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ORIGINAL ARTICLE

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Suitability of acetylated woods for clarinet reed*

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Abstract The density (ρ), dynamic Young's modulus (E), loss tangent ($\tan\delta_L$) in the longitudinal (L) direction, and the dynamic shear modulus (G), loss tangent ($\tan\delta_S$) in the LT or LR (T, tangential; R, radial) plane of woods and cane (*Arundo donax* L.) in air-dried and wet conditions were measured. The acoustic converting efficiency (ACE), expressed by $\sqrt{E/\rho^3}/\tan\delta_L$, and the factors of anisotropy, expressed by E/G and $\tan\delta_S/\tan\delta_L$, of woods were compared with those of the canes. Low-density coniferous woods had higher ACE values and were of a more anisotropic nature than the cane. These woods seemed appropriate for clarinet reed owing to their homogeneous cellular structure. The stability in vibrational properties and the anticreep properties of the woods were enhanced by the acetylation treatment. Professional clarinet players suggested that acetylated Glehn's spruce and sitka spruce were suitable for clarinet reeds.

Key words Clarinet reed · Cane · Vibrational property · Anisotropy · Acetylation

Introduction

Cane (*Arundo donax* L.) is widely used for the vibrating reed of woodwind instruments, such as the clarinet. When the cane reed is used for a long time or is soaked in water, its tone quality and controllability are degraded as it loses its water-soluble extractives.[1–3] In addition, the parenchymal cells of the cane collapse easily during drying.[4] The unstable nature of cane may cause problems in use. To improve stability and durability, some plastic materials have recently been used for the reeds. The plastic reeds are not preferred by professional players, however, owing to their poor tone quality.[3] Thus, no other materials seem to be comparable to cane as far as application for reeds is concerned.

On the other hand, wood is regarded as an appropriate material for the soundboard of musical instruments owing to its excellent vibrational properties. If wood could be used for reeds, woodwind players would have a wider choice of reed materials for more varied tone quality. This study explores the suitability of wood as reed material. The viscoelastic properties of some woods and cane were compared. Furthermore, the practical quality of wooden reeds was evaluated by professional clarinet players.

Materials and methods

Materials

Sixty internodes of cane (*Arundo donax* L.) harvested for clarinet reeds in Antibe (France) were used. Specimens of 100 × 10 × 1 mm in the longitudinal (L), tangential (T), and radial (R) directions, respectively, were prepared from the inner part of the internodes. Thirty specimens were soaked in water for 4 days to remove the water-soluble extractives, air-dried at room temperature, and then steamed at 60°C and 100% relative humidity (RH) for 12 h to recover the collapse that occurred during drying.

Twenty specimens of 100 (L) × 10 (R) × 1 (T) mm were made from each of nine wood species: balsa (BS, *Ochroma lagopus*), royal paulownia (RP, *Paulownia tomentosa*), Japanese ceder (JC, *Cryptomeria japonica*), Glehn's spruce (GS, *Picea glehnii*), sitka spruce (SS, *Picea sitchensis*), yellow poplar (YP, *Liriodendron tulipifera*), Japanese oak (JO, *Quercus mongolica*), Japanese birch (JB, *Betula maximowicziana*), and cherry (C, *Prunus sargentii*). Ten specimens of each species were acetylated at 120°C for 8 h with acetic anhydride.

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All of the specimens were conditioned at 25°C and 60% RH or soaked in water for a week before measuring their vibrational properties.

Measurement of vibrational properties

The dynamic Young's modulus (E) and the loss tangent ($\tan\delta_L$) of the specimens in the L direction were measured by a free-free flexural vibration method. The dynamic shear modulus (G) and loss tangent ($\tan\delta_S$) in the LT plane of the cane or LR plane of the woods were measured using the torsional vibration method.

The measurements were carried out at 25°C and 60% RH. Because the loss tangent of wood tends to increase under nonequilibrium conditions,[5] the wet specimens should be tested at 100% RH. It was confirmed, however, that the measurements at 60% RH and 100% RH gave the same result when they were completed in a few minutes.

