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Acoustic Property and Hardness of Coatings for Musical Instruments with Various Coating Thicknesses*1

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ABSTRACT

The relationship between acoustic property and coating hardness of musical instruments was investigated using a sound level meter and a pendulum hardness tester. Urethane topcoat, oil stain, natural oil varnish, and UV-curable epoxy acrylate coatings were applied on four different substrates: *Paulownia coreana, Pinus koraiensis, Castanea crenata* var. *dulcis* and *Pinus densiflora*. The influence of the coating type on the acoustic properties was stronger than that of the substrate. In the case of an oil stain formed with tacky coating layer, the sound pressure level (SPL) and surface hardness decreased with increasing of coating thickness. In the other coatings, SPL decreased and hardness increased as the coating layer thickened. However, SPL began to increase again at coating thickness above 100 μm.

Keywords : sound pressure level (SPL), pendulum hardness, acoustic property, thickness, coatings for musical instrument

1. INTRODUCTION

Wood has been used simply as a construction material or fuel by people for a long time, but in more modern times it used very widely in our life including interior decoration materials, furniture and wooden floorings. Because wood is a natural material, the parts touched by human skin are made by wooden materials so that human fulfills the desire to return to nature in the artificial modern life.

Humans seek beauty and desire in art, so wood is used as the material for musical instruments. Although the materials of the musical instruments have been replaced by iron, plastic and many other materials, wooden musical instruments retain a characteristic sound color and acoustic properties. So many musical instruments continue to be made by wood. Nevertheless, wooden musical instruments are still made by traditional methods, for which systematic and scientific study have not proceeded far (Chung *et al.*, 2003).

The viscoelastic and acoustic properties of

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Table 1. Species, moisture content and oven-dry specific gravity of the substrates

Species	Moisture content (%)	Oven-dry specific gravity
Paulownia coreana	6.67±0.63	0.27±0.004
Pinus koraiensis	9.75±0.88	0.36±0.025
Castanea crenata var. *dulcis*	11.44±0.31	0.50±0.034
Pinus densiflora	9.39±0.39	0.56±0.021

wood as a material for musical instruments were researched simply in terms of moisture content and frequency in early research (Dunlop, 1978). Since the dynamic modulus of elasticity of wood was researched using the resonance frequency (Dunlop, 1989; Dunlop *et al.*, 1991). The interrelationship between the vibration mode and the acoustic properties of wood for the body of violin has been investigated (Chung *et al.*, 1998; Chung *et al.*, 1999; Chung *et al.*, 2000).

Because wood has a characteristic nature, it needs a surface coating to improve the dimensional stability, hygroscopicity and durability (Jung *et al.*, 1999). Coatings on the surface of musical instruments influence both the acoustic and viscoelastic properties, and also improve the physical properties. The interrelationship between the acoustic property and viscoelasticity according to the kinds of coatings has recently also studied. (Choi *et al.*, 2005).

Sound pressure level (SPL) has mainly been used to measure sound insulation, and the sound absorption of buildings such as apartments, field stadiums and music halls (Park, 1999; Soeta *et al.*, 2001; Nam, *et al.*, 2002; Kim, *et al.*, 2003). It has also been used to measure the noise of several noise places such as subways (Kim, 1998). However, this is first study to use SPL to measure the acoustic property of the coated substrates for musical instruments in Korea.

The objective of this study was to use SPL to investigate the effect on acoustic property of variations in hardness and thickness of the coatings, after four kinds of coatings (natural oil varnish, oil stain, urethane topcoat, and UV-curable epoxy acrylate coatings) were applied four times onto four different species *(Paulownia coreana, Pinus koraiensis, Castanea crenata* var. *dulcis* and *Pinus densiflora*) in the construction of Korean musical instruments.

2. MATERIALS and METHODS

2.1. Materials

Paulownia coreana, Pinus koraiensis, Castanea crenata var. *dulcis*, and *Pinus densiflora* were used as substrates among various species for musical instruments. Table 1 shows the average moisture content and specific gravity of each substrate. In terms of the specific gravity, *P. densiflora* (0.56±0.021) was the heaviest substrate, followed by *C. crenata* var. *dulcis* (0.50 ±0.034). *P. coreana* (0.27±0.004) and *P. koraiensis* (0.36±0.025) had a relatively light specific gravity. Four different coatings were used: natural oil varnish, oil stain, urethane topcoat, and UV-curable epoxy acrylate coatings.

