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Characteristics of bamboo tissue in relation to cooling set

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Abstract To clarify the effects of tissue and structure of bamboo on its bending properties and set by cooling (bent at 90°C and cooled to 20°C with bending), the effects of set in bast-fiber-rich (B_{fib}) and parenchyma-cell-rich (B_{par}) specimens were investigated with regard to their dynamic viscoelastic properties, chemical composition, and recovery from deformation with time. The results are summarized as follows: (1) while no clear effect of the proportion of parenchyma cells and bast fibers on residual set immediately after cooling was found, the relative recovery from the deformation with time for B_{fib} was larger than that for B_{par}. (2) Slightly higher lignin content and α-cellulose were seen in B_{fib} than in B_{par}. (3) The peak temperature of loss modulus (E'') found for B_{par}, which was attributable to micro-Brownian motion of lignin, was obviously lower than that for B_{fib}. This was considered to be due to differences in the degree of condensation of lignin or higher-order structure. From these results, it was deduced that the bast-fiber-rich specimen, which showed a higher peak temperature regarding thermal softening of lignin allowing the induction of insufficient thermal-softening in the range of 20° to 90°C, caused a larger recovery from deformation with time.

Key words Bamboo · Plastic working · Cooling set · Thermal softening · Tissue

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Introduction

Generally, not only lowering the temperature but also decreasing the moisture content is essential for fixation of wood deformation such as drying set.[1–3] On the other hand, for practical plastic working of bamboo, there are traditional techniques used by skilled craftsman to straighten bamboo by loading with heating and cooling.[4] In these traditional methods, it is empirically recognized that the cooling process is important to fix the deformation. Although both bamboo and wood are classified as wooden resources, it is scientifically interesting to clarify why the actual working methods between wood and bamboo are so different.

In previous studies, the close relationship between cooling set and the thermal softening of lignin was observed from stress relaxation measurement and from the results of thermal recovery.[5] Thus, it can be considered that cooling set was principally caused by the freezing of micro-Brownian motion of lignin as the temperature fell below the thermal-softening temperature without unloading. However, the set ratio measured after unloading and the recovery from deformation with time were quite different between bamboo and wood.[6] Furthermore, the set ratio and recovery behavior were quite different whether the bamboo specimen was loaded on the endodermis (B_{endo}) or epidermis (B_{epi}) side.

Bamboo has a characteristic tissue; the primary tissue of bamboo culms consists of parenchyma cells with embedded vascular bundles composed of metaxylem vessels, and across the culm wall the percentage of vascular bundles, which consists mainly of bast fibers, decreases from the outside to the inside.[7–9] In addition, the two representative tissues also have different higher-order structures from each other.[10,11]

Thus, the difference in the set ratio and recovery behavior found in the previous study were considered to be related to the mechanical gradient caused by the arrangement of parenchyma cells and bast fibers. Therefore, it is important to investigate the effects of tissues (parenchyma cells and bast fibers) and their structure that cause mechani-

cal and physical gradients on the bending properties and fixation of the deformation for bamboo.

In this study, to clarify the effects of tissue and structure on the fixation of deformation, cooling set for bamboo specimens with different proportions of parenchyma cells and bast fibers was examined. The results were analyzed in detail with regard to dynamic viscoelastic properties, chemical composition, and the recovery from deformation with time.

Materials and methods

Materials

For bamboo samples, 4-year-old madake (*Phyllostachys bambusoides*) from Oita, felled in November, was used in this study. Specimens were taken at 3400–4400 mm culm height from the ground, and oily components adhering to the outer surface of the culms were removed by boiling (0.05% NaOH).[12] Wood specimens were obtained from the outer part of the heartwood of a log of hoonoki (*Magnolia obovata*) with straight grain.

The structure of bamboo is characteristic in terms that the percentage of bundle sheaths gradually decreases from the outside to the inside across the culm wall.[7–9] Thus, the proportion of parenchyma cells and bast fibers in the specimen depends on the part of the culm across the radial direction. Figure 1 shows the specimens used for residual set measurements. Five equal size specimens B_1, B_2, B_3, B_4, and B_5 were obtained from bamboo culms as shown in Fig. 1. The dimensions of each specimen were 100 mm (longitudinal, L) × 8 mm (tangential, T) × 1 mm (radial, R). Specimens B_1 and B_4 were milled to 60–80 mesh and used for the determination of chemical composition.

As shown in Fig. 2, water-saturated specimens with dimensions of 40 (L) × 0.25 (T) × 0.5 mm (R) were taken from thinly sliced specimens near the epidermis and endodermis side for dynamic viscoelastic measurement. In this measurement, parenchyma-cell-rich and bast-fiber-rich specimens need to be separated as fully as possible. Hence, after dynamic viscoelastic measurement, specimens were oven-dried, and the oven-dry density was measured. The results are shown in Fig. 3. The values were compared with the results of the variation of density across the culm wall obtained by Nakato.[13,14] Nakato estimated the mean value of the oven-dry density for parenchyma cells and bast fibers of moso bamboo at around 0.275 and 1.14 g/cm^3, respectively. On the other hand, for the specimens used in this study (madake bamboo), the lowest density was 0.26 g/cm^3 and the highest density was 1.16 g/cm^3. These values corresponded well with those of parenchyma cells and bast fibers estimated by Nakato. Considering the similarities in the tissue and structure between moso bamboo and madake bamboo,[15] the result means the specimens that showed the lowest density (specimen 2 from the endodermis side) and highest density (specimen 2 from the epidermis side) were predominantly composed of parenchyma cells and bast fibers, respectively. Thus, these specimens were named B_{par} and B_{fib}, respectively.