Measurement of creep deflection

The creep deflections of cane and SS wood were compared in the dimensions described above. The creep deflection was measured by three-point bending with an effective span of 80mm in an environmental chamber where the temperature was kept at 30°C. The specimens were loaded at their center, and the midspan deflection was detected using a laser transducer. A load of less than 15% of the breaking load was applied for each material. After loading, the RH inside the chamber was kept at 60% for an hour, then increased and maintained at 90% for 2h. Subsequently, the load was removed, and the creep recovery was observed for an hour at 60% RH.

Evaluation of the practical quality of wood reed

Acetylated GS, SS, and JC woods were converted to a German-type clarinet reed. The practical quality of these reeds was evaluated by seven professional clarinet players.

Results and discussion

Vibrational properties of the cane and woods

It is generally accepted that a high acoustic converting efficiency (ACE) and a high degree of anisotropy are required for the sound board of musical instruments.[6,7] The ACE is defined as the ratio of acoustic energy radiated from a beam to the energy given to vibrate the beam; it is proportional to $V/\rho \tan\delta_L$ or $\sqrt{E/\rho^3}/\tan\delta_L$, where V and ρ are the sound velocity and density, respectively.[8] The anisotropy of a material can be evaluated by E/G, which affects the frequency response of the bending vibration.[9,10] These vibrational factors, ACE and E/G, are valid in the evaluation of clarinet reed because a reed with higher E, lower ρ, and higher anisotropy in elastic moduli produces better tone quality.[11]

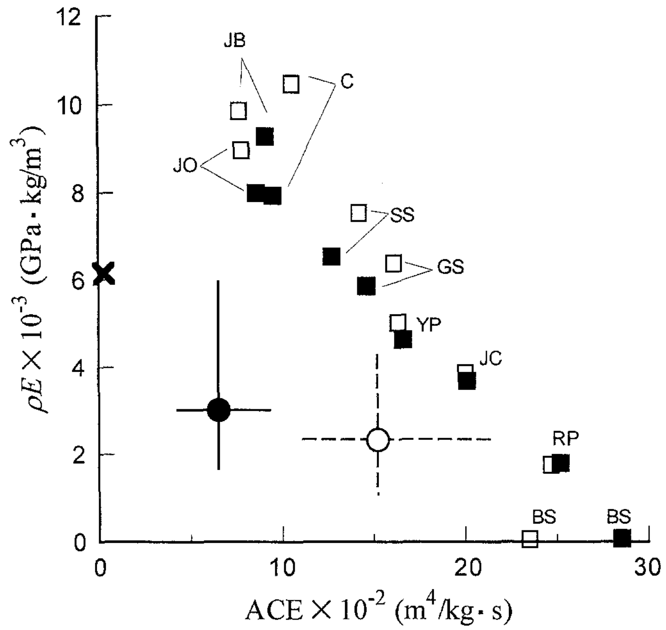

Fig. 1. Acoustic impedance (ρE) is plotted against acoustic converting efficiency (ACE) at 25°C and 60% relative humidity (RH). *Solid circle*, untreated cane; *open circle*, extracted cane; *open squares*, untreated woods; *solid squares*, acetylated wood; *cross*, acrylic resin[7]. For the *alphabetical abbreviations*, refer to Table 1

Another evaluation factor for reed material is ρE, which reflects the acoustic impedance. Because a reed with an extremely high ρE value is difficult to vibrate, a low ρE is preferred.

