0.024 (14.4)C	0.105 (5.8)AB	0.112 (3.2)A	0.102 (2.6)B	0.111 (3.9)A
250	0.020 (13.2)C	0.083 (4.3)B	0.104 (4.2)A	0.099 (2.7)A	0.097 (3.7)A	0.016 (16.5)C	0.095 (5.6)AB	0.102 (3.5)A	0.092 (4.5)B	0.099 (3.1)A
315	0.019 (13.9)D	0.073 (2.4)C	0.092 (2.9)A	0.083 (3.2)B	0.085 (5.1)AB	0.014 (18.9)B	0.080 (3.3)A	0.086 (3.1)A	0.082 (4.4)A	0.081 (3.3)A
400	0.019 (10.5)D	0.063 (5.7)C	0.088 (2.0)A	0.073 (6.3)B	0.073 (6.3)B	0.014 (7.1)C	0.069 (9.1)B	0.074 (3.6)AB	0.080 (4.5)A	0.069 (5.8)B
500	0.022 (19.8)D	0.060 (7.3)C	0.081 (4.5)A	0.070 (3.8)B	0.071 (3.7)B	0.018 (14.7)D	0.061 (5.9)C	0.066 (5.5)BC	0.076 (5.7)A	0.072 (7.2)AB
630	0.016 (6.3)D	0.048 (9.1)C	0.076 (3.5)A	0.056 (3.7)B	0.057 (8.0)B	0.014 (18.9)D	0.049 (7.4)C	0.053 (8.2)C	0.075 (4.8)A	0.062 (8.4)B
800	0.012 (14.4)D	0.038 (7.9)C	0.059 (6.1)A	0.047 (4.3)B	0.044 (9.9)B	0.017 (15.6)D	0.040 (10.9)C	0.045 (5.9)C	0.065 (8.1)A	0.057 (3.0)B
1000	0.018 (14.7)B	0.043 (8.4)A	0.044 (6.0)A	0.044 (6.0)A	0.041 (11.2)A	0.023 (17.8)D	0.043 (2.3)C	0.042 (14.5)C	0.065 (4.1)A	0.050 (5.3)B
1250	0.020 (13.2)C	0.046 (5.8)A	0.038 (7.0)B	0.040 (13.9)A	0.041 (11.2)A	0.020 (13.2)C	0.047 (7.7)B	0.040 (13.2)B	0.057 (4.6)A	0.041 (8.8)B
1600	0.027 (7.4)C	0.076 (11.7)A	0.055 (8.3)B	0.061 (8.7)B	0.058 (4.6)B	0.026 (17.6)D	0.101 (4.6)A	0.064 (9.8)B	0.064 (8.7)B	0.051 (2.3)C
2000	0.043 (6.2)C	0.063 (7.3)A	0.054 (8.5)B	0.058 (3.4)AB	0.061 (7.5)AB	0.035 (15.1)C	0.068 (3.9)A	0.059 (3.4)B	0.061 (9.1)AB	0.054 (9.8)B

[a] Values in parentheses are coefficients of variation in percentage; five means in each row within each combination of frequency by SG not followed by a common letter or two common letters are significantly different one from another at the $p = 0.05$ level.

grain orientation effects of three wood species, balsa (SG = 0.19), Chinese fir (SG = 0.36), and sassafras (SG = 0.59), on their sound absorption coefficients through testing these species under the frequency range from 50 to 6400 Hz and concluded that the lower SG wood yielded higher sound absorption coefficients, and the transverse section had the highest sound absorption coefficient (0.4053), followed by the tangential section (0.3043) and then the radial section (0.2794).

Limited literature is found to be related to the studies of coating effects on sound absorption coefficients of solid wood materials as piano soundboards, especially coating thickness. Chrisler (1940) investigated the effect of the application of an interior flat white oil paint on sound absorption coefficients of different porous materials, including the materials made of wood fibers, and indicated that the effect of a coat of paint in changing the absorption property of a porous material varies considerably for different types of materials. A material with large pores could have the sound absorption coefficient increased by the first few coats of paint, but finally a stage will be reached where the absorption property begins to decrease. It was pointed out that the point where the loss in the absorption property begins also depends on the sound frequency. Materials with small pores may have a considerable number of pores closed with the first coat of paint; therefore, one would expect a decrease in the sound absorption coefficient of the material painted. It was observed that some of the materials can be painted with only one or two coats before there is noticeable decrease in the sound absorption of the material, whereas other materials can be painted many times before the acoustic properties of the materials have been decreased. It was concluded that the principal factor affecting the decrease in absorption is the amount of pigment depositing on the material surface. In addition, it was pointed out that the results presented were not as complete as might be desired, but the materials evaluated were quite representative of most of the acoustic materials which were on the market at the time. Ivanova et al (2018) studied the effect of the protective coating (including water-soluble lacquer, PU lacquer, and hard wax oil) on the sound absorption coefficient of Scots pine (*Pinus sylvestris* L.) wood as flooring and wall lining materials when evaluated at the frequency range from 250 Hz to 2 kHz and observed that applying hard wax oil can significantly increase the sound absorption coefficient of Scots pine wood when tested at the frequency range from 700 to 2000 Hz, but when tested at the frequency range from 250 to 600 Hz, no significant increase trend was observed. Applying water-soluble lacquer or PU lacquer can significantly increase the sound absorption coefficient of Scots pine wood when tested at the frequency range from 1600 to 2000 Hz, but will lower the sound absorption coefficient of Scots pine wood at most of the cases when tested at the frequency range from 250 to 1500 Hz. Therefore, this study was carried out to mainly investigate the effects of coating thickness on the sound absorption performance of four wood species coated with different thicknesses of PU finish by measuring their sound absorption coefficients using the wave ratio method.

