Title: Effects of seasoning on the vibrational properties of wood for the soundboards of string instruments.

Running title: Effects of seasoning on wood properties

PACS number(s): 43.75.De, 43.75.Gh, 43.75.Mn, 43.35.Mr.

Eiichi Obataya, Nanami Zeniya and Kaoru Endo-Ujiie

Graduate School of Life and Environmental Sciences, University of Tsukuba

Tsukuba 305-8572, Ibaraki, Japan

Corresponding author: Eiichi Obataya

Graduate School of Life and Environmental Sciences

University of Tsukuba

Tsukuba 305-8572, Ibaraki, Japan

E-mail: obataya.eiichi.fu@u.tsukuba.ac.jp

Phone: +81-29-853-4894

Abstract

The vibrational properties of green spruce wood samples were measured intermittently during drying and subsequent conditioning in ambient condition to clarify the effects of seasoning. After drying, the equilibration of mass, the sound velocity of wood continued to increase and its internal friction significantly decreased during 6 months of seasoning. However, those seasoning effects disappeared once the wood was moistened at 100% RH. Physical aging and stress relaxation of wood polymers was assumed to be responsible for. This coincides with the empirical knowledge of violin makers: seasoning for a few years is more important than long-term aging over centuries.

I. INTRODUCTION

Wood is widely used for the soundboards of various string instruments such as violins, guitars and harps. Its lightness, elasticity, appropriate damping, and excellent durability are suitable for that purpose, and synthetic materials cannot currently replace its workability, availability, and sustainability.

Wood aging has been of interest to musicians and artisans dealing with musical instruments, because the acoustic quality of wood is believed to improve by long-term aging over centuries. Although there are few direct evidences for such an "aging effect", recent studies on hygrothermal acceleration of aging predicted a slight increase in the specific dynamic Young's modulus (E_L'/ρ), and a decrease in the internal friction (Q_L^{-1}) of spruce wood by aging at room temperature (20 °C) and moderate relative humidity (60–80% RH) for several hundred years (Zeniya *et al.*, 2019a; 2019b). This fact suggests that there is a slight improvement in acoustic conversion efficiency due to long-term aging; and this coincides with the empirical knowledge of musicians and artisans.

On the other hand, the effect of short-term aging for less than 5 years, defined as the "seasoning effect", is still debatable. Most violin makers consider the seasoning, rather than long-term aging for the acoustic quality of instruments (Carlier *et al.*, 2015). However, wood scientists have not paid attention to the seasoning effect because wood is chemically stable, and no significant change is expected over such a short period of time (Kohara, 1958).

It should be remembered that wood is a natural polymer composite in which hydrophobic crystalline fibers are embedded in hydrophilic amorphous matrix substances. In general, the mechanical and viscoelastic properties of polymers can change over time through their conformational change, even when their chemical structure remains unchanged (Struik, 1978). Such a phenomenon is called physical aging and may be a major mechanism behind the seasoning effect; however, only a few studies so far have dealt with the physical aging of wood (Hunt and Gril, 1996).

In this study, we first observed the vibrational properties of wood during drying from their green state and subsequent seasoning in ordinary conditions to determine the effects of seasoning. The reversibility of the seasoning effect was also discussed by comparing the vibrational properties of seasoned and aged wood specimens before and after moisture treatment. The results explain the mysterious effects of seasoning, and may help musicians appropriately use their instruments.

II. MATERIALS AND METHODS

A. Short-term seasoning of green wood

Green spruce wood were dried and seasoned over 6 months, while its vibrational properties were intermittently measured. The term "green" means recently cut fresh wood that has never been dried. Twenty green Sitka spruce (*Picea sitchensis*) lumber were cut into 20 samples with dimensions of 4 – 5 mm (tangential, T) × 18 – 20 mm (radial, R) × 180 mm (longitudinal, L), and these samples were dried in a conditioning room at 20±0.1 °C and 60±1% RH. After the drying for 1 day, those samples were precisely re-shaped using a hand planer into 3 mm (T) × 17 mm (R) × 180 mm (L), and continuously conditioned for 212 days while their mass, density (ρ), E_L', Q_L^{-1}, and sound velocity (V_L) along the grain were measured intermittently. The detailed method of vibration measurement will be described later on. Next, the wood samples were moistened at 20 °C and 100% RH for 1 month, conditioned at 20 °C and 60% RH for 2 days, and then their properties were measured again. Finally, the wood specimens were oven-dried at 105 °C for 24 h to determine their absolute dry mass.

B. Vibration measurement of seasoned wood

In order to characterize the acoustic behavior of wooden musical instruments, we need to know the viscoelastic constants of wood in three different directions (L, R and T), because wood is an anisotropic material (Haines, 2000; Bucur, 2016). In the present study, however, the dimensions of seasoned and aged wood samples were not enough to precisely measure their properties in R and T directions. Therefore, we decided to focus on the wood properties in L direction as the first step. Seasoned or aged spruce lumber were acquired from artisans and companies making violins, harps, pianos or guitars. These lumber were cut into strips with dimensions of 0.9–5.0 mm (T) × 8–21 mm (R) × 83–181 mm (L), depending on the size of the original lumber. The origin of the samples and their estimated seasoning time are listed in Table 1. Most samples were identified to be from the spruce family. Two lumber (S9 and S14) could not be clearly identified but may possibly be spruce or cedar wood. As the precise time of cutting was unknown in most of the seasoned wood samples (S5 – S15), the acquisition year was regarded as the year of cutting.

The vibrational properties of wood strongly depend on its moisture sorption history, as well as its moisture content (MC). To compare the vibrational properties of wood samples under the same conditions, all samples were once dried completely at 20 °C with P_2O_5, and then conditioned at 20±0.1 °C and 60±2% RH for 1 month prior to the vibration measurement.

TABLE I. Origin of tested wood samples.