Table 1 lists the weight gain/loss (WG) due to the acetylation/extraction treatments, moisture content (mc), and ρ of the treated and untreated cane and woods. Table 2 lists the E, $\tan\delta_L$, G, $\tan\delta_S$, and various vibrational factors for the air-dried cane and woods measured at 25°C and 60% RH. Those properties of the wet cane and woods are listed in Table 3. Figure 1 shows the ρE of air-dried cane and woods plotted against their ACE. The ACE of untreated cane was lower than that of the extracted specimens because the water-soluble extractives markedly enhanced the $\tan\delta_L$.[1] The BS and RP had higher ACE and lower ρE values than did the cane. Meanwhile, the SS, GS, YP, and JC had almost the same ACE and higher ρE values than the extracted cane. The ACE values of the JB, JO, and C were similar to those of the untreated cane, and their ρE values were the highest among the materials tested. Acetylation treatment did not markedly affect the ACE and ρE values of the woods in the air-dried state.

Figure 2 shows the ρE of wet cane and woods plotted against their ACEs. With a marked increase of ρ due to water absorption, the ACE values decreased and ρE values increased. The ACE and ρE values of untreated cane were almost the same as those for extracted cane because its water-soluble extractives were lost by soaking in water. The ACE value of BS was extremely low and almost the same as that of acrylic resin.[7] The ρE and ACE values of RP were almost the same as those of the cane. The other untreated woods have similar ACEs but higher ρE values than the

Table 1. Weight gain/loss due to acetylation/extraction, moisture content, and density of the cane and woods

Species	WG[a](%)	Air-dried[c]		Wet[d]	
		mc (%)	ρ (kg/m^3)	mc (%)	ρ (kg/m^3)
Cane					
Untreated (UC)		8.8	439	189	1078
Extracted (EC)	−12.8[b]	8.0	371	232	1076
Untreated woods					
Balsa (BS)		7.5	81.7	1363	1004
Royal paulownia (RP)		9.2	276	354	1055
Japanese cedar (JC)		8.9	394	229	1089
Yellow poplar (YP)		9.0	458	195	1094
Glehn's spruce (GS)		9.2	475	187	1102
Sitka spruce (SS)		9.2	502	172	1107
Japanese oak (JO)		9.4	663	119	1140
Japanese birch (JB)		9.2	690	106	1143
Cherry (C)		8.4	699	106	1163
Acetylated woods					
BS	12.3	2.7	95.5	1030	1002
RP	18.1	3.8	296	276	1042
JC	17.5	3.8	418	177	1076
YP	17.1	4.1	474	143	1064
GS	19.8	4.3	505	130	1055
SS	17.4	5.1	526	123	1052
JO	20.9	3.8	685	73	1096
JB	19.2	3.9	713	72	1124
C	9.6	4.1	666	87	1145
Acrylic resin[7] (AC)			1180		

WG, weight gain/loss; mc, moisture content; ρ, density.
[a] Based on the oven-dried weight of the untreated specimen.
[b] Due to the removal of extractives.
[c] Conditioned at 25°C and 60% relative humidity.
[d] Soaked in water for a week.

Table 2. Acoustic properties of air-dried cane and woods

Species[a]	E (GPa)	$\tan\delta_L \times 10^3$	G (GPa)	$\tan\delta_S \times 10^3$	ACE[b] $\times 10^{-2}$ (m^4/kg·s)	$\rho E \times 10^{-3}$ (GPa·kg/m^3)	E/G	$\tan\delta_S/\tan\delta_L$
Cane								
UC	6.92	14.8	0.74	26.5	6.35	3.09	9.43	1.81
EC	6.32	7.4	0.76	15.0	15.28	2.39	8.39	2.05
Untreated woods								
BS	0.70	15.2	0.10	21.8	23.51	0.06	7.15	1.43
RP	6.36	7.0	0.49	18.8	24.69	1.75	12.85	2.68
JC	9.81	6.3	0.68	20.8	20.04	3.86	14.47	3.30
YP	10.96	6.5	0.83	17.2	16.35	5.02	13.24	2.64
GS	13.40	6.9	0.84	18.8	16.15	6.37	16.04	2.72
SS	15.01	7.7	0.83	25.2	14.24	7.53	18.05	3.30
JO	13.53	8.7	1.34	17.2	7.82	8.97	10.24	1.98
JB	14.28	8.6	1.28	19.6	7.70	9.86	11.14	2.30
C	14.95	6.2	1.49	13.8	10.58	10.46	10.05	2.32
Acetylated woods								
BS	0.86	10.8	0.11	19.2	28.53	0.08	7.55	1.78
RP	6.07	6.0	0.46	15.8	25.20	1.80	13.15	2.62
JC	8.82	5.5	0.59	17.4	20.13	3.68	14.88	3.19
YP	9.78	5.8	0.76	15.8	16.62	4.63	12.83	2.74
GS	11.60	6.5	0.69	18.2	14.62	5.87	16.87	2.81
SS	12.43	7.3	0.71	24.2	12.75	6.53	17.58	3.34
JO	11.68	7.0	1.11	16.0	8.61	8.00	10.56	2.29
JB	13.02	6.6	1.12	15.4	9.13	9.29	11.65	2.35
C	11.91	6.7	1.24	15.4	9.53	7.94	9.64	2.32
AC[7]	5.25	51.4	1.91	62.0	0.35	6.20	2.75	1.21