MATERIALS AND METHODS

Materials

Four pieces of 5000-mm-long × 200-mm-wide × 300-mm-thick quarter-sawn boards of each of four evaluated wood species, far east Korean spruce (*Picea glehnii*), European spruce (*Picea abies*), Sitka spruce (*Picea sitchenrsis*), and *Picea brachytyla*, were used in this study. The origins of Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla* were Russian Far East, European Alps region, AK regions of West Coast North America, and the Sichuan-Yunnan-Tibet region, respectively. The primer used in the experiment was a mixture of PU primer, curing agent, and thinner at the volume ratio of 1:0.5:0.7. The finish coating is a mixture of PU topcoat, curing agent, and thinner at the volume ratio of 1:0.5:0.8.

Experimental Design

Figure 1 illustrates the instrument setup used in this study for measuring the sound absorption

Table 2. Mean values of sound absorption coefficients for each combination of input sound vibration frequency (2500-4000 Hz) by wood specific gravity (SG) by coating thickness and mean comparisons of the sound absorption coefficient for coating thickness within each combination of frequency by SG.

	SG									
	0.39					0.42				
	Thickness (mm)[a]									
Frequency (Hz)	0	0.15	0.30	0.45	0.60	0	0.15	0.30	0.45	0.60
2500	0.055 (6.6)C	0.123 (2.2)A	0.055 (5.6)C	0.066 (7.5)B	0.069 (8.0)B	0.054 (13.0)C	0.099 (4.4)A	0.058 (10.5)C	0.061 (7.5)B	0.066 (9.5)B
3150	0.068 (6.7)E	0.238 (2.6)A	0.097 (3.7)D	0.118 (3.0)C	0.128 (4.6)B	0.072 (7.3)D	0.201 (2.2)A	0.091 (4.8)C	0.104 (5.1)B	0.109 (4.0)B
4000	0.130 (3.1)C	0.278 (1.5)A	0.233 (5.2)B	0.275 (2.3)A	0.279 (1.5)A	0.151 (2.9)E	0.286 (2.2)A	0.210 (2.9)D	0.247 (2.3)C	0.256 (2.4)B

	SG									
	0.44					0.51				
	Thickness (mm)[a]									
Frequency (Hz)	0	0.15	0.30	0.45	0.60	0	0.15	0.30	0.45	0.60
2500	0.043 (12.9)D	0.094 (5.9)A	0.061 (7.1)C	0.066 (4.0)B	0.069 (9.5)B	0.031 (8.5)D	0.154 (1.9)A	0.069 (9.6)C	0.075 (3.5)BC	0.080 (4.5)B
3150	0.074 (4.9)D	0.198 (3.2)A	0.106 (1.6)C	0.109 (4.2)BC	0.116 (4.8)B	0.045 (4.4)E	0.223 (2.4)A	0.096 (3.8)D	0.132 (2.7)C	0.155 (3.4)B
4000	0.111 (5.0)D	0.254 (2.8)A	0.219 (3.0)C	0.240 (1.8)B	0.242 (2.7)B	0.081 (6.9)D	0.263 (2.4)A	0.192 (3.4)C	0.240 (1.8)B	0.247 (2.9)B

[a] Values in parentheses are coefficients of variation in percentage; five means in each row within each combination of frequency by SG not followed by a common letter or two common letters are significantly different one from another at the $p = 0.05$ level.

coefficient of wood materials. In general, a disc with its nominal dimensions of 10 mm thickness and 100 mm diameter was used for the measurement of the sound absorption coefficient of wood materials when the input sound vibration frequency range is set from 125 to 2000 Hz, whereas a disc of 10 mm thickness and 50 mm diameter was used when the input frequency range was from 2000 to 4000 Hz (CNS 2004).

Therefore, in this experiment, two sets of three-factor factorial experiments with three replications per combination were performed to evaluate three factors, especially coating thickness, on the sound absorption coefficient of wood discs with nominal diameters of 50 and 100 mm, respectively. The three factors were SG of wood, PU coating thickness, and input sound vibration frequency. The first set of experiments had the combinations of four levels of wood SG (0.39, 0.42, 0.44, and 0.51, which were represented by four wood species, Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla*, respectively) by five levels of PU coating thickness (0, 0.15, 0.30, 0.45, and 0.60 mm) by 13 levels of input sound vibration frequency (125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, and 2000 Hz). The second set of experiments had the combinations of four levels of wood SG (0.39, 0.42, 0.44, and 0.51, which were represented by four wood species, Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla*, respectively) by PU coating thickness (0, 0.15, 0.30, 0.45, and 0.60 mm) by three levels of input sound vibration frequency (2500, 3150, and 4000 Hz).

Specimen Preparation and Testing

Two different sized discs with smooth surface were randomly selected from their corresponding two suppliers prepared by cutting full-size quarter-sawn boards of each of the four wood species evaluated in this experiment. Before the coating process, all discs were conditioned in a humidity chamber controlled at 30°C and 35% RH for 40 h. SG and MC of the four wood species were tested according to CNS (2009a, 2009b). The complete cycle of a coating process started with measuring the thickness of each uncoated disc at three different points selected (CNS 2013), followed by spraying the primer on one side of each disc, sanding out burrs after 4 h of primer spraying, then applying the finish coating, allowing overnight curing, and then completing the coating on the opposite side of the same disc by repeating the previous steps. The first coating thickness level of 0.15 mm was obtained by completing one full coating cycle, whereas 0.30-, 0.45-, and 0.60-mm thickness levels were obtained through the completion of two, three, and four full coating cycles, respectively. All coated discs were placed in a humidity chamber controlled at 30°C and 35% RH for 10 to 15 d to ensure all coated discs were completely dried before thickness measuring. The coating thickness of each coated disc was obtained through subtracting the thickness of a disc measured without coating from the measured thickness of a disc with coating (CNS 2013).