Category	Abbreviation	Use	Species	Year of cutting or acquisition [a]	Year of testing	Seasoning time (year) [b]
New	N	Common	*Picea sitchensis*	2017	2017	0
	S1	Violin	*Picea sitchensis*	2014	2017	3
	S2	Guitar	*Picea sitchensis*	2013	2018	5
	S3	Harp	*Picea sitchensis*	2011	2018	7
	S4	Common	*Picea abies*	1995	2018	23
	S5	Unknown	*Picea abies*	1990	2018	28
	S6	Violin	*Picea abies*	1980	2018	38
	S7	Lute	*Picea abies*	1975	2018	43
Seasoned	S8	Violin	*Picea abies*	1970	2018	48
	S9	House	Unidentified	1914	2017	103
	S10	Guitar	*Picea sitchensis*	1905	2018	113
	S11	Unknown	*Picea abies*	1898	2018	120
	S12	Unknown	*Picea abies*	1840	2018	178
	S13	Unknown	*Picea abies*	1780	2018	238
	S14	Violin	Unidentified	1715	2017	302
	S15	Unknown	*Picea abies*	1700	2018	318

a) For commercially supplied wood, the year of cutting may be 1–2 years earlier than that of purchase.
b) Estimated time elapsed after cutting or acquisition.

To investigate the reversibility of seasoning effect, the vibration measurements were repeated after the moistening treatment: wood samples were moistened at 20 °C and 100% RH for more than 1 month. After the moistening, the wood samples were dried completely at 20 °C on P_2O_5, conditioned at 20 °C and 60% for 1 month, and then their vibrational properties were determined again. These moistening–drying–conditioning processes were repeated twice as shown in FIG. 1.

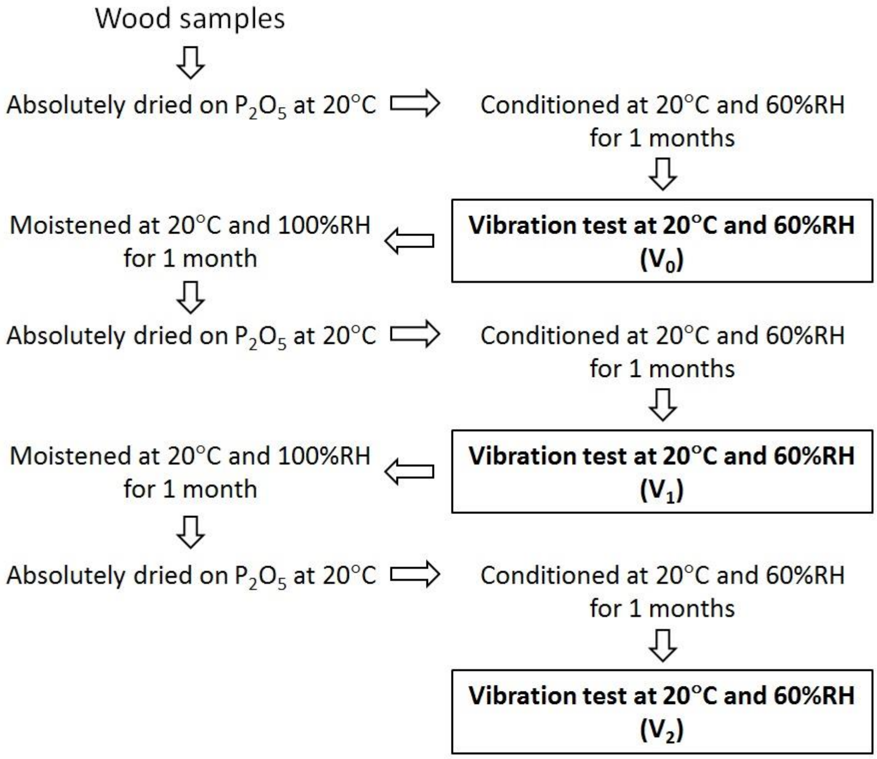

FIG.1. Flow of repeated drying-conditioning-moistening tests.

C. Vibration measurement

The E_L', V_L and Q_L^{-1} values of wood were determined using free flexural vibration method, which is widely used to measure the vibrational properties of wood (Obataya *et al.*, 2000; Brémaud, 2012; Brémaud *et al.*, 2012). The strip-shaped sample was horizontally hung by silk threads, and its resonant vibration was excited by a magnetic driver or an audio speaker, while the amplitude of vibration was measured using an eddy-current sensor (Keyence, EX-202), a laser displacement sensor (Keyence, LK-G30), or a precision microphone (Ono Sokki, MI-1431). An appropriate combination of driver and sensor was selected for precision, depending on the mass and resonant frequency of wood samples. The combinations of equipment are illustrated in FIG. 2. Method I is popular and employed frequently in the vibration measurement of wood: small iron pieces are glued at the ends of a specimen with one end excited by a magnetic driver, while the deflection at the other end is detected by an eddy-current sensor. This method achieves sufficient precision when the mass of the iron piece (< 0.05 g) is negligibly smaller than the wood sample (> 2 g). The first-mode resonance frequency was in the range from 300 Hz to 800 Hz. When the frequency was higher than 900 Hz, the deflection was observed using a microphone, while the vibration was excited by a magnetic driver placed at the center of the sample (method II). Vibrations were excited using a speaker beneath the sample for particularly thin and/or light (0.5–0.9 g) samples, and the deflection was detected by an eddy-current sensor (method III) or a laser displacement sensor (method IV).