[a] Refer to Table 1 for abbreviations.
[b] Expressed by $\sqrt{E/\rho^3}/\tan\delta_L$.

Table 3. Acoustic properties of wet cane and woods

Species[a]	E (GPa)	$\tan\delta_L \times 10^3$	G (GPa)	$\tan\delta_S \times 10^3$	ACE[b] $\times 10^{-2}$ ($m^4/kg \cdot s$)	$\rho E \times 10^{-3}$ ($GPa \cdot kg/m^3$)	E/G	$\tan\delta_S/\tan\delta_L$
Cane								
UC	5.82	8.4	0.59	22.7	2.57	6.29	9.97	2.70
EC	5.74	9.0	0.57	20.7	2.39	6.19	10.10	2.31
Untreated woods								
BS	0.62	22.4	0.07	38.8	0.35	0.62	8.69	1.73
RP	5.50	9.7	0.35	30.3	2.23	5.81	15.78	3.12
JC	8.35	8.4	0.49	23.8	3.01	9.09	17.14	2.82
YP	8.75	10.9	0.52	31.0	2.36	9.58	16.69	2.85
GS	10.32	10.8	0.45	27.3	2.57	11.37	23.12	2.54
SS	11.54	11.3	0.45	34.8	2.57	12.78	25.40	3.06
JO	9.77	14.3	0.72	35.3	1.79	11.14	13.54	2.47
JB	10.37	14.3	0.75	40.3	1.84	11.84	13.96	2.85
C	10.93	12.7	0.92	35.7	2.08	12.70	11.91	2.90
Acetylated woods								
BS	0.80	15.1	0.09	25.1	0.61	0.86	9.42	1.66
RP	6.02	7.1	0.40	23.0	3.28	6.33	15.19	3.26
JC	8.55	6.5	0.58	21.0	4.02	9.20	14.67	3.22
YP	9.30	6.6	0.64	21.7	4.20	9.90	14.50	3.29
GS	10.60	8.2	0.55	24.3	3.67	11.18	19.41	2.97
SS	11.05	8.8	0.58	27.3	3.49	11.62	19.23	3.09
JO	10.70	8.4	1.00	21.6	3.41	11.72	10.75	2.59
JB	11.87	7.8	1.05	21.2	3.69	13.34	11.33	2.70
C	11.05	7.9	1.08	19.3	3.45	12.65	10.16	2.48

[a] Refer to Table 1 for abbreviations.
[b] Expressed by $\sqrt{E/\rho^3}/\tan\delta_L$.