The sound absorption coefficient of a specimen was measured using the JTZB sound absorption coefficient test system (Fig 1) based on the standing wave ratio method (CNS 2004). The instrument, equipped with a power amplifier, a dedicated spectrum analyzer, and a standing wave tube, is capable of measuring the sound absorption coefficient of a wooden disc with the frequency of an input testing plane sound wave ranging from 125 to 6300 Hz. A low-frequency standing wave tube (125-2000 Hz) was used in Experiment #1, whereas an intermediate-frequency standing wave tube (200-4000 Hz) was used in Experiment #2. During testing, a disc was placed at one end of the standing wave tube (Fig 1). Once the plane sound wave of a generated frequency was vertically emitted from the loudspeaker, a standing wave was formed in the tube. The maximum sound pressure value $p_{\max}$, dB (corresponding to the maximum sound pressure level, $l_{\max}$) and the minimum sound pressure $p_{\min}$, dB (corresponding to the minimum sound pressure level $l_{\min}$) were measured using the probe tube.

The sound absorption coefficient α is calculated using the following formula (CNS 2004):

$$\alpha = \frac{4 \times 10^{\Delta L/20}}{\left(10^{\Delta L/20} + 1\right)^2} \tag{1}$$

where ΔL is the difference between the maximum and minimum sound pressure values, dB.

Statistical Analyses

A three-factor analysis of variance (ANOVA) general linear model (GLM) procedure was performed to analyze significances of three main effects and their interactions. Mean comparisons using the protected least significant difference (LSD) multiple comparison procedure were performed if any significant interaction was identified; otherwise, main effects were concluded. All statistical analyses were performed at the 5% significance level.

RESULTS AND ANALYSIS

Physical Properties

The SG of Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla* discs averaged 0.39, 0.42, 0.44, and 0.51, respectively, and their corresponding coefficients of variation (COV) averaged 8.24%, 10.20%, 6.95%, and 9.36%, respectively. The MC values averaged 6.95%, 7.04%, 7.12%, and 7.35%, respectively, and their corresponding COV values averaged 13.21%, 8.12%, 10.40%, and 7.49%, respectively, for Korean spruce, European spruce, Sitka spruce, and *Picea brachytyla* discs.

Mean Comparisons and Factor Analyses

Tables 1 and 2 summarize mean values of sound absorption coefficients of the four wood species evaluated in two experiments in this study. Table 3 summarizes ANOVA results of the GLM procedure performed for each of the two experiments, indicating that the three-factor interaction was significant for each of the two experiments. This suggested that further analyses should be focused on each of the two significant three-factor interactions. Two one-way classifications of 260 and 60 treatment combinations were created, respectively, to evaluate mean differences among those combinations using the protected LSD multiple comparison procedure. The LSD values used for performing mean comparisons of sound absorption coefficients in Experiments #1 and #2 were 0.0081 and 0.0085, respectively.

The results of mean comparisons of sound absorption coefficients in Experiments #1 and #2 for the coating thickness within each combination of sound vibration frequency and wood SG are summarized in Tables 1 and 2, respectively. The results of mean comparisons of sound absorption coefficients in Experiments #1 and #2 for SG within each combination of sound vibration frequency and coating thickness are summarized in Tables 4 and 5, respectively. In addition, in assisting the vitalization of general trends of sound absorption coefficients as a function of sound vibration frequency under the influence of coating thickness and wood SG, Figs 2-5 are plotted. Figure 2 plots mean values of sound absorption coefficients as a function of sound

Table 3. Summary of analysis of variance results of the general linear model procedure performed on three factors for each of two experiments conducted in this study.

	Experiment #1		Experiment #2	
Source	*F* value	*p* value	*F* value	*p* value
SG	33.36	<0.0001	55.08	<0.0001
Thickness	2090.49	<0.0001	2668.82	<0.0001
SG × thickness	41.74	<0.0001	43.88	<0.0001
Frequency	2244.06	<0.0001	12,500.9	<0.0001
SG × frequency	7.61	<0.0001	66.21	<0.0001
Thickness × frequency	85.53	<0.0001	330.70	<0.0001
SG × thickness × frequency	8.89	<0.0001	9.77	<0.0001

SG, specific gravity.

Table 4. Mean comparisons of sound absorption coefficients for wood specific gravity (SG) within each combination of input sound vibration frequency (125-2000 Hz) by coating thickness.

	Thickness (mm)											
	0				0.15				0.30			
	SG[a]											
Frequency (Hz)	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51
125	0.083 C	0.117 A	0.106 B	0.108 B	0.146 A	0.132 BC	0.124 D	0.139 AB	0.139 B	0.138 B	0.136 B	0.148 A
160	0.074 C	0.103 A	0.092 B	0.095 B	0.133 A	0.125 B	0.123 B	0.128 AB	0.132 AB	0.122 C	0.126 B	0.139 A
200	0.022 A	0.017 A	0.024 A	0.024 A	0.112 A	0.104 B	0.094 C	0.105 AB	0.101 BC	0.097 C	0.106 AB	0.112 A
250	0.015 AB	0.009 B	0.020 A	0.016 AB	0.096 A	0.096 A	0.083 B	0.095 A	0.098 A	0.088 B	0.104 A	0.102 A
315	0.016 A	0.014 A	0.019 A	0.014 A	0.084 A	0.082 A	0.073 B	0.080 AB	0.072 B	0.072 B	0.092 A	0.086 A
400	0.018 A	0.018 A	0.019 A	0.014 A	0.078 A	0.068 B	0.063 B	0.069 B	0.061 C	0.062 C	0.088 A	0.074 B
500	0.026 A	0.028 A	0.022 AB	0.018 B	0.062 A	0.062 A	0.060 A	0.061 A	0.054 C	0.057 C	0.081 A	0.066 B
630	0.025 A	0.030 A	0.016 B	0.014 B	0.049 A	0.045 A	0.048 A	0.049 A	0.041 C	0.045 C	0.076 A	0.053 B
800	0.032 B	0.040 A	0.012 C	0.017 C	0.039 A	0.034 A	0.038 A	0.040 A	0.035 C	0.039 BC	0.059 A	0.045 B
1000	0.050 A	0.055 A	0.018 B	0.023 B	0.040 A	0.039 A	0.043 A	0.043 A	0.031 B	0.040 A	0.044 A	0.042 A
1250	0.057 A	0.054 A	0.020 B	0.020 B	0.044 A	0.044 A	0.046 A	0.047 A	0.035 B	0.045 A	0.038 AB	0.040 AB
1600	0.059 A	0.058 A	0.027 B	0.026 B	0.080 C	0.092 B	0.076 C	0.102 A	0.055 B	0.056 B	0.055 B	0.064 A
2000	0.068 A	0.061 A	0.043 B	0.035 C	0.075 AB	0.077 A	0.063 C	0.068 B	0.049 B	0.053 AB	0.054 AB	0.059 A