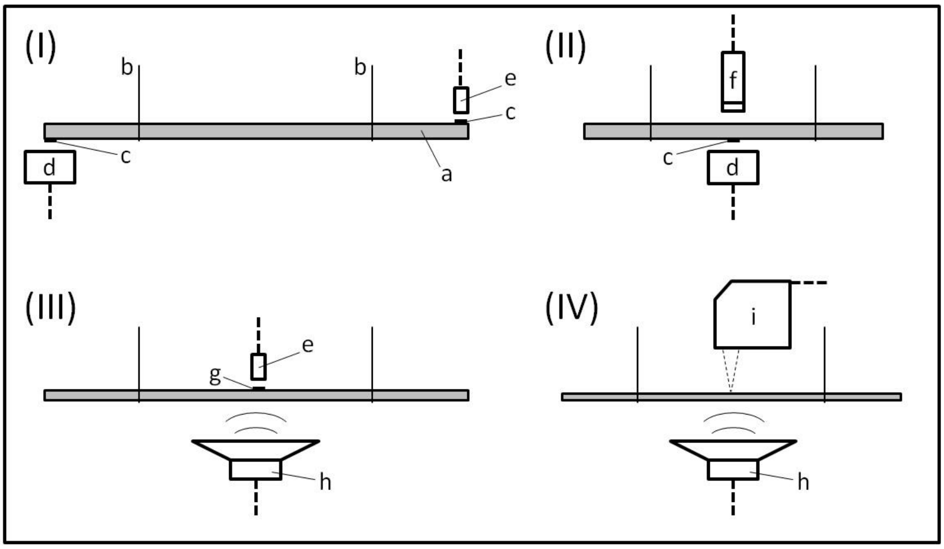

FIG.2. Combination of exciter and detector used in vibration test.
(a) Wood specimen; (b) supporting thread; (c) iron piece; (d) magnetic driver; (e) eddy current sensor; (f) microphone; (g) aluminum foil; (h) audio speaker; (i) laser displacement sensor.

The $E_L{}'$ and V_L values were calculated from the dimension and resonance frequency (f_r) according to the following equation (Hearmon, 1958):

$$V_{\mathrm{L}} = \sqrt{\frac{E_{\mathrm{L}}{}'}{\rho}} = \frac{4\sqrt{3}\pi l^2 f_r}{{m_n}^2 h}, \qquad (1)$$

where the h and l are height and length of the sample, respectively. The m_n is a constant depending on the mode of vibration, and m_1=4.73 for the first-mode flexural vibration. The Q_L^{-1} value was determined by approximating the resonance curve with the theoretical equation for viscoelastic solid. An example of the approximation of a resonance curve is exhibited in FIG. 3.

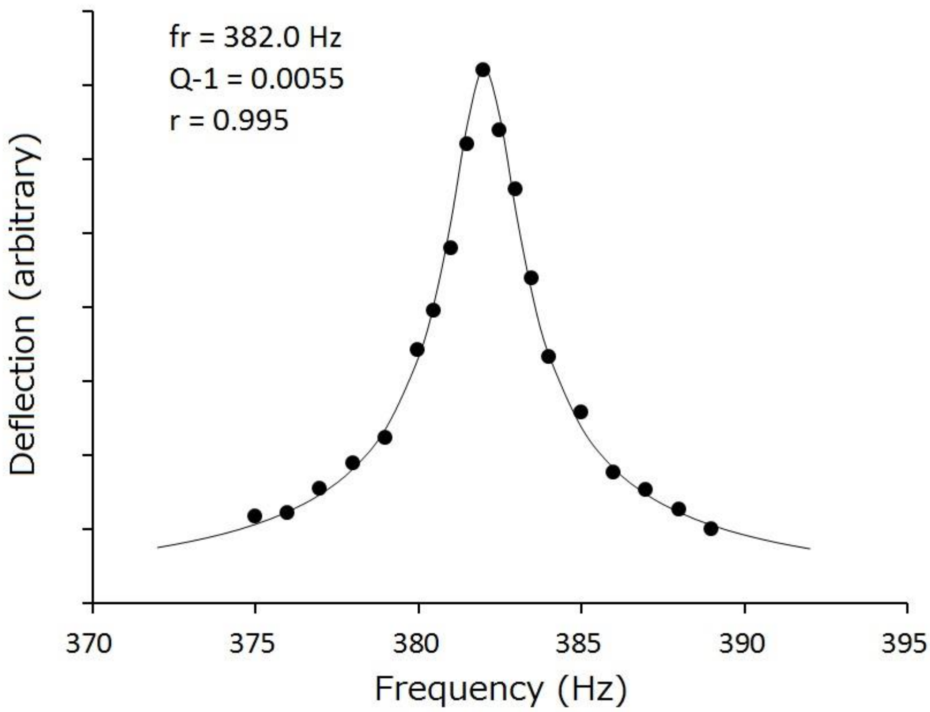

FIG.3. Example of the resonance curve: amplitude of deflection of a wood sample plotted against frequency.
Plots, experimental values; curve, approximated values.

III. CHANGES IN WOOD PROPERTIES DURING SEASONING

MC is an important factor affecting the vibrational properties of wood (Obataya *et al.*, 1998). The MC value is defined as

$$\text{MC (\%)} = 100 \times \frac{\text{Mass of moisture in wood}}{\text{Absolute dry mass of wood}} \qquad (2)$$