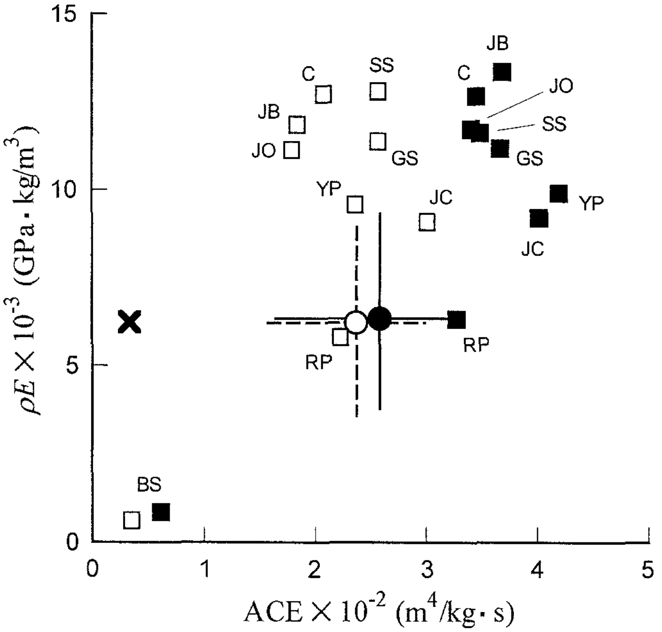

Fig. 2. ρE of cane and woods is plotted against acoustic converting efficiency (ACE) in the wet condition. Symbols: Refer to Fig. 1

cane. In the wet condition, acetylation treatment increased the ACE values of wood, with little effect on their ρE values.

Because reeds are used in various moisture conditions, the quality of reed material should be better than that of cane irrespective of the moisture condition. The BS seems inappropriate for the reed because its ACE value is low in the wet condition. The RP seems the most appropriate material for the reed, because it has higher ACE and lower ρE values in the air-dried condition, and its ACE and ρE values are close to those of cane in the wet condition. Irrespective of the moisture condition, the ACE values of untreated SS, GS, YP, and JC are similar to those of cane, whereas their ρE values are slightly higher. Acetylated SS, GS, YP, and JC have higher ACE values in the wet condition. Untreated JB, JO, and C with relatively low ACE and high ρE values might cause difficulty in vibration. The ACEs of JB, JO, and C in the wet condition are improved by acetylation, but those in the dry condition remain unchanged.

Figure 3 shows the relations between $\tan\delta_S/\tan\delta_L$ and E/G for the air-dried cane and woods. The E/G and $\tan\delta_S/\tan\delta_L$ values of the cane and woods were higher than those of isotropic materials, such as acrylic resin.[7] Except for BS, all other wood species recorded higher E/G and $\tan\delta_S/\tan\delta_L$ values than those for cane. The low-density coniferous woods such as GS, SS, and JC, showed especially marked anisotropy. In the air-dried state, the acetylation treatment had little effect on the E/G and $\tan\delta_S/\tan\delta_L$ values of the woods.

Figure 4 shows the relations between $\tan\delta_S/\tan\delta_L$ and E/G for the wet cane and woods. The E/G and $\tan\delta_S/\tan\delta_L$ values were larger than those in the air-dried state. Acetylation treatment reduced the E/G values for woods in the wet condition. However, E/G and $\tan\delta_S/\tan\delta_L$ values of acetylated low-density woods such as the GS, SS, JC, YP, and RP