	Thickness (mm)							
	0.45				0.60			
	SG[a]							
Frequency (Hz)	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51
125	0.139 B	0.191 A	0.146 B	0.130 C	0.191 A	0.168 B	0.139 D	0.158 C
160	0.131 B	0.153 A	0.137 B	0.124 C	0.165 A	0.152 B	0.128 D	0.142 C
200	0.128 A	0.114 B	0.108 BC	0.102 C	0.133 A	0.114 B	0.107 B	0.111 B
250	0.118 A	0.099 B	0.099 B	0.092 B	0.116 A	0.103 B	0.097 B	0.099 B
315	0.094 A	0.076 C	0.083 BC	0.082 BC	0.089 A	0.083 A	0.085 A	0.081 B
400	0.083 A	0.065 C	0.073 B	0.080 AB	0.072 A	0.074 A	0.073 A	0.069 A
500	0.076 A	0.064 B	0.070 AB	0.076 A	0.070 A	0.072 A	0.071 A	0.072 A
630	0.064 B	0.055 C	0.056 C	0.075 A	0.068 A	0.065 A	0.057 B	0.062 AB
800	0.059 A	0.057 B	0.047 C	0.065 A	0.056 A	0.051 AB	0.044 B	0.057 A
1000	0.045 B	0.058 A	0.044 B	0.065 A	0.047 AB	0.054 A	0.041 B	0.050 A
1250	0.042 B	0.045 B	0.040 B	0.057 A	0.045 AB	0.050 A	0.041 B	0.041 B
1600	0.061 A	0.056 B	0.061 A	0.064 A	0.062 A	0.055 AB	0.058 AB	0.051 B
2000	0.061 A	0.056 A	0.058 A	0.061 A	0.062 A	0.062 A	0.061 A	0.054 B

[a] Four means in each row within each combination of frequency by coating thickness not followed by a common letter or two common letters are significantly different one from another at the $p = 0.05$ level.

vibration frequency for all five coating thickness levels in Experiment #1 within each of the four wood species, respectively. Figure 3 plots mean values of sound absorption coefficients as a function of sound vibration frequency for all five coating thickness levels in Experiment #2 within each of the four wood species, respectively. Figure 4 plots mean values of sound absorption coefficients of the four evaluated wood species as a function of sound vibration frequency from 125 to 2000 Hz, that is, the data in Experiment #1, for each of five coating thickness levels, respectively. Figure 5 plots mean values of sound absorption coefficients of the four evaluated wood species as a function of sound vibration frequency from 2500 to 4000 Hz, that is, the data in Experiment #2, for each of five coating thickness levels, respectively.

Film thickness effects. Figure 2(a) and (b) indicates in general that when tested under the sound vibration frequency less than 800 Hz, Korean and European spruces coated with PU exhibited significantly higher sound absorption coefficients than those uncoated (Table 1). Within these two coated spruces, the ones coated with 0.15- and 0.30-mm-thick PU tended to have significantly lower sound absorption coefficients than the ones with 0.45- and 0.60-mm-thick PU, and the ones coated with 0.30-mm-thick PU tended to have the lowest sound absorption coefficients among the four coated thicknesses. When tested under the sound vibration frequency equal to or greater than 800 Hz (Fig 2[a] and [b]), the significant trend of the two coated spruces exhibiting higher sound absorption coefficients was not found, that is, Korean and European spruces, especially coated with 0.30-, 0.45-, and 0.60-mm-thick PU, tended to show equal or lower sound absorption coefficients than the uncoated ones, and two spruces coated with 0.30-mm-thick PU tended to show significantly lower sound absorption coefficients than the uncoated ones (Table 1).

Figure 2(c) indicates that coated Sitka spruce yielded significantly higher sound absorption coefficients than uncoated ones when tested under the sound vibration frequency ranging from 125 to 2000 Hz. Within coated Sitka spruces, when tested under the sound vibration frequency ranging from 125 to 800 Hz, the ones coated with 0.30-mm-thick PU had the highest sound absorption coefficient among the ones coated with four evaluated PU thicknesses, followed by the ones coated with 0.45-mm-thick PU, which was not significantly different from the ones coated with 0.6-mm-thick PU, and then the ones coated with 0.15-mm-thick PU which had the lowest sound absorption coefficient among the ones coated with four evaluated PU thicknesses (Table 1). When tested under the sound vibration frequency ranging from 1000 to 2000 Hz, the ones coated with 0.30-, 0.45-, and 0.60-mm-thick PU tended to have similar sound absorption coefficients and were lower than the ones coated with 0.15-mm-thick PU.