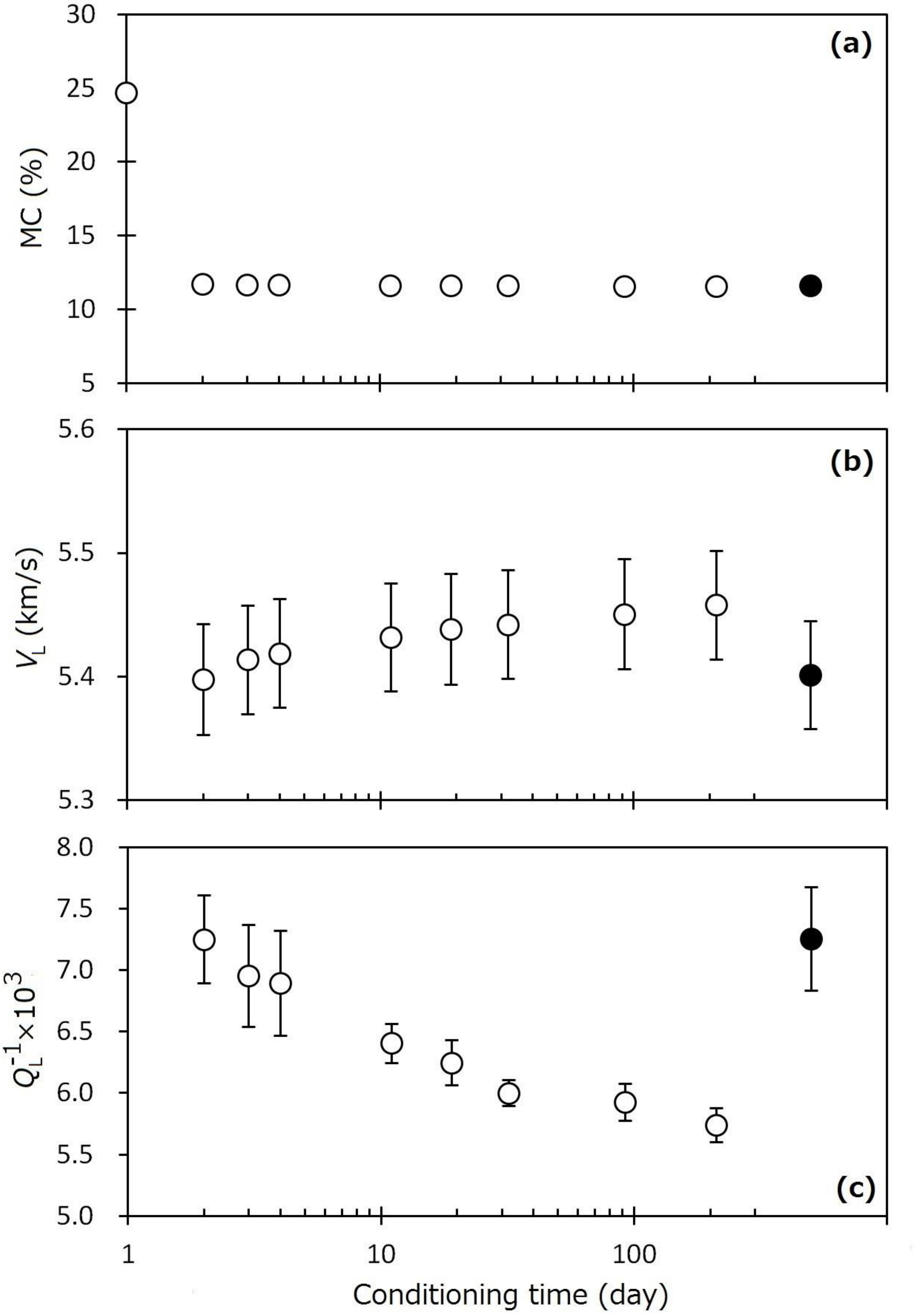

FIG.4. Changes in MC, V_L, and Q_L^{-1} values of spruce wood during the 6-month conditioning. Open circle, green wood was dried and conditioned; filled circle, conditioned sample moistened once and then conditioned; bars indicate standard deviations.

FIG. 4 shows the changes in MC, V_L and Q_L^{-1} values of wood plotted against the conditioning time over six months. The MC value of green wood (80–100%) was reduced to 25% within 1 day, and then almost equilibrated at 11.7 % within 2 days. In this case, the initial two days are the drying period, and the following conditioning is regarded as the seasoning period. Some artisans suggest that the seasoning improves the dimensional stability of wood, but in the present case, MC value or hygroscopicity of wood remained unchanged during the seasoning. This fact indicates that no dimensional stabilization is expected by the seasoning. Probably the term “stabilization” for artisans means "stabilization of shape of lumber" due to the viscoelastic relaxation of internal stress (growth stress and drying stress), rather than the reduction in the hygroscopicity of wood.

If the seasoning is just a drying process as artisans sometimes say, the vibrational properties of wood should remain unchanged after the equilibration of MC. However, the V_L value continued to increase, and Q_L^{-1} value decreased with the elapse of time even after the equilibration of MC. This fact indicates that the seasoning is not just a drying process, but also a kind of treatment that affects the vibrational properties of wood. In general, the soundboards of strings made from particular wood species, such as spruce, western red cedar, and paulownia present relatively low ρ and high V_L values (Brémaud, 2012) or a low anti-vibration parameter, ρ/V_L (Yoshikawa, 2007). In fact the overall quality of spruce lumber evaluated by violin makers show a significant and positive correlation with the radiation ratio, V_L/ρ (Carlier *et al.*, 2018). In addition, higher V_L and lower Q_L^{-1} give greater acoustic conversion efficiency, VQ/ρ (Yankovskii, 1967) or greater transmission parameter, VQ (Yoshikawa, 2007). According to Ono (1996), greater E_L'/ρ (=V_L^2)

and smaller Q_L^{-1} of wood result in greater amplitude of sound radiation. Therefore, the seasoning effects, increase in V_L and decrease in Q_L^{-1}, are ideal for efficient sound radiation from wooden soundboards.

Despite the advantageous effect of seasoning, its process is still debatable. Because wood is chemically stable in dry conditions, several months of seasoning is not enough to induce significant chemical changes in the wood polymers. Therefore, the most probable mechanism behind the seasoning is the physical aging of wood polymers. Physical aging is the time-dependent approach of a polymer towards thermodynamic equilibrium, and that of artificial polymers has been extensively studied by Struik (1978). The physical aging of wood was first reported by Hunt and Gril (1996). Once the wood was destabilized via moistening or drying they found that the E_L' and Q_L^{-1} of wood can change with little changes in the MC. This delayed equilibration of viscoelastic properties is qualitatively similar to our present results.

The viscoelastic stress relaxation of wood polymers explain their destabilization and stabilization during drying, and the subsequent seasoning. FIG. 5 illustrates the structure of wood and its cell wall. The wood cell wall forms fiber-reinforced structures where rigid crystalline cellulose (microfibrils) are embedded in amorphous matrix substances consisting of lignin and hemicelluloses. FIG. 6 illustrates the structural changes in the wood cell wall during drying and the subsequent seasoning. Note that this model simply explains the initiation and relaxation of internal stress in the cell wall, and cannot be used to calculate the V_L and Q_L^{-1} values of wood. In green wood, the matrix polymers are completely swollen with the adsorbed water, whereas the crystalline microfibrils contain no moisture (FIG. 6a). During drying, the matrix polymers shrink with the removal of adsorbed water; however, their shrinkage is mechanically restricted by the adjacent microfibrils. Consequently, the stressed matrix polymers are unnaturally distorted, likely resulting in lower rigidity and greater mobility in the matrix polymers (FIG. 6b). In the subsequent seasoning, the remaining stress gradually relaxes because the matrix polymers are viscoelastic (FIG.6c). In this relaxation process, V_L increases and Q_L^{-1} decreases with the rearrangement of matrix polymers and the reformation of intermolecular hydrogen bonds. This model has been originally proposed to explain the temporary changes in wood properties due to heat treatment (Obataya and Tomita, 2002; Obataya, 2010; Endo *et al.*, 2016), and reasonably explains the effects of seasoning.