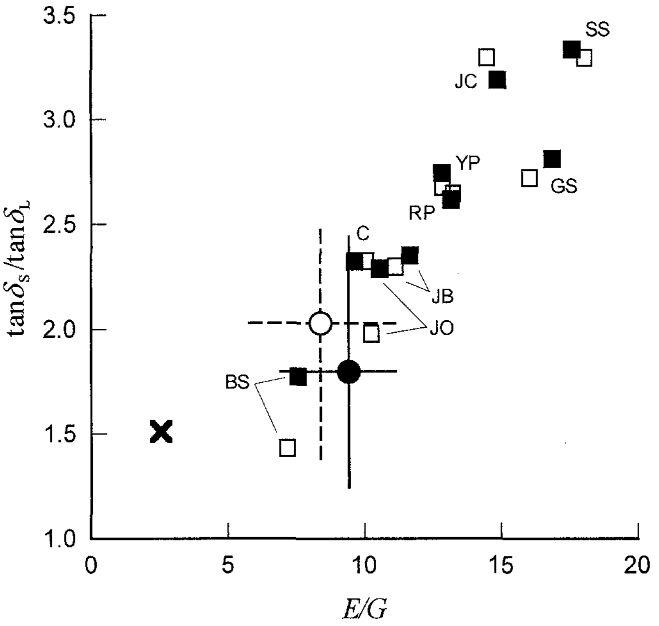

Fig. 3. Relations between the ratio of loss tangents ($\tan\delta_S/\tan\delta_L$) and that of dynamic elastic moduli (*E*/*G*) for cane and woods at 25°C and 60% RH. Symbols: refer to Fig. 1

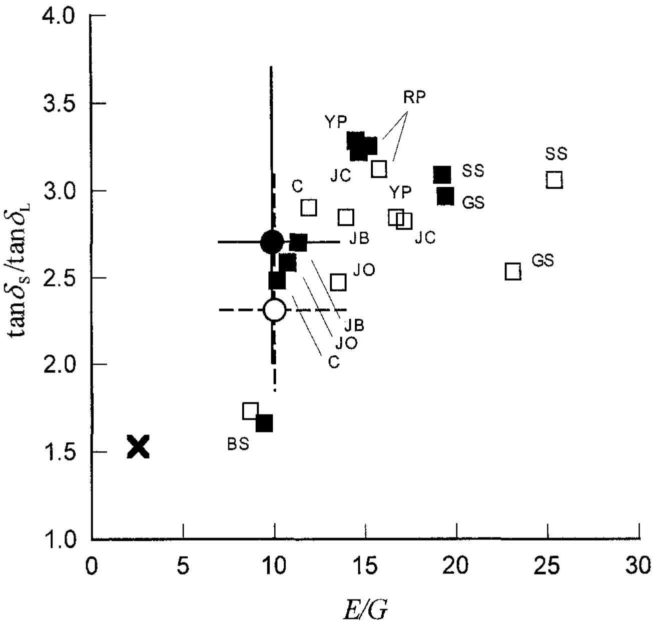

Fig. 4. Relations between the ratio of loss tangents ($\tan\delta_S/\tan\delta_L$) and that of dynamic elastic moduli (*E*/*G*) for cane and woods in the wet condition. Symbols: refer to Fig. 1

were higher than those of the cane. The JB, JO, and C had *E*/*G* and $\tan\delta_S/\tan\delta_L$ values similar to those for cane. As far as the anisotropic nature is concerned, GS, SS, JC, YP, and RP seem appropriate for reeds.

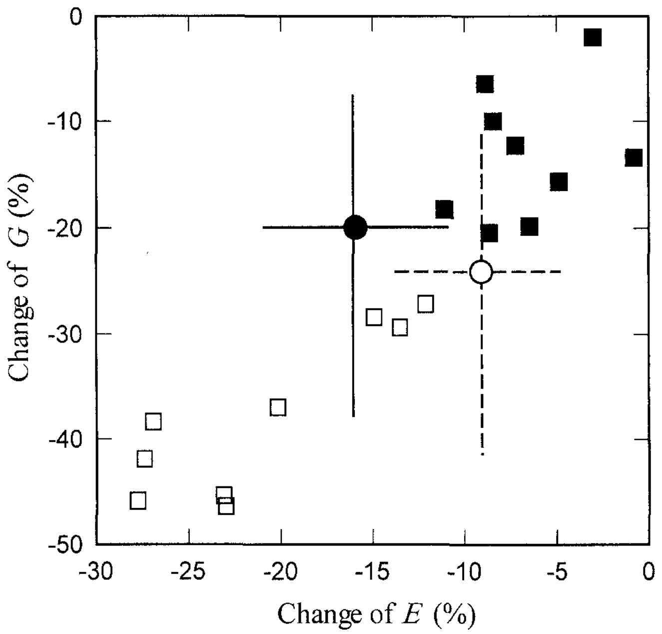

Fig. 5. Relations between the change of dynamic shear modulus (*G*) and that of dynamic Young's modulus (*E*) due to water absorption for cane and woods. Symbols: refer to Fig. 1

