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ORIGINAL ARTICLE

Eiichi Obataya · Joseph Gril · Bernard Thibaut

Shrinkage of cane (*Arundo donax*) I. Irregular shrinkage of green cane due to the collapse of parenchyma cells

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Abstract Shrinkage of green cane (*Arundo donax* L.) was measured during air-drying at room temperature. The cane began to shrink at 150% moisture content due to a remarkable collapse of parenchyma cells. The collapse recovered after boiling in water, but more serious collapse (recollapse) was induced by the following drying. On the other hand, the collapse recovered almost completely after steaming with saturated water vapor at 92°–96°C without recollapse. By comparing the thickness of cane specimens before and after steaming, the degree of cell collapse remaining in dry cane was evaluated. When the green cane was frozen prior to drying, the degree of collapse was reduced whereas the drying rate remained unchanged. The effect of prefreezing was interpreted as the generation of air bubbles in the cell lumen which hinder the effective loading of liquid tension on the cell wall. Even when the cane was carefully dried using a conventional method used by reed manufacturers, the degree of collapse was very large and it increased with elevating internode position.

Key words *Arundo donax* · Drying · Shrinkage · Collapse

Introduction

The cane *Arundo donax* L. is specially cultivated for manufacture of the vibrating plate (reed) of woodwind instruments, such as clarinets and saxophones. Because the performance of instruments depends strongly on the quality of the reed, we have so far dealt with the mechanical and acoustic properties of cane.[1–3] However, the shrinking and swelling behavior of cane is still unclear, whereas its dimensional stability is important because the reed is used in a highly humid condition when in use in an instrument.

Figure 1 shows the top part of a clarinet. The reed should fit well to the flat face of the mouthpiece for an effective concentration of the air flow (Fig. 1a). However, the back surface of the reed sometimes swells irreversibly (Fig. 1b). Such a problem must be due to the recovery of cell collapse. Usually, the cane is processed into reeds after drying in open air for several months. At the beginning of drying, remarkable cell collapse must occur and remains in the final products. The collapse does not immediately recover in water unless it is heated, but it can gradually recover with repeated dry–wet cycles.[4] This is the major reason for the problematic irreversible swelling of reed.

To improve the drying method to give less collapse, or to establish a method for the effective recovery of collapse, it is necessary to understand the shrinking and swelling behavior of green cane. In this article, we describe the shrinkage of green cane, especially that due to the collapse of parenchyma cells.

Materials and methods

Cane sample

Two green canes (1.5 years old) and three dry canes (2 years old) were obtained from a farm owned by Marca Reed Inc. near Toulon in France. The green cane poles were sectioned into tubes, and each tube was wrapped with poly vinylidene chloride (PVDC) film to prevent dehydration. The three dried cane poles had been dried by a conventional method used by reed manufacturers: the fresh cane poles were placed upright in the open air for 4 months without being exposed to direct sunlight (January–April, 2002), and were then cut into shorter poles that were dried under sunlight for 3 months (May–July, 2002), and, finally, were stored at room temperature without humidity control. The average moisture content (M) of cane was reduced to

E. Obataya[1] (✉) · J. Gril · B. Thibaut
Laboratoire de Mécanique et Génie Civil, Université Montpellier II, 34095 Montpellier cdx 5, France

Present address:
[1] Institute of Wood Technology, Akita Prefectural University, Noshiro 016-0876, Japan
Tel. +81-185-52-6984; Fax +81-185-52-6976
e-mail: obataya@iwt.akita-pu.ac.jp

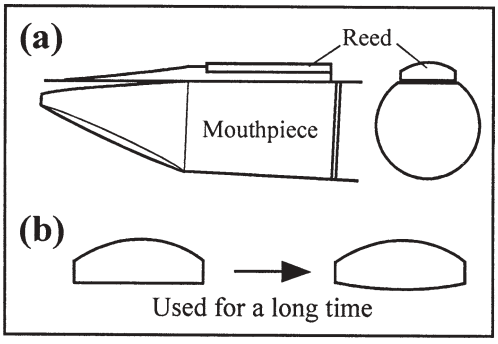

Fig. 1. Top part of a clarinet (**a**) and irreversible swelling of a reed after prolonged use (**b**)