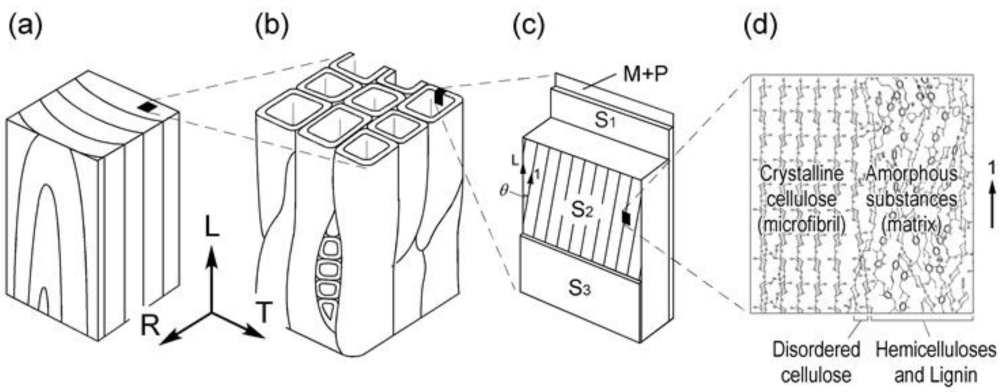

FIG.5. Appearance of wood at the macroscopic level (a), cellular structure at the microscopic level (b), laminated structure of the wood cell wall (c) and fiber-matrix composite structure at the macromolecular level (d).

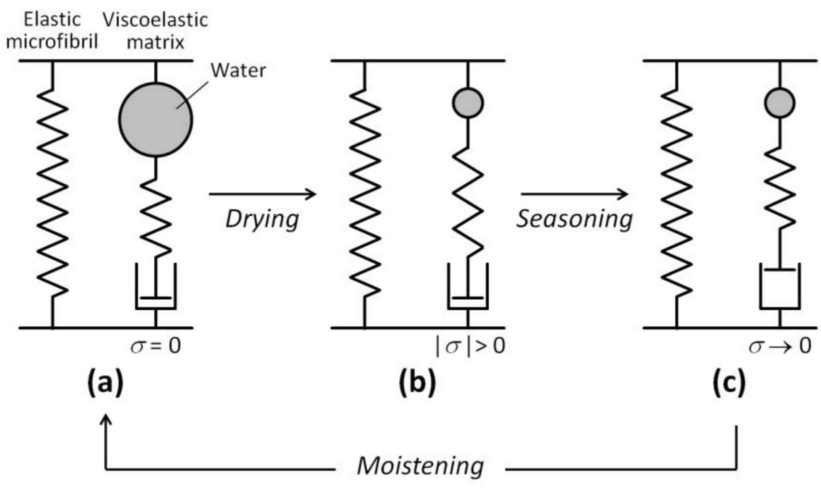

FIG.6. Schematic illustration for the initiation and relaxation of drying stress in the cell wall.

If the hypothesis above is valid, the seasoning effects are predicted to disappear once the wood is exposed to humid conditions (FIG.6a) where the matrix polymers can recover their original conformation, and then dried (FIG.6b). In FIG. 4, the filled circles indicate the MC, V_L, and Q_L^{-1} values of wood after moistening. The V_L and Q_L^{-1} of the seasoned wood recovered their initial values almost completely as predicted. This fact proves that the seasoning is not an irreversible chemical reaction but a temporary phenomenon, which can be recovered via moistening.

IV. DIFFERENT EFFECTS OF SEASONING AND LONG-TERM AGING

In contrast to the recoverable effect of seasoning, long-term aging (> 100 years) induces irreversible chemical changes of wood polymers, such as oxidation of lignin, hydrolysis of amorphous polysaccharides, and crystallization of cellulose (Kohara, 1958). Here we define the term “seasoning” as the reversible change in wood properties that can be recovered by moistening, whereas "aging" is the irreversible change due to the chemical reaction in wood polymers.

The effect of aging has been discussed by comparing the physical properties of aged wood with those of “new” recently cut wood (Kohara, 1958; Yokoyama *et al.*, 2009, Kraditz *et al.*, 2016). However, in many cases conclusions are unclear because of the numerous original variations in wood properties. As wood is a natural material, its density and density-dependent mechanical properties vary widely even in a single tree. Even at the same density, vibrational properties of wood also vary widely depending on the average angle of microfibrils in the cell wall (Obataya *et al.*, 2000). Thus, it is difficult to discuss the effect of aging as long as we compare new and aged wood samples, which originate from different sources. On the other hand, Zeniya *et al.* have recently proposed time-temperature-humidity superposition, allowing artificial acceleration of aging and precise reproduction of aged wood (Zeniya *et al.*, 2019a; 2019b). Currently, their results are the most reliable because 1) the temporary effects of seasoning were excluded by moistening treatment prior to the vibration measurement, and 2) the same sample was tested before and after the artificial aging to eliminate the natural variation in wood. The result of the artificial aging predicted that the V_L value of spruce wood would increase by 2% and its Q_L^{-1} value would decrease by 2% during 2000 years of aging at 20 °C and 63–81% RH. That is, the acoustic conversion efficiency of wood can be slightly improved by natural aging over centuries, when the wood is kept at moderate RH levels. Those changes are qualitatively similar to the effects of seasoning, but less than those due to seasoning, which reduces Q_L^{-1} by 20% as shown in FIG. 4. Therefore, it is reasonable that violin makers prefer seasoning for years or a few decades rather than long-term aging over centuries (Carlier *et al.*, 2015).