Stability in the vibrational properties of the cane and woods

Because clarinet reed is gradually moistened by the saliva of a player, it is important that the vibrational properties of the reed material are stable under water absorption. If the vibrational properties of a reed change remarkably during playing, the players can hardly control the tone. Figure 5 shows the relations between the changes of *E* and *G* due to water absorption. The *E* and *G* of untreated woods decreased more remarkably with moisture absorption than the cane, indicating that the untreated woods are inferior to the cane in terms of the stability in their vibrational properties. On the other hand, the acetylated woods had excellent stability under varied moisture conditions.

Creep deflection of the cane and woods

The reed is pressed by the lower lip of a player as shown in Fig. 6. The strong pressure from the lip during continuous playing sometimes makes the reed bend irreversibly toward the mouthpiece. This deflection is often called "yielding," and it causes trouble in use because the tone quality and controllability of the reed are degraded as the reed opening becomes narrower.[12,13] Thus, a good anticreep property is a requirement for the reed material. Figure 7 shows the relative creep deflection of SS wood and cane. The creep deflection of canes and untreated wood progressed markedly during moisture adsorption. A part of these deflections remained even after removal of the load. On the other hand, the acetylated wood showed excellent anticreep properties. These results indicate that acetylation improves the suitability of wood for reeds.

Anatomical structure requirement of reed material

Generally, the tip of the reed is made to be 100 μm thick or less. Because most woods have a larger pE value than cane, the tip of the wooden reed should be made thinner than 100 μm. Figure 8 shows the cross sections of cane, SS, RP, and JB. RP and JB with large vessels cause difficulty when making reeds because the thin tip of the reed tends to split at the vessels. On the other hand, coniferous woods such as GS, SS, and JC, which have a more homogeneous anatomical structure, could be used easily.

Practical quality of wooden reed

Based on the considerations above, the GS, SS, and JC were selected as materials for clarinet reeds. The German-type clarinet reeds were made from acetylated specimens. According to the professional players, the GS or SS wood reed had a "sonorous tone," "good response," and "good stability during playing." These comments indicated that the