Figure 2(d) indicates that coated *Picea brachytyla* yielded significantly higher sound absorption coefficients than the uncoated ones when tested under the sound vibration frequency ranging from 125 to 2000 Hz. Within coated *Picea brachytyla*, when tested under the sound vibration frequency ranging from 125 to 315 Hz (Table 1), the ones coated with 0.15- and 0.45-mm-thick PU tended to have lower sound absorption coefficients than the ones coated with other two thicknesses. When tested under the sound vibration frequency ranging from 400 to 800 Hz, the ones coated with 0.15- and 0.30-mm-thick PU tended to have lower sound absorption coefficients than the ones coated with other two thicknesses. When tested under the sound vibration frequency ranging from 1000 to 2000 Hz, the ones coated with 0.30- and 0.60-mm-thick PU tended to have lower sound absorption coefficients than the ones coated with other two thicknesses.

Figure 3 indicated that when tested under the sound vibration frequency greater than 2500 Hz, the coated species exhibited significantly higher sound absorption coefficients than the uncoated ones (Table 2). Within the four coated species, sound absorption coefficients increased as the coating thickness increased from 0.30 to 0.60 mm with an increment of 0.15 mm at each of three sound vibration frequency levels, and species coated with 0.15-mm-thick PU had significantly higher sound absorption coefficients than the ones coated with other three thicker PU.

Table 5. Mean comparisons of sound absorption coefficients for wood specific gravity (SG) within each combination of input sound vibration frequency (2500-4000 Hz) by coating thickness.

	Thickness (mm)											
	0				0.15				0.30			
	SG[a]											
Frequency (Hz)	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51
2500	0.055 A	0.054 A	0.043 B	0.031 C	0.123 B	0.099 C	0.094 C	0.154 A	0.055 C	0.058 C	0.061 B	0.069 A
3150	0.068 A	0.072 A	0.074 A	0.045 B	0.238 A	0.201 C	0.198 C	0.223 B	0.097 B	0.091 B	0.106 A	0.096 B
4000	0.130 B	0.151 A	0.111 C	0.081 D	0.278 B	0.286 A	0.254 D	0.263 C	0.233 A	0.210 C	0.219 B	0.192 D

	Thickness (mm)							
	0.45				0.60			
	SG[a]							
Frequency (Hz)	0.39	0.42	0.44	0.51	0.39	0.42	0.44	0.51
2500	0.066 B	0.061 B	0.066 B	0.075 A	0.069 B	0.066 B	0.069 B	0.080 A
3150	0.118 B	0.104 C	0.109 C	0.132 A	0.128 B	0.109 C	0.116 C	0.155 A
4000	0.275 A	0.247 B	0.240 B	0.240 B	0.279 A	0.256 B	0.242 C	0.247 C

[a] Four means in each row within each combination of frequency by coating thickness not followed by a common letter or two common letters are significantly different one from another at the $p = 0.05$ level.

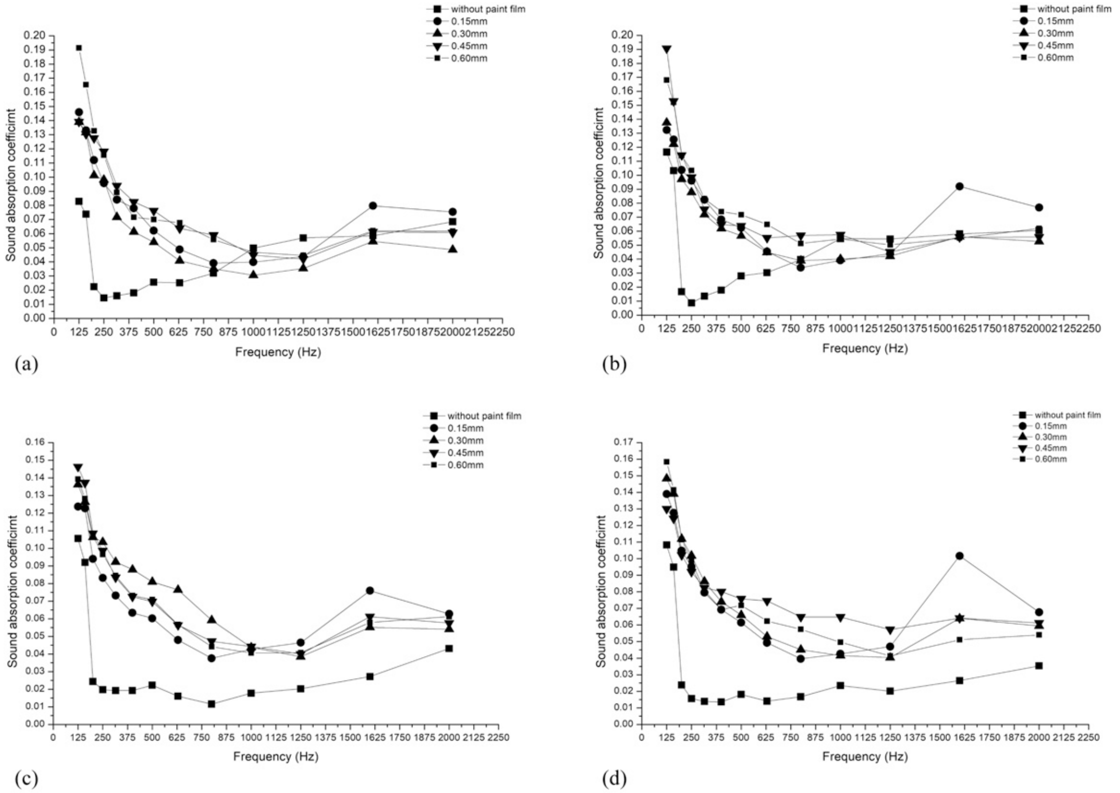

Figure 2. Sound absorption coefficients as a function of sound vibration frequency ranging from 125 to 2000 Hz for five coating thicknesses within each of four wood species: Korean spruce (a), European spruce (b), Sitka spruce (c), and *Picea brachytyla* (d).