V. EVALUATION OF SEASONING EFFECT

Because the seasoning effect disappears once they undergo moistening, the vibrational properties of seasoned or aged wood are expected to irreversibly change once exposed to humid conditions. Therefore, the degree of seasoning can be evaluated by comparing the vibrational properties of wood before and after the moistening. Table 2 shows the vibrational properties of new and aged wood specimens. No correlation was recognized between the vibrational properties and seasoning time (correlation coefficient ≤ 0.07), because the effects of seasoning and aging were masked by numerous original variations in wood properties.

TABLE II. Average values ± standard deviation of moisture content (MC), dynamic Young's modulus (E_L'), sound velocity (V_L), internal friction (Q_L^{-1}), and acoustic conversion efficiency (ACE_L) of wood samples at 20 °C and 60% RH before moistening treatment (V_0).

	Seasoning time (year) [c]	n [a]	Method [b]	MC (%)	ρ (kg/m^3)	E_L' (GPa)	V_L (m/s)	$Q_L^{-1} \times 10^3$	ACE_L [c] (m^4/s kg)
N	0	20	I	11.7±0.3	474±8	14.7±0.4	5572±58	5.9±0.2	1984±84
S1	3	8	II	11.3±0.1	370±8	9.1±0.3	4973±77	7.7±0.3	1746±77
S2	5	8	I	10.9±0.4	422±14	12.4±0.9	5415±111	5.9±0.3	2170±117
S3	7	20	IV	10.8±0.3	489±21	12.2±1.5	5001±247	6.5±0.5	1583±182
S4	23	20	I	10.9±0.2	486±13	11.5±0.7	4868±105	6.2±0.3	1620±95
S5	28	2	I	11.7±0.2	418±5	8.8±0.4	4583±127	6.3±0.0	1752±73
S6	38	5	I	11.3±0.4	459±21	12.3±1.3	5170±174	6.4±0.2	1770±47
S7	43	8	I	10.8±0.3	553±34	15.4±1.7	5267±211	5.9±0.5	1618±170
S8	48	8	I	12.0±0.1	393±3	10.2±0.3	5097±77	6.0±0.4	2176±166
S9	103	19	III	10.9±0.1	426±26	11.4±1.5	5172±270	6.1±0.5	1994±228
S10	113	17	I	11.1±0.3	515±33	11.8±1.2	4785±127	7.3±0.5	1284±109
S11	120	7	II	11.5±0.1	528±29	14.8±1.7	5298±181	7.0±1.2	1471±252
S12	178	14	I	11.8±0.3	415±17	9.3±1.5	4737±316	6.9±0.6	1675±217
S13	238	5	II	11.5±0.3	418±8	10.9±0.4	5119±117	6.3±0.5	1962±245
S14	302	16	II	10.7±0.2	477±15	15.0±0.7	5613±143	6.0±0.6	1966±192
S15	318	9	I	11.3±0.6	458±16	11.3±1.4	4963±302	6.6±0.7	1660±228

a) Number of samples tested; b) combination of exciter and detector shown in FIG. 1; c) ACE_L is defined as $V_L Q_L/\rho$.

TABLE 3 and FIG. 7 show the changes in wood properties from repeated moistening treatment. The new wood showed little change in MC, V_L, and Q_L^{-1} after the moistening. This fact suggests that the seasoning effect was small in the recently cut wood. In contrast, seasoned and aged wood specimens showed a significant decrease in V_L and increase in Q_L^{-1} after the first moistening treatment, and no remarkable change in their properties occurred after the second moistening treatment. This indicates that the temporary effect of seasoning (increase in V_L and decrease in Q_L^{-1}) disappeared when the wood was exposed to humid condition, in which the wood polymers recovered their original conformation.

TABLE III. Average values ± standard deviation of changes in wood properties by repeated moistening treatment.

	Seasoning time (year)	n [a]	Changes in MC (%) [b]		Changes in E_L' (%) [c]		Changes in V_L (%) [c]		Changes in Q_L^{-1}(%) [c]		Changes in ACE_L (%) [c]	
			V_0 to V_1	V_0 to V_2	V_0 to V_1	V_0 to V_2	V_0 to V_1	V_0 to V_2	V_0 to V_1	V_0 to V_2	V_0 to V_1	V_0 to V_2
N	0	20	0.1± 0.1	0.2±0.0	0.0±0.2	-0.2±0.2	0.0±0.1	-0.2±0.1	1.1±2.8	2.0±4.3	-1.1±2.8	-2.2±4.1
S1	3	8	-0.2±0.1	0.1±0.1	-0.8±0.2	-1.2±0.1	-0.3±0.1	-0.6±0.1	2.6±8.6	5.0±4.1	-2.0±3.0	-5.2±3.8
S2	5	8	0.5±0.1	0.8±0.0	-1.7±0.3	-2.6±0.3	-1.1±0.2	-1.6±0.1	9.7±4.6	13.0±5.1	-10.1±3.8	-13.4±3.9
S3	7	20	0.6±0.2	0.8±0.1	-1.0±0.5	-0.8±0.6	-0.8±0.3	-0.7±0.3	12.4±4.1	12.1±5.6	-12.0±3.3	-11.8±4.5
S4	23	20	0.4±0.1	0.6±0.1	-0.8±1.3	-1.1±1.5	-0.6±0.6	-0.8±0.7	10.3±3.9	12.6±4.1	-10.1±3.4	-12.3±3.2
S5	28	2	0.3±0.0	0.4±0.0	-1.0±0.1	-1.3±0.4	-0.6±0.0	-0.8±0.2	17.9±2.4	18.4±0.9	-15.9±1.7	-16.5±0.5
S6	38	5	0.2±0.0	0.3±0.1	-0.8±0.3	-1.5±0.2	-0.5±0.2	-0.9±0.1	8.5±2.9	16.3±3.6	-8.4±2.5	-15.0±2.7
S7	43	8	0.0±0.0	0.1±0.0	-1.0±0.2	-0.6±0.4	-0.5±0.1	-0.4±0.2	7.4±8.1	9.0±6.6	-6.8±7.5	-8.4±5.6
S8	48	8	-0.1±0.1	0.0±0.2	-1.3±0.5	-1.7±0.3	-0.6±0.3	-0.9±0.2	15.6±6.8	15.3±7.0	-13.7±5.0	-13.8±5.7
S9	103	19	-0.2±0.1	0.1±0.1	-1.4±0.5	-1.4±0.9	-0.7±0.2	-0.7±0.5	10.0±9.2	16.9±8.7	-8.9±7.6	-14.7±6.2
S10	113	17	-0.1±0.0	0.1±0.1	-2.1±0.5	-2.3±0.3	-1.0±0.3	-1.2±0.1	11.5±8.4	11.8±10.0	-10.8±6.0	-11.2±7.2
S11	120	7	0.0±0.1	0.2±0.1	-1.0±1.2	-1.8±0.7	-0.5±0.6	-1.0±0.4	9.6±5.2	8.8±7.6	-4.8±3.6	-7.7±7.5
S12	178	14	-0.2±0.1	-0.1±0.1	-1.5±0.6	-1.0±0.6	-0.6±0.3	-0.5±0.3	10.5±5.2	11.6±5.7	-9.8±4.3	-10.5±4.7
S13	238	5	0.1±0.1	0.1±0.1	-1.5±0.8	-0.2±0.9	-0.8±0.4	-0.8±0.4	9.9±5.7	16.3±4.3	-9.5±4.5	-14.2±2.8
S14	302	16	-0.1±0.1	0.3±0.2	-1.4±0.2	-1.8±0.4	-0.6±0.1	-1.0±0.2	14.9±12.6	16.1±10.9	-12.4±9.4	-14.1±8.0
S15	318	9	0.2±0.0	0.3±0.0	-0.7±0.4	-1.0±0.5	-0.5±0.2	-0.6±0.2	11.2±6.4	13.4±9.0	-10.4±4.9	-12.1±6.7