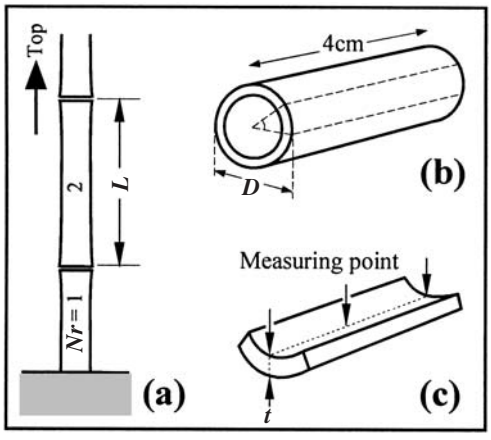

Fig. 2. Geometry of a cane specimen

24%–52% by the initial outdoor drying, and it reached 8%–9% on completion. Most of the free water must have been removed in the first 4 months of outdoor drying. Because the clarinet reed is usually made from the 5–10 internodes above the base, we used the lower 20 internodes for the experiments. Hereafter, the position of the internode is identified by the node number (Nr) from 1 (the lowest part) to 20 (the highest part).

Drying and rewetting

The practical problem discussed here is caused by the shrinkage and swelling of cane in its radial direction. Therefore, we focused on the changes in the thickness of cane stem during drying and rewetting. As shown in Fig. 2, several straight internodes (Nr = 1, 4, 6, 7, 9, and 11) were selected from a green cane pole. Their center part was cut into hollow cylinders that were 4 cm long (Fig. 2b), and then separated into eight specimens (Fig. 2c). These specimens were divided into four groups (A–D). Group A was previously soaked in water for a week, and the other groups remained untreated. All specimens were then dried at 20°C and 65% relative humidity (RH) for 2 weeks, and their thickness was measured intermittently. After the weight of specimens was equilibrated, these were completely dried in vacuo over SiO_2 and P_2O_5.

The swelling of specimens was measured at 20°C and 65% RH for 1 week and at 100% RH for 2 weeks. The groups A, B, and C were then soaked in water for 1 week, and the groups A and B were subsequently boiled for 1 hour. Meanwhile, group D was steamed under saturated water vapor at 92°–96°C for 1 hour using a cooking steamer. Finally, all specimens were dried again at 20°C and 65% RH and completely dried in vacuo, and their second shrinkage was measured. The average moisture contents (M) of specimens were based on their absolute dry weight.

Microscopic observation

The transverse cross sections of green cane specimens were planed using a microtome, and observed during drying and after steaming. Some specimens were quickly dried in an oven at 105°C just after the steaming, to see the occurrence of recollapse by the severe kiln drying.

Prefreezing

Seven green cane internodes (Nr = 3, 5, 7, 9, 11, 13, and 15) were used. Two tubes of 2–4 cm in length were made from each internode and divided into two groups. One group was kept green in water. The other group was packed with PVDC, frozen in a refrigerator at −12°C for 1 week and defrosted at room temperature overnight. All tubes were then dried at 20°C and 65% RH for 1 month followed by complete drying in vacuo. Next, each tube was divided into 8–12 strips, and their thicknesses were measured in the absolute dried condition. These specimens were then steamed by the method described above and their thicknesses measured. Finally these specimens were completely dried again in vacuo to measure their thickness.

Evaluation of cell collapse remaining in canes dried by a conventional method

Dry cane tubes were divided into strips as shown in Fig. 2c. Their thicknesses in the absolute dry condition were measured before and after steaming. The specimens were then soaked in water under vacuum for 1 week, and their wet volumes measured by the Archimedes method. The basic density (ρ') of each specimen was calculated from the absolute dry weight and the wet volume of specimen.