2.2. Sample Preparing and Curing

Prepared samples sized 5 cm × 10 cm were maintained at 22±1°C and 50±2% R.H. for more than one month. Four different coatings were applied on the four different substrates by a bar coater (No. 22). Natural oil varnish, oil stain and urethane topcoat were sufficiently cured for seven days at 22±1°C and 50±2% R.H. UV-curable epoxy acylate coatings were

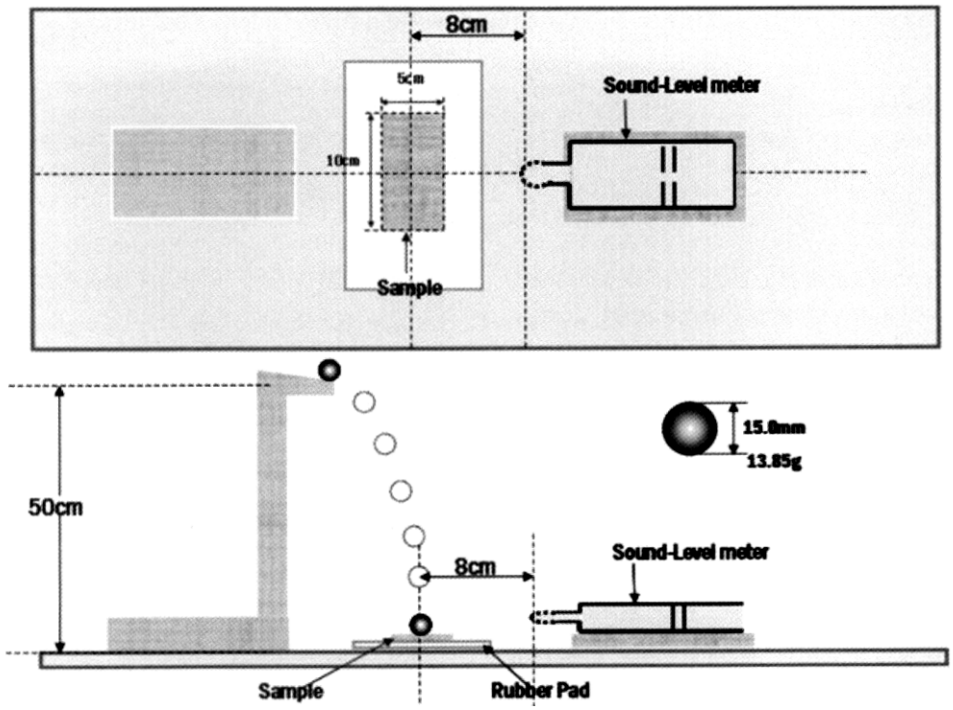

Fig. 1. Schematic diagram of sound pressure level test.

cured using high-pressure mercury lamp (100 W/cm, main wavelength: 365 nm). The UV dose measured by dosimetry (IL390C Light Bug, International light Inc., USA) was 2,000 mJ/cm^2. The coating thickness was controlled by coating times (1~4 times) and measured by a thickness measuring instrument (ID-C 112, Mitutoyo Corp., Japan).

2.3. Analysis

2.3.1. Pendulum Hardness Test

A König pendulum hardness tester (Ref. 707PK, Sheen Instruments Ltd., UK) was used to investigate the effect of surface hardness on acoustic property. The pendulum hardness of the cured surface was measured with pendulum oscillation time at 23±1°C and 50±2% R.H. The pendulum hardness test is based on the principle that the harder a measured surface, the greater the amplitude time of pendulum oscillation (ASTM D 4366).

2.3.2. Sound Pressure Level (SPL) Test

SPL of coatings for the musical instruments was measured to investigate the acoustic property of the coated substrates with various coating thicknesses and substrates.