a) Number of samples tested; b) amount of change in percent; c) percentage rate of change.

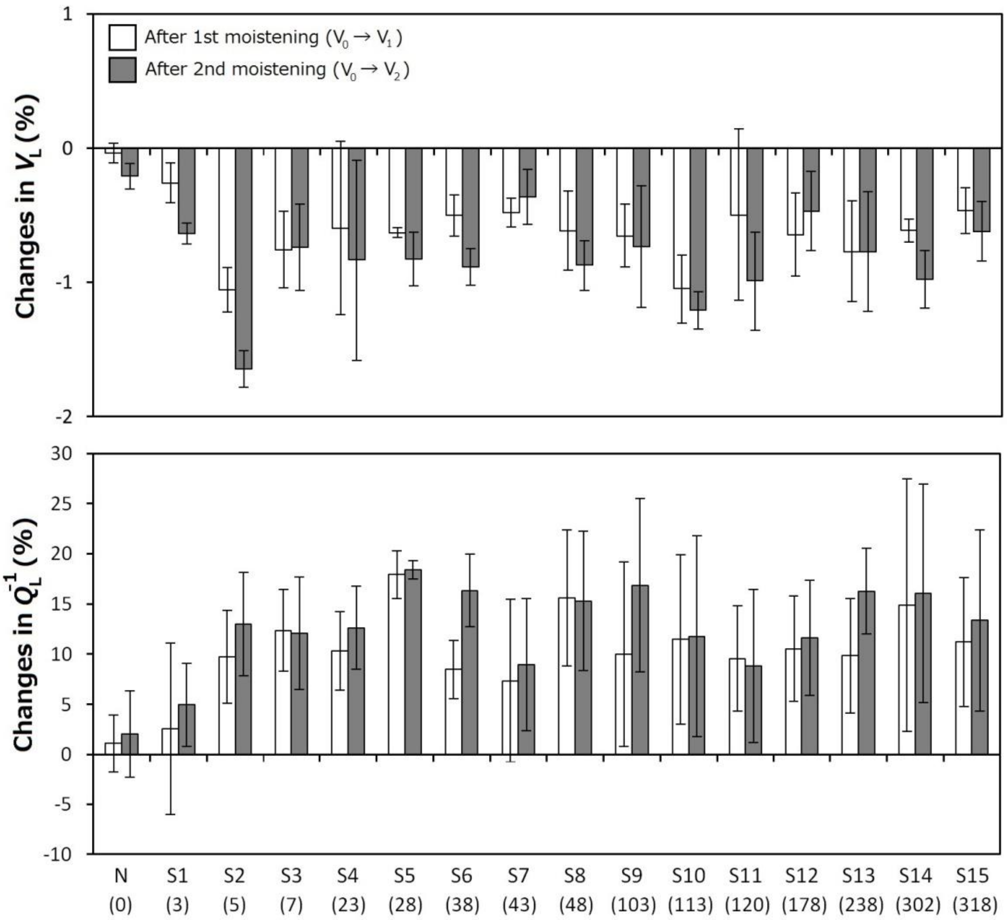

FIG.7. Changes in sound velocity (V_L) and internal friction (Q_L^{-1}) of wood samples due to repeated moistening. Bars indicate standard deviations. Values in parenthesis indicate the estimated seasoning time (year).

Judging from the degree of seasoning (changes in V_L and Q_L^{-1}), the seasoning was thought to be completed within several years, and no further effect is expected by prolonged seasoning over centuries. Therefore, it is logical that violin makers think much of the initial seasoning for a few years rather than long-term aging over centuries (Carlier *et al.*, 2015).

Some samples (e.g. S7, 10–12) showed relatively smaller changes in V_L and Q_L^{-1} after the moistening. Although their moisture sorption histories are unknown, these lumber may have experienced humid conditions (humid place or long humid season), and therefore, the seasoning effects were partly lost. In any case, the acoustic quality of seasoned and aged wood is irreversibly degraded when exposed to humid conditions. To maintain the quality of seasoned and aged instruments, it is advisable to keep them dry.

Finally we need to mention the limitation of the present result. In this paper, we focused on the vibrational properties in L direction as the first step. However, that is not enough to describe the acoustic behavior of wooden musical instruments, because the wood is an anisotropic material. For clearer understanding of the seasoning effects, the other wood properties in R and T directions should be clarified in the future.