Results and discussion

Shrinkage and swelling of cane

Figure 3 shows an example of the shrinkage of green cane (Nr = 11) in the radial direction plotted against the average moisture content (M). The thickness (t) was normalized to that in the green state (t_g). The cane began to shrink at 150% M, while marked shrinkage below 20% M was attrib-

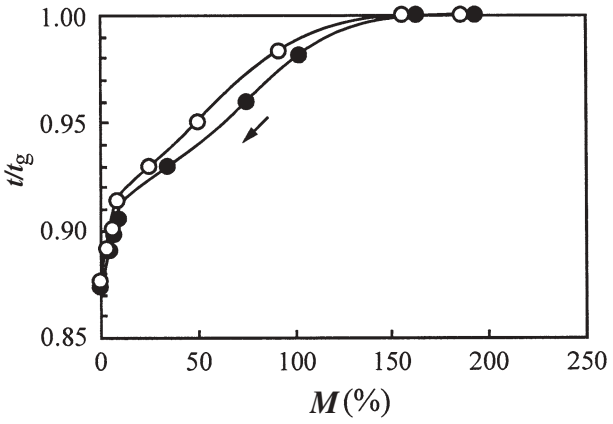

Fig. 3. Change in the relative thickness (t/t_g) of cane specimens (Nr = 11) during drying plotted against the average moisture content (M). *Open circles*, green cane; *filled circles*, green cane previously soaked in water for 1 week

uted to normal shrinkage, i.e., the shrinkage of the cell wall itself. Similar trends were observed in all internodes tested. The previous soaking had little influence on the initial M value and the following shrinkage. This fact indicated that the green cane had already been saturated with water, and that the water-soluble substances in the cell lumen did not affect the shrinkage of cane.

Figure 4 shows the cross section of a green cane (Nr = 4). The cane mainly consists of vascular bundles and parenchyma cells. Most of the parenchyma cells showed round shapes in their green state. Figure 5 shows the changes in the cane cells during drying. No irregular shrinkage was observed in the first 2 h of drying, but many cells crushed after 4 h of drying. Only the parenchyma cells collapsed while the vascular bundles remained unchanged throughout the drying process. The collapse did not develop cell by cell, but multiple cells yielded synchronously. The collapse was frequently found in the outer and middle layers, and was especially noticeable in the radial direction.

Figure 6 shows the reswelling of cane specimens (Nr = 7). The thickness of cane increased linearly with increasing M up to 20%, but it did not reach its maximum level even after soaking in water for 1 week. On the other hand, the thickness of cane recovered almost completely by boiling or steaming. It was considered that the cane cell wall should be well softened by moisture and heat above 90°C, the softening temperature of wet cane,[3] for the complete recovery of cell collapse.

Figure 7 shows the shrinkage of cane specimens (Nr = 7) during the second drying. The rewetted cane shrunk considerably again, and the total shrinkage after the second drying was twice that achieved by the first drying. The effect of boiling is sometimes explained by the disappearance of air bubbles in the free water,[5] but it should be remembered that the intensity of collapse was also enhanced by soaking in cold water. Therefore, the disappearance of air bubbles is not a major reason for the larger shrinkage of rewetted cane. In general, the degree of collapse is reduced by the improvement of permeability. For example, checks at pits due to