When a material oscillates, a shock wave is generated which affects the atmospheric pressure. Sound is the pressure change of the atmospheric pressure, and the amount of this change is sound pressure, i.e., the physical size of sound. Sound pressure is measure in Pa units because it is pressure (Rossing, 2002). The sound intensity (I) is defined as follows,

Table 2. Thickness of coatings

Coatings	No. of Coatings	Thickness of Coatings (μm)			
		Paulownia coreana	*Pinus koraiensis*	*Castanea crenata* var. *dulcis*	*Pinus densiflora*
Natural Oil Varnish	1	13.50±2.10	24.20±3.58	14.33±3.19	12.50±3.96
	2	22.33±3.36	36.50±5.77	21.00±4.05	20.83±4.15
	3	52.17±8.15	54.33±7.71	45.17±5.94	47.33±8.20
	4	77.33±7.14	75.67±9.42	57.17±6.80	56.40±8.09
Oil Stain	1	17.50±1.38	21.20±3.14	15.33±3.33	18.70±3.99
	2	22.40±4.02	35.77±6.64	23.17±4.57	25.30±4.56
	3	29.80±9.42	46.50±6.79	28.17±5.73	34.80±6.02
	4	36.20±9.03	53.40±6.62	30.83±4.96	43.20±6.26
Urethane Topcoat	1	46.33±10.30	49.50±4.39	40.33±5.69	47.50±7.27
	2	65.33±14.62	90.50±6.10	50.67±6.63	62.00±8.54
	3	90.00±16.60	117.67±14.61	76.00±7.94	74.33±8.96
	4	117.50±19.23	137.50±14.72	97.83±9.97	120.33±6.65
UV-curable Epoxy Acrylate coatings	1	78.50±15.37	75.00±12.54	69.83±10.17	74.33±12.98
	2	145.90±6.15	138.00±15.66	126.50±10.17	126.00±31.93
	3	253.50±24.35	256.00±20.02	193.80±15.15	191.67±26.87
	4	376.83±20.48	404.83±26.13	301.00±21.62	276.83±23.72

$$I=\frac{p^2}{\rho c}\ (W/m^2)$$

where ρ is the density (kg/m^3) of medium, c is the velocity of sound, ρc is specific acoustic impedance, and p is a virtual value of sound pressure. Sound intensity is proportional to the square of sound pressure. The equation of sound pressure level is defined as follows,

Sound Pressure Level (SPL)

$$= 20\log_{10}\frac{p}{p_0}\ [dB]$$

where p_0 is 2×10^{-4} μbar (= 20 μPa) and p is the sound pressure of materials. SPL is measured by a sound level meter consisting of a microphone, an amplifier and a meter that reads in decibels (Hall, 1993; Fahy, 1995; Speaks, 1996).

Fig. 1 presents the schematic diagram of SPL test. A sample was placed on a rubber pad and a sound level meter was located at about 8 cm horizontally from the sample. The produced sound was measured using a sound level meter when a steel ball (diameter : 15.0 mm, weight : 13.85 g) falls free on the sample from a height of 50 cm.

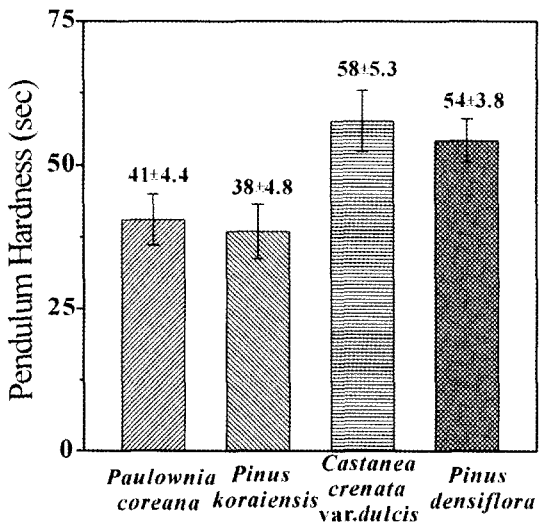

Fig. 2. Pendulum hardness of various substrates.