SG effects. Figure 4(a) indicates that in the case of uncoated species tested in the sound vibration frequency ranging from 500 to 2000 Hz, the higher SG species such as Sitka spruce and *Picea brachytyla* had significantly (Table 4) lower sound absorption coefficients than the lower SG species such as Korean and European spruce (Wang et al 2015), and there were no significant differences in sound absorption coefficients between two species within each of low and high SG groups. When tested in the sound vibration frequency ranging from 200 to 400 Hz, there were no significant differences in sound absorption coefficients among the four species within each input sound vibration frequency level, and these observations were different from the ones concluded by Wang et al (2015). When tested at the lower frequency range from 125 to 160 Hz, the lowest SG species Korean spruce had significantly lower sound absorption coefficients than other three, and this observation was different from the ones concluded by Wang et al (2015), and the higher SG species such as Sitka spruce and *Picea brachytyla* had significantly lower sound absorption coefficients than low SG European spruce (Table 5). Figure 5(a) shows that when tested in the sound vibration frequency ranging from 2500 to 4000 Hz, the high SG species such as Sitka spruce and *Picea brachytyla* tended to show significantly lower sound absorption coefficients than low SG ones such as Korean and European spruce (Table 5), and the highest SG species *Picea brachytyla* had the lowest sound vibration frequency among the four species (Wang et al 2015).

Figures 4(b) and 5(b) indicate that coating 0.15-mm-thick PU on the four species tested in two

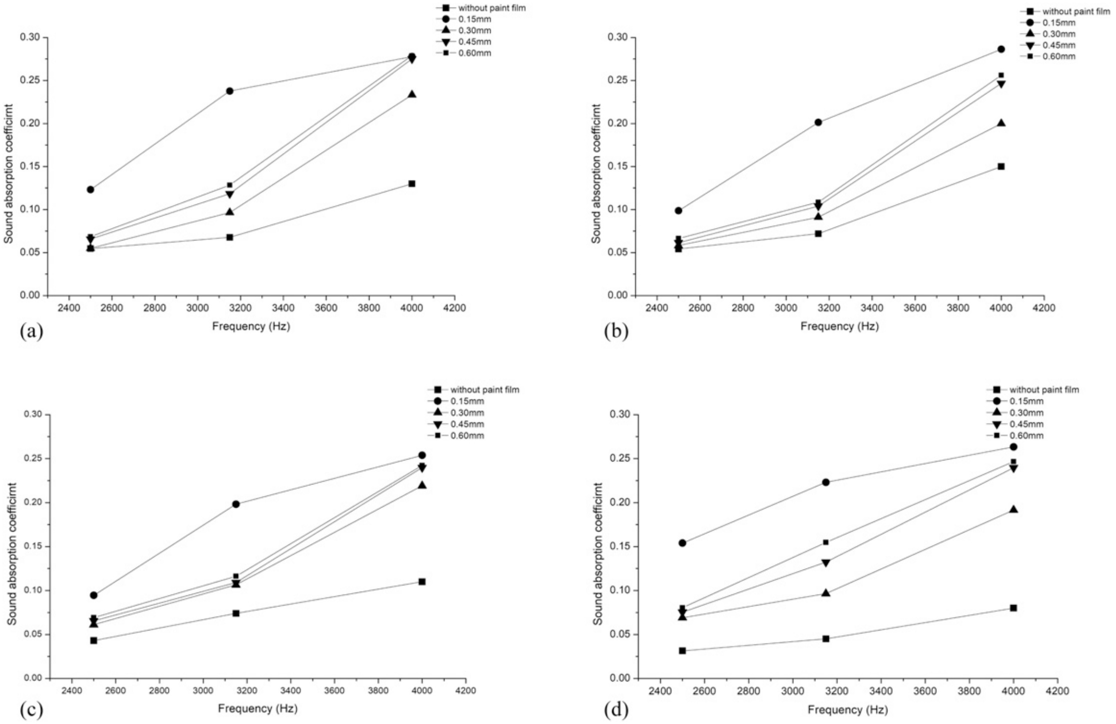

Figure 3. Sound absorption coefficients as a function of sound vibration frequency ranging from 2500 to 4000 Hz for five coating thicknesses within each of four wood species: Korean spruce (a), European spruce (b), Sitka spruce (c), and *Picea brachytyla* (d).

input sound vibration frequency ranges resulted in no significant difference trend in sound absorption coefficients among the four coated species, and only coated Sitka spruce tended to have lower sound absorption coefficients than the other three coated species (Table 5).

Figure 4(c) indicates that coating 0.30-mm-thick PU on the four species tested in two input sound vibration frequency ranges resulted in the lower SG species such as Korean and European spruces tending to show lower sound absorption coefficients than the higher SG species such as Sitka spruce and *Picea brachytyla*. This difference was significant within the frequency range from 315 to 1000 Hz (Table 4), and especially, coated Sitka spruce had significantly higher sound absorption coefficients than the other three coated species, whereas coated Korean spruce yielded significantly lower sound absorption coefficients among the four coated species.

Figure 4(d) indicates that coating 0.45-mm-thick PU on the four species tested in the input sound vibration frequency range from 125 to 250 Hz resulted in the highest SG species *Picea brachytyla* tending to show the lowest sound absorption coefficients among the four coated species, but showing the highest sound absorption coefficients among the four coated species (Table 5) when tested in the frequency range from 500 to 3150 Hz (Fig 5[d]). Coated European spruce showed lower sound absorption coefficients among the four coated species when tested in two frequency ranges of 315-630 Hz and 1600-3150 Hz. Coated Sitka spruce had lower sound absorption coefficients among the four coated species when tested in the frequency range from 800 to 1250 Hz.