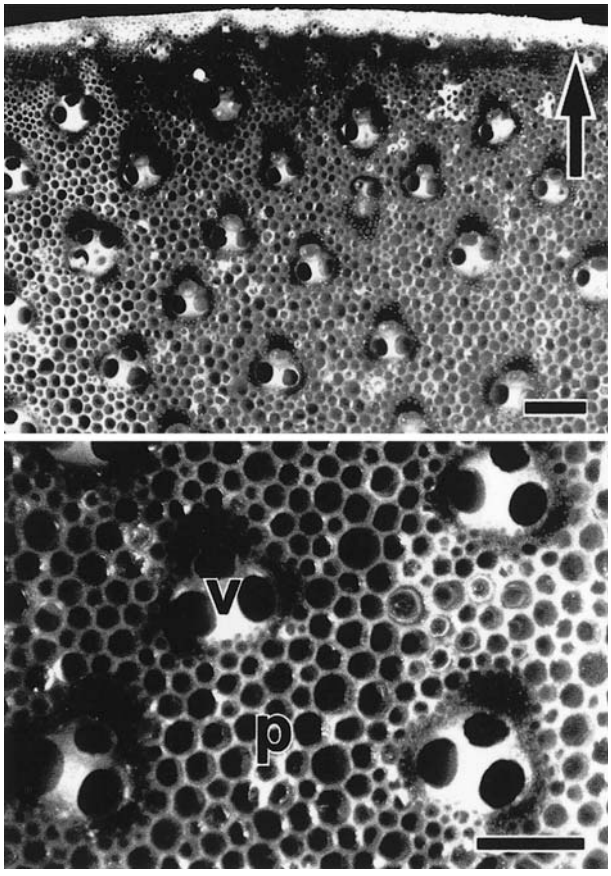

Fig. 4. Cross sections of a green cane (Nr = 4) showing vascular bundles (V) and parenchyma cells (P). *Arrow*, radial direction. *Bars* 200 μm

Table 1. Weight percent loss of cane specimen due to the extraction in water

Nr	Hot water extraction[a]		Cold water extraction[b]
	Control	Presoaked[c]	
1	7.5	6.1	6.4
4	5.9	5.6	4.2
6	6.6	6.6	4.9
7	6.1	6.3	5.1
9	7.0	7.7	6.0
11	9.6	8.4	8.5

[a] Green cane was dried once, soaked in water for 1 week, and then boiled for 1 h
[b] Green cane was dried once and soaked in water for 1 week
[c] Green cane was soaked in water for 1 week and dried prior to extraction

dynamic compression[6] or to prefreezing[7] can reduce the degree of collapse. In the present case, however, the drying rate remained unchanged or slightly increased after soaking in water, probably because of the removal of hydrophilic extractives. Thus the remarkable recollapse of rewetted cane cannot be explained by the change of permeability.

Table 1 lists the weight loss (WL) of cane specimens due to the extraction in water. As reported before, the cane contains much water-soluble extractive materials, mainly consisting of sugars.[1] Interestingly, the WL value remained