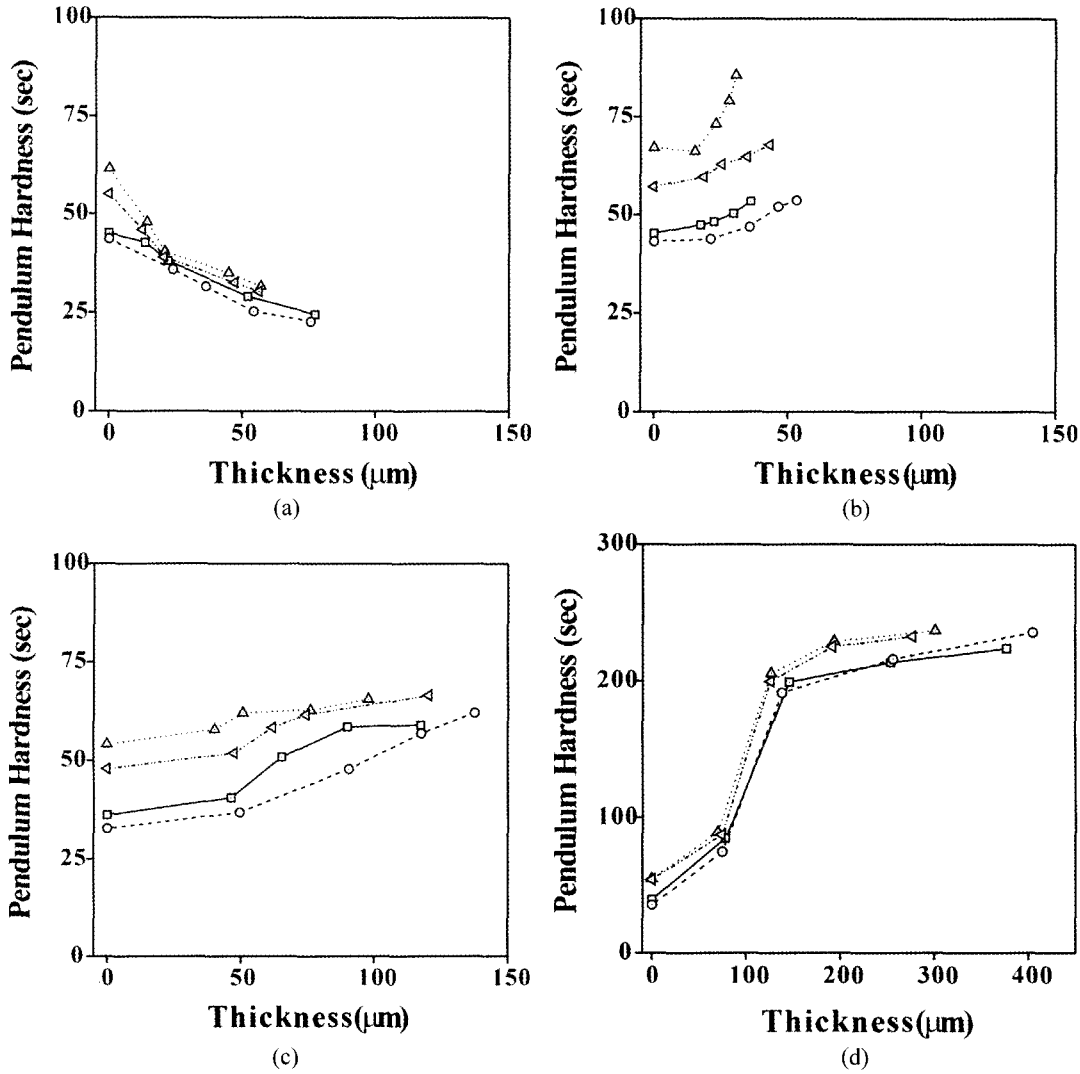

Fig. 3. Effect of coating thickness on pendulum hardness of various coatings. (a) natural oil varnish, (b) oil stain, (c) urethane topcoat, (d) UV-curable epoxy acrylate coatings.
□ : *Paulownia coreana* ○ : *Pinus koraiensis* △ : *Castanea crenata* var. *dulcis* ◁ : *Pinus densiflora*

3. RESULTS and DISCUSSION

3.1. Thickness of Coatings

The coating thickness was varied with the type of coatings as shown in Table 2. Oil stain and natural oil varnish, with their low viscosity, formed very thin coating layer. Urethane topcoat, with its relatively high viscosity, was coated thickly. UV-curable epoxy acrylate coatings formed the thickest layer because another layer is coated on the original layer when almost cured. In addition, *P. coreana* and *P. koraiensis* were coated more thickly than *C. crenata* var. *dulcis* and *P. densiflora*.