Figure 4(e) indicates that coating 0.60-mm-thick PU on the four species tested in the input sound vibration frequency range from 125 to 2000 Hz resulted in two lower SG species Korean and European spruces tending to have higher sound

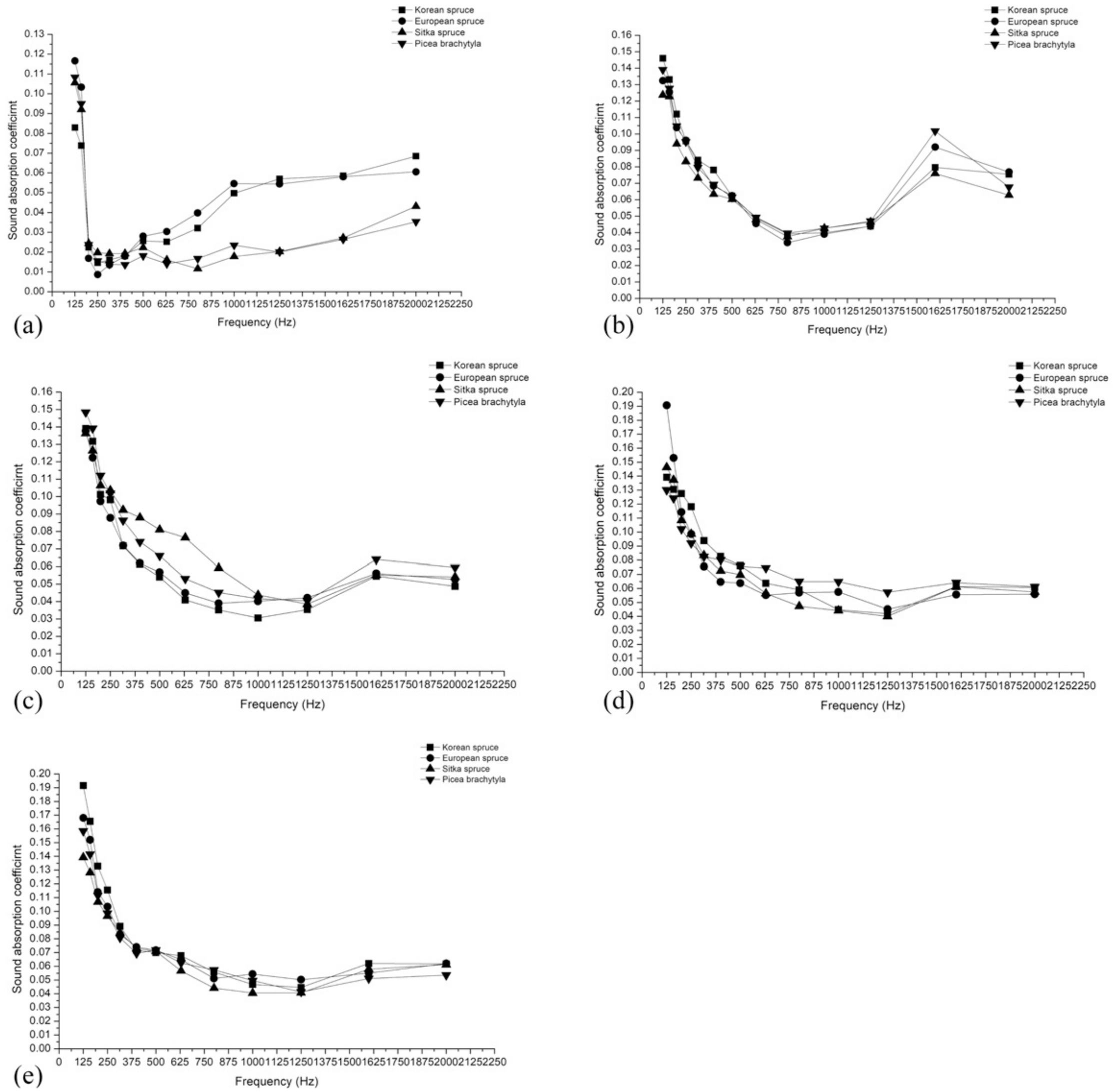

Figure 4. Sound absorption coefficients as a function of sound vibration frequency ranging from 125 to 2000 Hz for four wood species within each of five coating thicknesses: (a) 0, (b) 0.15, (c) 0.30, (d) 0.45, and (e) 0.60 mm, respectively.

absorption coefficients than the two higher SG species Sitka spruce and *Picea brachytyla* (Table 5). Coated Sitka spruce tends to have the lowest sound absorption coefficients among the four coated species when tested in two frequency ranges of 125-250 Hz and 630-1250 Hz, whereas coated *Picea brachytyla* tends to have the lowest sound absorption coefficients among the four coated species when tested in two frequency ranges of 315-500 Hz and 1600-2000 Hz.

CONCLUSIONS

The effects of PU coating thicknesses on sound absorption coefficients of four wood species with their averaged SG values ranging from 0.39 to 0.51 were investigated under two different sound vibration frequency ranges. These two ranges were 125-2000 Hz and 2500-4000 Hz.

Experimental results indicated that the mean values of sound absorption coefficients measured for the