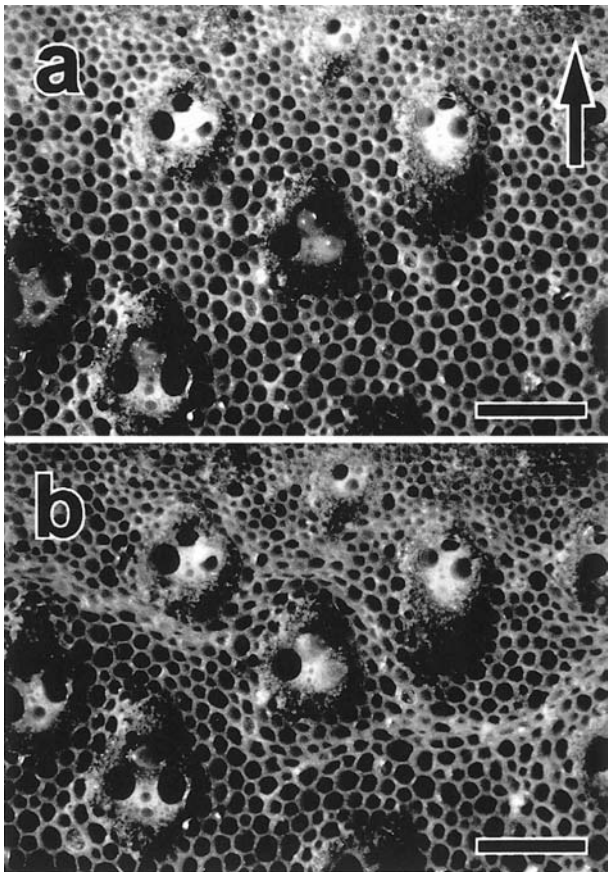

Fig. 5a,b. Cross sections of a cane (Nr = 4) during drying. **a** Dried at 20°C and 65% relative humidity (RH) for 2 h; **b** dried for 4 h; *arrow*, radial direction. *Bars* 200 μm

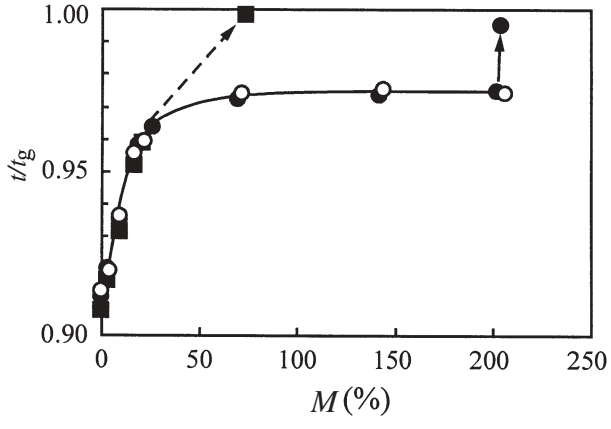

Fig. 6. Change in relative thickness (t/t_g) of cane specimens (Nr = 7) with moistening and rewetting plotted against the average moisture content (M). *Open circles*, moistened at 100% RH and soaked in water; *filled circles*, moistened and boiled; *squares*, moistened and steamed; *solid arrow*, boiling; *broken arrow*, steaming

almost unchanged by the previous soaking in water for 1 week, whereas the extractives could be easily removed from dried cane even in cold water. This fact indicates that most extractives are retained in green cane cells unless the cane is dried. It is speculated that the first drying causes some damage of the cane cell wall which allows the easier removal of

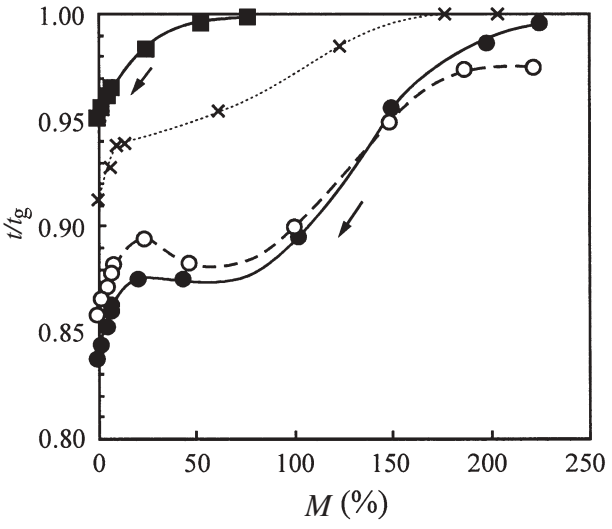

Fig. 7. Change in relative thickness (t/t_g) of cane specimens (Nr = 7) during the second drying plotted against the average moisture content (M). *Crosses*, shrinkage from the green state (the first drying); *open circles*, soaked in water and dried; *filled circles*, boiled and dried; *squares*, steamed and dried

extractives. Such damage and/or subsequent removal of cell wall components might be responsible for the easier yield of cane cells in the second drying. A similar phenomenon has already been observed in bamboo.[8]

As shown in Fig. 7, the steamed specimen showed less shrinkage than the rewetted specimens. The M of cane slightly increased by steaming, but such an increase was not enough to fill many cell lumens with free water. Consequently, little recollapse occurred in the following drying. Figure 8 shows the cross section of cane before and after steaming. No serious collapse was found in the steamed specimens, and no significant weight loss was induced by the steaming. Although there must be slight chemical changes, such as hydrolysis of hemicelluloses, the steaming seems a convenient method to recover the collapse of cane.