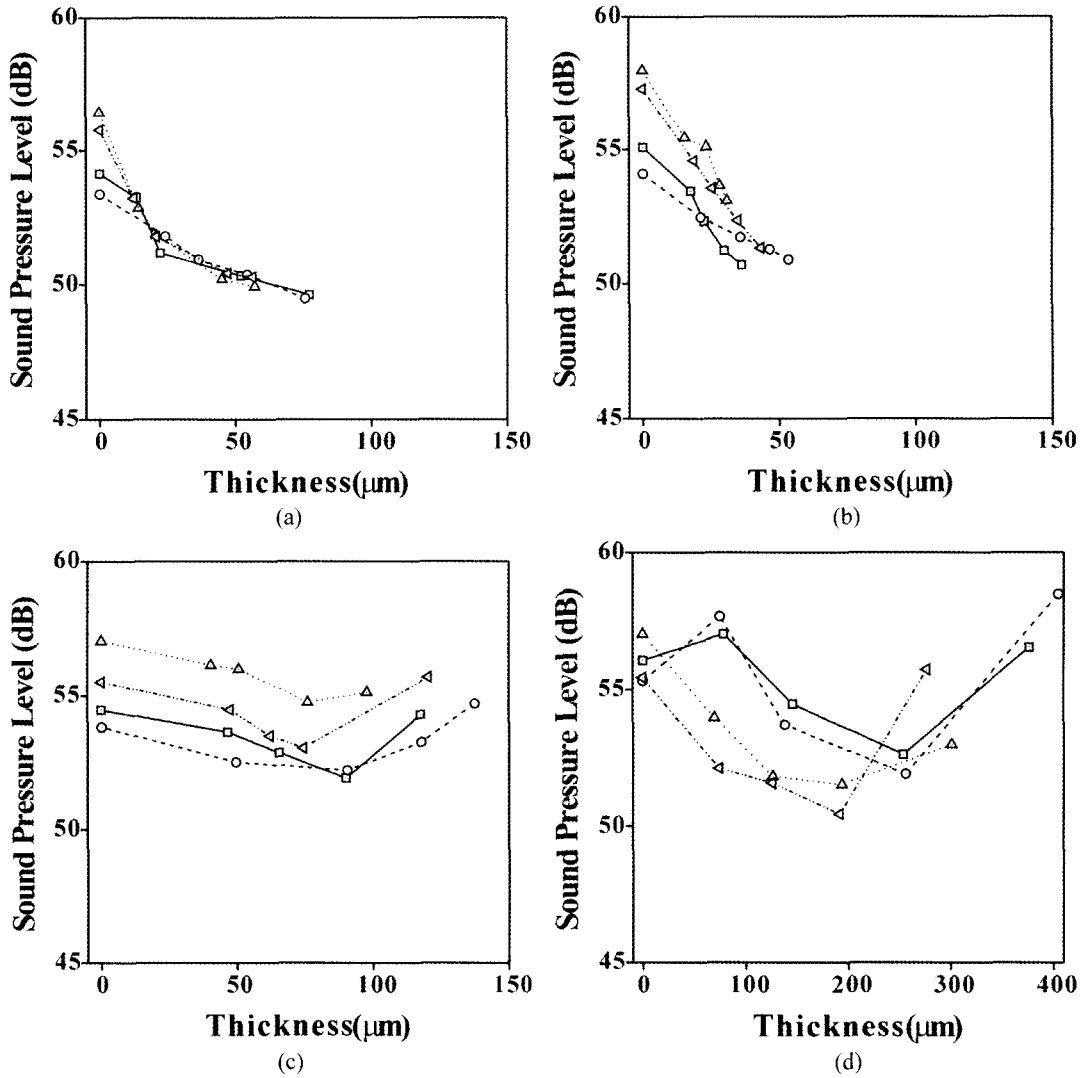

Fig. 4. Effect of coating thickness on sound pressure level of various coatings. (a) natural oil varnish, (b) oil stain, (c) urethane topcoat, (d) UV-curable epoxy acrylate coatings.
□ : *Paulownia coreana* ○ : *Pinus koraiensis* △ : *Castanea crenata* var. *dulcis* ◁ : *Pinus densiflora*

3.2. Pendulum Hardness of Substrates and Coatings

As shown in Fig. 2, the hardness of the substrates was more related to the cell density of wood than to the specific gravity. *P. coreana* was the lowest in the specific gravity, but in pendulum hardness it was higher than *P. koraiensis*. *P. densiflora* was the highest in specific gravity, but it was lower than *C. crenata* var. *dulcis* in pendulum hardness.