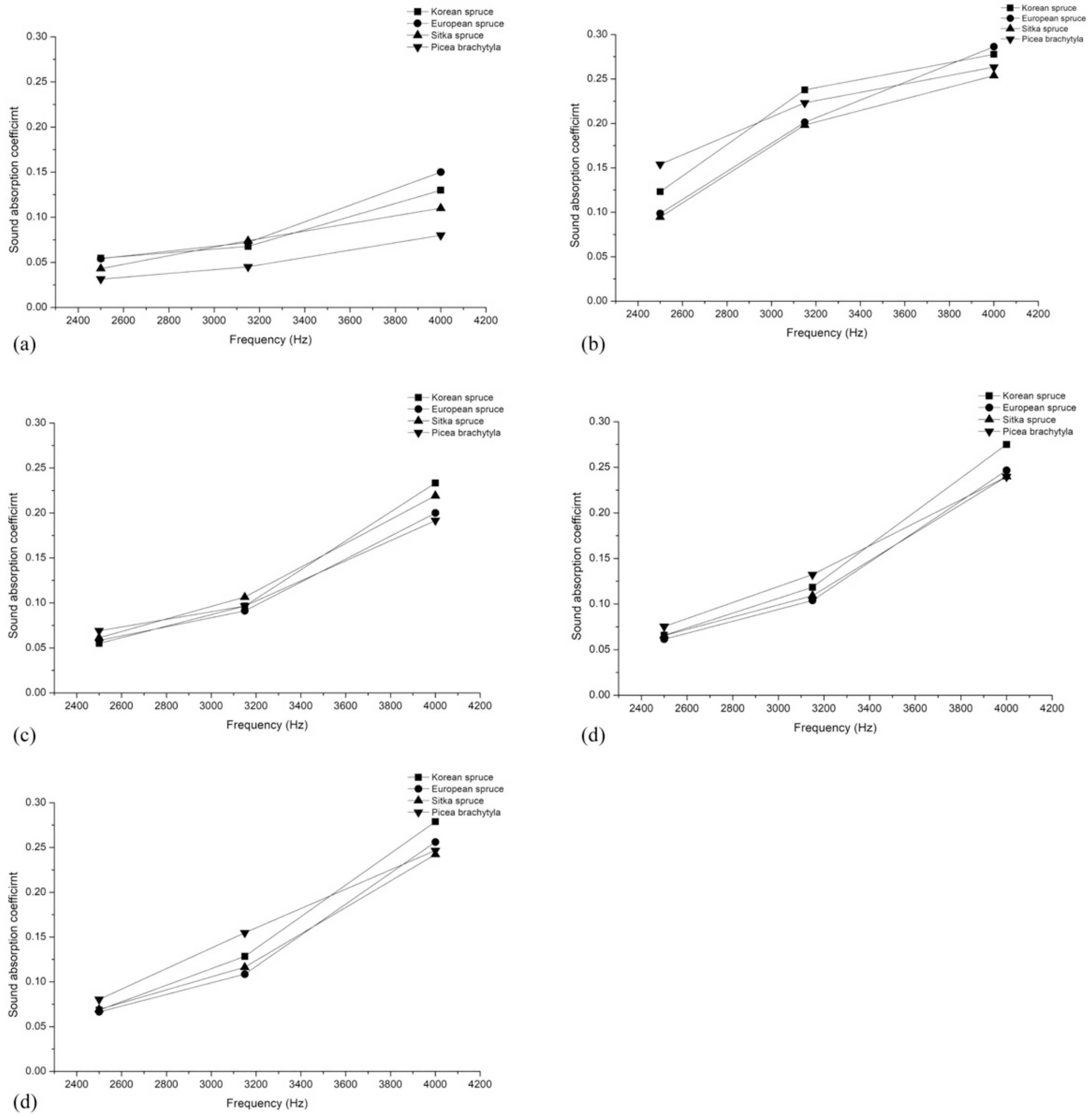

Figure 5. Sound absorption coefficients as a function of sound vibration frequency ranging from 2500 to 4000 Hz for four wood species within each of five coating thicknesses: (a) 0, (b) 0.15, (c) 0.30, (d) 0.45, and (e) 0.60 mm, respectively.

four evaluated species ranged from 0.014 to 0.286 with their COV values ranging from 1.3% to 18.9%. In general, coating PU on four evaluated spruce species significantly increased their sound absorption coefficients when compared with the uncoated ones, except for two lower SG species such as Korean and European spruces, when tested under the sound vibration frequency ranging from 1000 to 2000 Hz where coating PU on the two species did not significantly increase their sound absorption coefficients, specifically, and coating 0.30-mm-thick PU on the two spruces significantly lowered their sound absorption coefficients when compared with the uncoated ones.

Coating 0.30-mm-thick PU on Korean and European spruces tends to yield significantly lower sound absorption coefficients when compared with the ones coated with other three thicknesses when tested under the sound vibration frequency less than 800 Hz. Sitka spruce and *Picea brachytyla* coated with 0.15-mm-thick PU tend to have the lowest sound absorption coefficients among the ones coated with four PU thicknesses when tested under the sound vibration frequency ranging from 125 to 800 Hz, but when tested under the sound vibration frequency ranging from 1000 to 2000 Hz, the ones coated with 0.30- and 0.6-mm-thick PU had lower sound absorption coefficients. When tested under the sound vibration frequency greater than 2500 Hz, sound absorption coefficients of the four coated species increased as the coating thickness increased from 0.30 to 0.60 mm with an increment of 0.15 mm, but these four species coated with thicker PU had significantly lower sound absorption coefficients than the ones coated with 0.15-mm-thick PU.

The uncoated higher SG species such as Sitka spruce and *Picea brachytyla* tended to have significantly lower sound absorption coefficients than the uncoated lower SG ones such as Korean and European spruce when tested in the sound vibration frequency ranging from 500 to 4000 Hz. There were no significant differences in sound absorption coefficients among the four uncoated species when tested in the sound vibration frequency ranging from 200 to 400 Hz. When tested at the lower frequency range from 125 to 160 Hz, the order of sound vibration frequency from low to high among the four uncoated species became Korean spruce, Sitka spruce, *Picea brachytyla*, and European spruce.

Coating the four evaluated species with different thicknesses of PU could alter the effects of SG on their sound absorption coefficients. Specifically, coating the four species with 0.15-mm-thick PU resulted in no significant difference in sound absorption coefficients among the four species with four different SG levels. Coating with 0.30-mm-thick PU can lead lower SG species to have lower sound absorption coefficients than higher SG species. Coating 0.45-mm-thick PU on the four species tested in the sound vibration frequency ranging from 125 to 250 Hz resulted in *Picea brachytyla* having the lowest sound absorption coefficients, but when tested in two sound vibration frequency ranges of 315-630 Hz and 1600-3150 Hz, European spruce yielded the lowest sound absorption coefficients, and when tested in an input sound vibration frequency ranging from 800 to 1250 Hz, Sitka spruce was the one with the lowest sound absorption coefficients.

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