Cell collapse is generally explained by the liquid tension of free water,[9] but some species such as western red-cedar clearly show cell collapse even by drying from its fiber saturation point (FSP) where no free water exists.[10] In such a case, the collapse could be explained by the differential shrinkage involving drying stress. In the present case, however, the steamed cane, i.e., cane at FSP, showed no recollapse even with severe kiln drying. This fact suggests that the collapse of cane barely occurs in the absence of free water.

Effect of prefreezing

In this discussion, the total shrinkage of cane due to initial drying (S_t) is separated into the components due to cell collapse (S_c) and that of the cell wall itself (normal shrinkage, S_n) by the following equations:

$$S_t = S_c + S_n$$

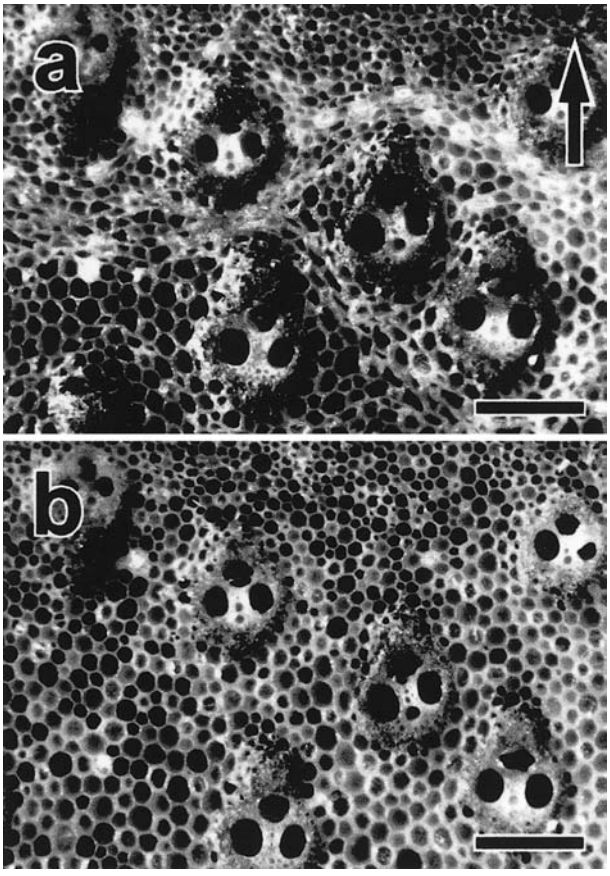

Fig. 8. Cross sections of a dry cane (Nr = 4) before (**a**) and after (**b**) steaming. *Bars* 200 μm

$$S_c = \frac{t_2 - t_1}{t_s}$$

$$S_n = \frac{t_s - t_2}{t_s}$$

where t_1, t_s, and t_2 are the thickness of cane specimen after the first drying, after steaming, and after the second drying, respectively. This enables the evaluation of the intensity of collapse remaining in dried cane, even if its thickness in the green state is unknown. Figure 9 shows the effects of prefreezing on the shrinkage of cane. The S_c value was reduced by prefreezing, while no significant change was recognized in the S_n value. The effect of prefreezing on the reduction of collapse is interpreted by the occurrence of checks at pits which improves the water permeability[11] and/or the formation of air bubbles in the free water.[7] The former interpretation is not applicable to the present case because the drying rate remained unchanged by prefreezing. Thus the latter must be the dominant mechanism in the prefreezing of cane: when green cane is frozen, a certain amount of air dissolving in free water is liberated, and it forms small bubbles which remain for a long time even after the melting of ice. On drying, the liquid tension of free water is not effectively loaded on the cell wall, but is consumed in the expansion of air bubbles. Consequently, the intensity of cell collapse is reduced.