Fig. 3 shows the effect of the coating thickness on the pendulum hardness. The pendulum hardness of natural oil varnish decreased with increasing coating thickness because it was not cured perfectly even after 7-day cure, at which

time the coating surface was still tacky. In addition, tacky natural oil varnish covered over the surface of the substrate, the influence of substrate on the hardness was not appeared regardless of species. Because oil stain was low viscosity, the coating layer was formed thinly. Therefore, the hardness of the substrate greatly affected the hardness of the coated substrate. Urethane topcoat, with its high viscosity, was formed with a thick coating layer. Unlike the general expectation, the hardness did not increase in proportion to the coating thickness because the urethane topcoat is flexible and soft itself. In the case of UV-curable epoxy acrylate coatings, the formed coating layer was about 100 μm thick after coating once and UV irradiation. After second curing, the pendulum hardness increased significantly.

The hardness increased with increasing coating thickness except for natural oil varnish that formed a tacky coating layer. Thus the physical properties of the substrate such as the hardness were changed as well as the protection added to the surface of the substrate, if the coating materials were coated on the wood surface. Therefore, coatings can affect the acoustic property of the musical instruments.

3.3. Sound Pressure Level (SPL)

Fig. 4 shows the effect of the coating thickness on SPL. In the case of natural oil varnish, SPL value appeared in the order of the hardness of the substrate before coating. After the first coating, SPL decreased to a similar value irrespective of the species because the surface of the substrate was tacky. In oil stain that formed the thinnest coating layer, SPL decreased as the coating thickness increased. The substrate species affected the acoustic property at first, but not greatly once the coating was thickened. Natural oil varnish and oil stain formed a thin coating layer. As the coating thickness increased, SPL decreased greatly.

For urethane topcoat, SPL decreased, but only slightly, with increasing coating thickness because the formed coating was flexible and soft itself. Even if the coating thickness increased, the tendency for the order of SPL to agree with the order of the substrate hardness did not change. After the third coating, the coating thickness became about 100 μm, after which SPL increased again. Therefore, the coatings absorbed the sound until the coating thickness was about 100 μm, but if the coating thickness was thicker than 100 μm, SPL increased again by the hardness of the coating layer itself.

When UV-curable epoxy acrylate coatings were applied onto *Paulownia coreana* and *Pinus koraiensis*, SPL was higher than the substrates themselves after the first coating, because a very thick coating layer of about 100 μm was formed on each coating operation. *P. coreana* and *P. koraiensis* had low specific gravity and surface hardness. Therefore the effect of the coating itself appeared first when the substrate hardness was low. Although SPL decreased continuously to the third coating in *C. crenata* var. *dulcis* and *P. densiflora*, it started to increase after the fourth coating. If the substrate hardness was low, the coating layer was formed thickly. Accordingly the soft substrate had higher SPL than the harder substrate after the fourth coating.

3.4. Relationship between Pendulum Hardness and Sound Pressure Level (SPL)

Fig. 5 shows the relationship between pendulum hardness and SPL. In natural oil varnish, SPL and hardness decreased together with more coating. In the case of oil stain, the hardness was inversely proportional with SPL, and the