VI. CONCLUSIONS

When green wood was dried and conditioned at 20 °C and 60% RH, its sound velocity (V_L) gradually increased and its internal friction (Q_L^{-1}) decreased significantly over 6 months, whereas its moisture content equilibrated within 2 days. That "seasoning effect" was explained using the physical aging and stress relaxation of wood polymers. The seasoning effect was lost after the seasoned wood was moistened and reconditioned. It is advisable not to expose the seasoned instrument to humid conditions to keep its improved acoustic quality. The effects of seasoning were greater than those of long-term aging, while involving irreversible chemical changes. This fact coincides with the empirical knowledge of violin makers that seasoning is more important than long-term aging over centuries.

ACKNOWLEDGEMENTS

We are grateful to artisans and companies, David van Edwards, Eric Blot Jr., Elisa Scrollavezza, Andrea

Zanre, Kohno Guitar Manufacturing Co., Aoyama Harp Co., for their kind donation of precious aged lumber. We also thank Dr. Sandie Leconte, Institut National du Patrimoine, for providing aged wood samples.

REFERENCE

Brémaud, I. (**2012**). “Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity,” J. Acoust. Soc. Am. **131**(1), 807–818.

Brémaud, I., Kaïm, Y. I., Guibal, D., Minato, K., Thibaut, B., and Gril, J. (**2012**). “Characterization and categorization of the diversity in viscoelastic vibrational properties between 98 wood types,” Annals Forest Sci. **69**, 373–386.

Carlier, C., Brémaud, I, and Gril, J. (**2015**). “The role of tonewood selection and aging in instrument “quality” as viewed by violin makers,” in *2nd Annual Conference of COST FP1302 WoodMusICK*, edited by G. R. Ragnoni and A. M. Barry, 9–10 September, 2015, London, UK, pp. 35–37.

Carlier, C., Alkadri, A., Gril, J., and Brémaud, I. (**2018**). “Revisiting the Notion of “Resonance Wood” Choice: A Decompartmentalized Approach from Violin-Makers’ Opinion and Perception to Characterization of Material Properties’ Variability,” in Wooden Musical Instruments – Different Forms of Knowledge, edited by M. A. Pérez and E. Marconi, Cité de la Musique, Paris, pp. 119–139.

Endo, K., Obataya, E., Zeniya, N., Matsuo, M. (**2016**). “Effects of heating humidity on the physical properties of hydrothermally treated spruce wood,” Wood Sci. Technol. **50**, 1161–1179.

Haines, D.W. (**2000**). “The essential mechanical properties of wood prepared for musical instruments,” Catgut Acoust. Soc. J. **4**(2), 20–32.

Hearmon, R.F.S. (**1958**). “The influence of shear and rotatory inertia on the free flexural vibration of wooden beams,” Br. J. Appl. Phys. **9**(10), 381–388.

Hunt, D.G., and Gril, J. (**1996**). “Evidence of a physical ageing phenomenon in wood,” J. Mater. Sci. Lett. **15**, 80–82.

Kohara, J. (**1958**). “Study on the old timber,” Res. Rep. Fac. Technol. Chiba Univ. **19**(16), 1–97.

Kránitz, K., Sonderegger, W., Bues, C. T., Niemz, P. (**2016**). “Effects of aging on wood: a literature review,” Wood Sci. Technol. **50**, 7–22.

Obataya, E., Gril, J., and Norimoto, M. (**1998**). “The effects of adsorbed water on dynamic mechanical properties of wood,” Polymer **39**(14), 3059–3064.

Obataya, E., Ono, T., and Norimoto, M. (**2000**). “Vibrational properties of wood along the grain,” J. Mater. Sci. **35**, 2993–3001, 6317.

Obataya, E., and Tomita, B. (**2002**). “Hygroscopicity of heat-treated wood II. Reversible and irreversible reductions in the hygroscopicity of wood due to heating,” Mokuzai Gakkaishi **48**, 288–295.

Obataya, E. (**2010**). “Effects of ageing and heating on the mechanical properties of wood,” In: Luca Uzielli Ed. Wood science for conservation of cultural heritage. Proceedings of the International Conference on COST ACTION IE0601 in Florence, Firenze University Press, pp. 16–23.

Ono, T. (**1996**). “Frequency responses of wood for musical instruments in relation to the vibrational properties,” J. Acoust. Soc. Jpn. (E) **17**, 183–193.

Struik, L. C. E. (**1978**). “Physical aging in amorphous polymers and other materials,” Elsevier, Amsterdam.

Bucur, V. (**2016**) “Handbook of materials for string musical instruments,” Springer-Verlag Berlin Heidelberg.

Yokoyama, M., Gril, J., Matsuo, M., Yano, H., Sugiyama, J., Clair, B., Kubodera, S., Mitsutani, T., Sakamoto, M., Ozaki, H., Imamura, M., Kawai, S. (**2009**). “Mechanical characteristics of aged Hinoki wood from Japanese historical buildings,” C. R. Phys. **10**, 601–611.

Yankovskii, B. A. (**1967**). “Dissimilarity of the acoustic parameters of unseasoned and aged wood,” Sov. Phys. Acoust. **13**, 125–127.

Yoshikawa, S. (**2007**). “Acoustical classification of woods for string instruments,” J. Acoust. Soc. Am. **122**(1), 568–573.

Zeniya, N., Obataya, E., Endo-Ujiie, K., and Matsuo-Ueda, M. (**2019a**). “Application of time–temperature–humidity superposition to the mass loss of wood through hygrothermally accelerated ageing at 95–140 °C and different relative humidity levels,” SN Appl. Sci., **1**(3). https://doi.org/10.1007/s42452-018-0009-8.

Zeniya, N., Obataya, E., Endo-Ujiie, K., and Matsuo-Ueda, M. (**2019b**). “Changes in vibrational properties and colour of spruce wood by hygrothermally accelerated ageing at 95–140 °C and different relative humidity levels,” SN Appl. Sci. **1**(7). https://doi.org/10.1007/s42452-018-0004-0.