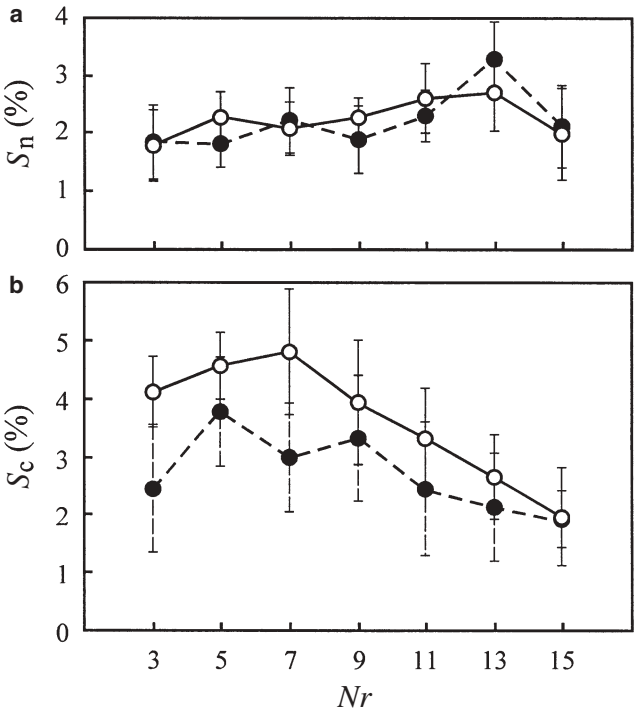

Fig. 9. Effects of prefreezing on **a** normal (S_n) and **b** abnormal (S_c) shrinkage as a function of node number (*Nr*). *Open circles*, control; *filled circles*, prefrozen; *bars*, standard deviations

Degree of collapse remaining in canes dried by a conventional method

Figure 10 shows the dimension profile of three cane poles dried by a conventional method and the following conditioning at 20°C and 65% RH. The length of internode had a peak between Nr = 5 and 10, while the diameter and thickness of cane decreased with elevating position. On the other hand, ρ' was independent of Nr.

Figure 11 shows the S_n and S_c values of cane specimens as a function of Nr. The S_n value was almost constant or increased very slightly with increasing Nr. The S_c value also increased with increasing Nr while its variation was larger than that of S_n. Because it is well known that higher internodes are less lignified,[12] the larger S_c for higher internodes was assumed to be due to the lower degree of lignification. However, as shown in Fig. 9, the S_c value decreased with Nr when each internode was cut into short tubes prior to drying. That contradiction might be due to the effect of drying rate. When a cane is dried very slowly by a traditional method, a low degree of lignification causes high intensity of collapse as shown in Fig. 11. On the other hand, higher internodes having thin walls dry faster than lower internodes when they are cut into short tubes. Because fast drying generally results in low collapse in cane[4] and also in wood,[13] the high internodes show less collapse as shown in Fig. 9. The effect of drying rate will be discussed in a following article.