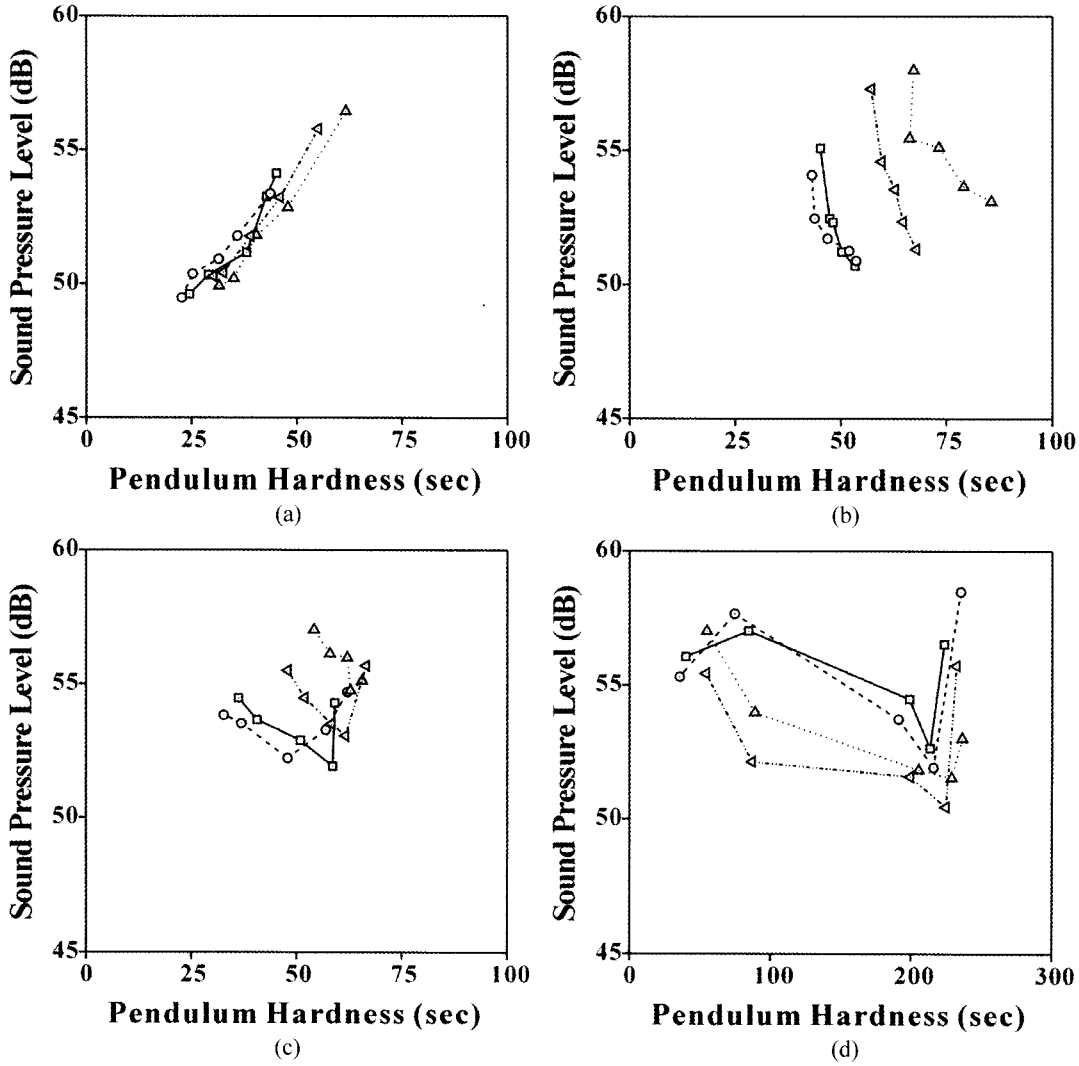

Fig. 5. Relationship between pendulum hardness and sound pressure level. (a) natural oil varnish, (b) oil stain, (c) urethane topcoat, (d) UV-curable epoxy acrylate coatings.
□ : *Paulownia coreana* ○ : *Pinus koraiensis* △ : *Castanea crenata* var. *dulcis* ◁ : *Pinus densiflora*

substrate hardness affected SPL more than other factors because oil stain formed the thinnest coating layer. In urethane topcoat, the hardness did not greatly affect SPL. SPL was similar regardless of the increasing hardness and species. SPL decreased continuously to the third coating, and then increased again after the fourth coating. For UV-curable epoxy acrylate coatings, the effect of hardness and coating thickness on SPL showed similar results. In the case of *P. coreana* and *P. koraiensis*, the hardness increased continuously but SPL increased after the first coating then decreased to the third coating, and at last increased again after fourth coating. The substrates hardness of *C. crenata* var. *dulcis* and *P. densiflora* was relatively high, SPL de-

creased continually to the third coating, and then increased again. These results confirmed that the coating thickness, rather than the coating hardness, was a dominant factor on the acoustic property when the coatings formed with a very thick coating layer.

4. CONCLUSIONS

When the wood of musical instruments was coated, both the acoustic property and the physical property such as the hardness were changed. To investigate the relationship between the acoustic property and the physical property of the coatings, pendulum hardness and SPL were measured with various coating thicknesses and substrates. Because the viscosity of coatings differed each other, the coating thickness was formed variously.

The surface of the substrate coated with oil stain was tacky and SPL and the surface hardness decreased with increasing coating thickness. For the other coatings, SPL decreased and the hardness increased with increasing coating thickness. However, at coating thickness more than about 100 μm, SPL increased again. Because the coating layer absorbed the sound with increasing coating thickness to some degree, after coating thickness was thicker than about 100 μm, the hardness of the coating layer itself effect on SPL. Therefore, the choice of a suitable coating thickness is the important factor according to coatings and species when coatings are applied onto the surface of musical instruments.

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