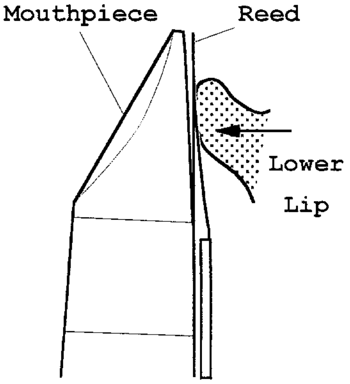

Fig. 6. Clarinet reed in use

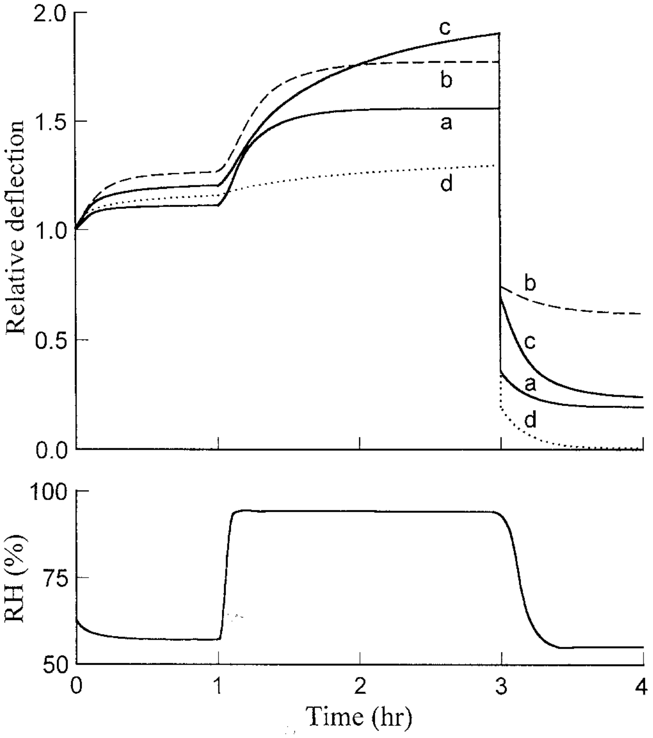

Fig. 7. Relative creep deflections of cane and sitka spruce during moisture adsorption. *a*, untreated cane; *b*, extracted cane; *c*, untreated sitka spruce; *d*, acetylated sitka spruce

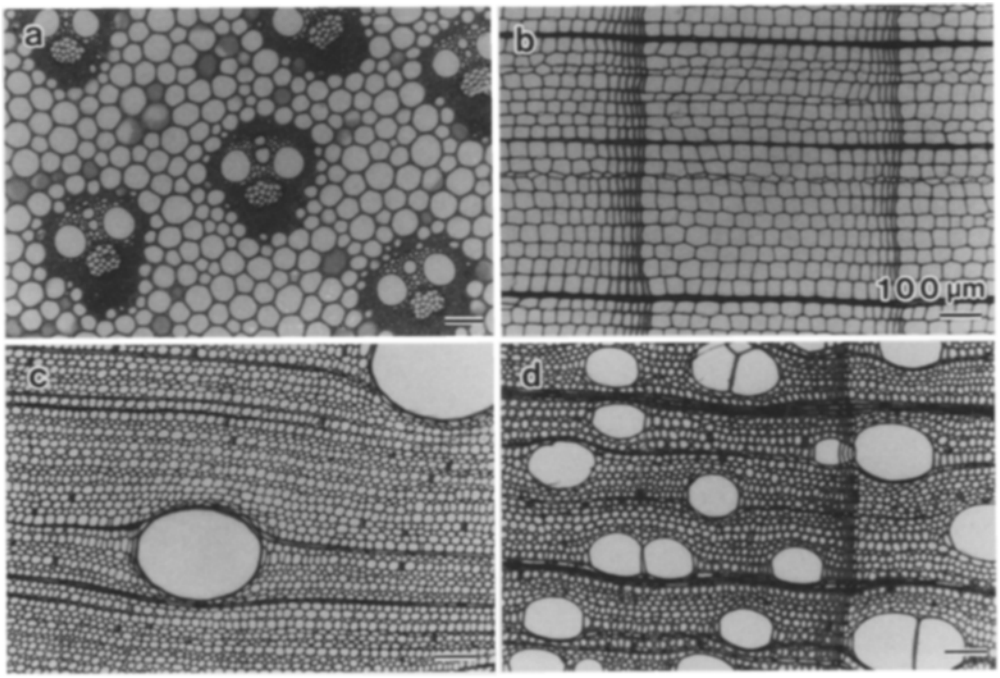

Fig. 8. Cross sections of cane (**a**), sitka spruce (**b**), royal paulownia (**c**), and Japanese birch (**d**)

acetylated wooden reeds meet the basic requirements. On the other hand, two of the seven players claimed that these wooden reeds were "heavy to some extent" or "difficult for tone controlling." These defects are thought to be due to the higher density and elastic modulus of the wood and can be solved by "tuning" the shape of the reed.

The stability of acetylated wood is better than that of cane, and its vibrational properties are not affected by the extractives. In addition, its cell wall does not collapse easily during drying. Thus acetylated wood is expected to be a new material for the clarinet reed.

Conclusions

The vibrational properties and creep deflection of acetylated wood suggest that it is suitable for reed material. The characteristics of the acetylated wooden reed could be summarized as follows:

1. Acetylated Glehn's spruce or sitka spruce had high acoustical converting efficiency, a high degree of anisotropy, and excellent stability under varied moisture conditions.
2. The wooden reed had "sonorous tone," "good response", and "good stability during playing."

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