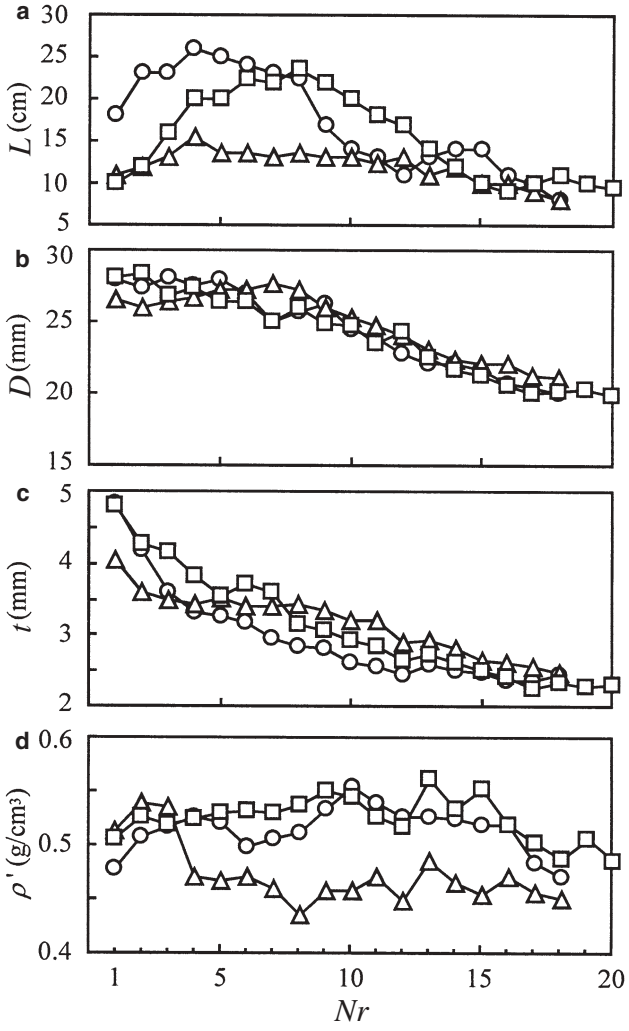

Fig. 10. **a** Length (L), **b** diameter (D), **c** average thickness (t), and **d** basic density (ρ') of three different dry cane poles plotted against the node number (Nr). Different plots indicate different cane poles

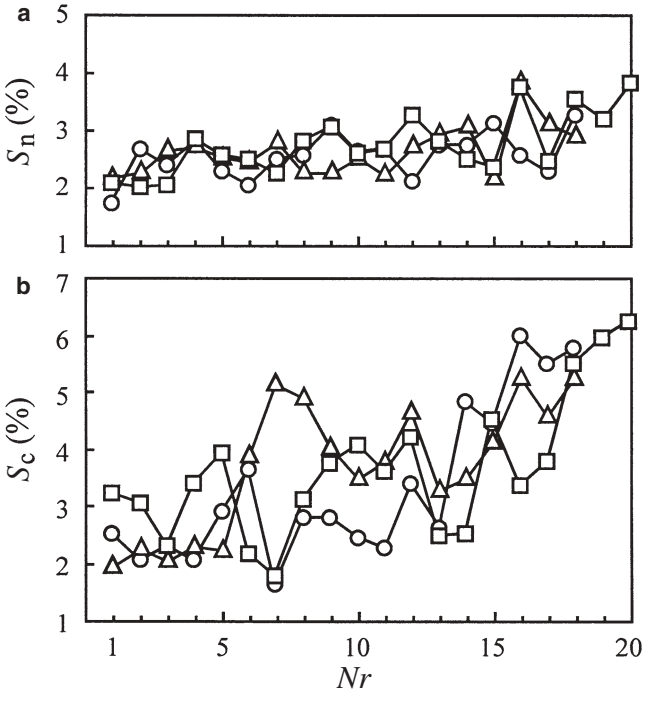

Fig. 11. **a** Normal (S_n) and **b** abnormal (S_c) shrinkage of cane due to the conventional drying method plotted against the node number (Nr)

Conclusion

The parenchyma cells showed remarkable collapse during drying. The cells recovered their initial shape after boiling, but more serious recollapse was induced in the following drying process. On the other hand, cell collapse recovered almost completely by steaming, and no recollapse was observed in the steamed cane even after severe kiln drying. The intensity of collapse was reduced by prefreezing to some extent. Despite the careful use of the conventional drying process used by reed manufacturers, shrinkage due to the cell collapse was very large, and it increased with elevating position of the internode.

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