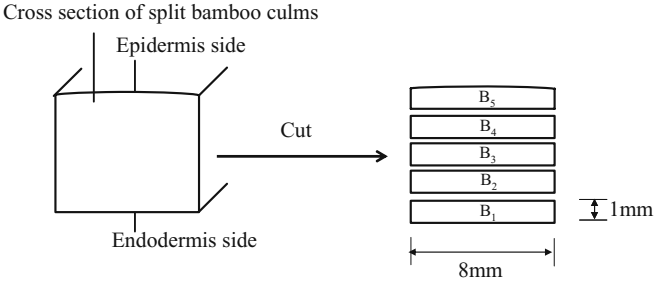

Fig. 1. Specimens used for residual set measurement. Split bamboo culms were divided into five parts of equal size (B_1–B_5) across a radial section

Measurements

Residual deflection and recovery from the deformation with time

A material testing instrument (Tensilon UTM-4L, Toyo Measuring Instruments) was employed for residual set

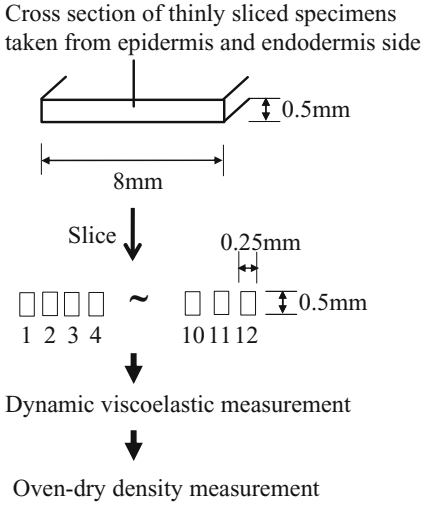

Fig. 2. Specimens used for measurements of dynamic viscoelasticity and oven-dry density

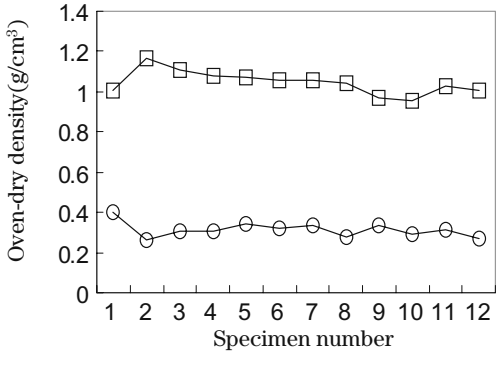

Fig. 3. Oven-dry density for specimens used for dynamic viscoelastic measurements. *Squares*, specimens sliced successively from epidermis side; *circles*, specimens sliced successively from endodermis side

measurements. The specimen was supported on a stand with a span of 80 mm, and the initial deflection was applied to the center of the span at 20°C in water. The water temperature was elevated to 90°C, followed by cooling back to 20°C. After the cooling process, the specimen was unloaded, and then the residual deflection was read from the chart. The recovery from deformation with time was followed without moving the set specimen after removal of the load. As in the preceding study,[5] the residual deflection was read from the chart at predetermined periods after the removal of the load.

Dynamic viscoelastic properties

The temperature dependencies of dynamic elastic modulus (E') and loss modulus (E'') in the longitudinal direction were measured by the tensile forced oscillation method using an automatic dynamic viscoelastometer (DMS6100, Seiko Instruments). The measurements were conducted over a temperature range of about 5°–100°C for water-saturated specimens at programmed heating rates. Frequencies for the measurement were 0.05, 0.5, 1, 5, and 10 Hz, the span was 20 mm, and the displacement amplitude was 5 μm.

Determination of chemical composition

Holocellulose, Klason lignin, α-cellulose, and the extracted contents of specimens B_1 (inner part of culm) and B_4 (outer part of culm) were measured according to standard methods for wood analysis.

Results

Effects of tissue and structure on residual set

The residual set ratios for specimens consisting of different proportions of parenchyma cells and bast fibers are shown in Table 1. Differences in specific gravity were caused by differences in the volume fraction of bast fibers and parenchyma cells. The tissue composition in a specimen depends on the portion across the radial direction, and the mechanical and physical properties change considerably according to the tissue composition. However, no clear relationship between the volume fraction of the tissues and residual set was found; the proportion of parenchyma cells and bast fibers in bamboo does not influence cooling set.

In the previous report,[5] for the specimens that were not sliced, around 75% of the set ratio was found for B_{endo} (bamboo specimens loaded on the endodermis side) whereas about 65% of the set ratio was found for B_{epi} (specimens loaded on epidermis side). On the other hand, as shown in Table 1, the set ratio was in the range of 61% to 66% for thinly sliced specimens B_1 to B_5.

For these specimens, mechanical gradients caused by the structure of bamboo are minimized and a much smaller difference in elastic modulus between loading on the epidermis side and endodermis side was found than between B_{epi} and B_{endo}. Interestingly, the set ratio obtained for thinly sliced specimens (B_1 to B_5) did not vary regardless of whether the specimen was loaded on the epidermis or endodermis side. This suggests that for the set ratio measured immediately after cooling, it is not important whether the specimen mainly consists of bast fibers or parenchyma cells but how these elements are distributed; the arrangement of these elements that causes the mechanical gradient is important.

In fact, the largest deformation occurred when a specimen with a larger mechanical gradient due to its structure was loaded on the endodermis side. However, as mentioned above, the results clarified that not only the set ratio measured immediately after cooling but also that measured a long time after the specimen was unloaded was different whether the bamboo specimen was loaded on the endodermis side or the epidermis side in the preceding study. Hence, recovery from the deformation with time should be also measured for the specimens used in this study.

Recovery from the deformation with time for B_1 and B_4 is shown in Fig. 4. Because the thickness of these specimens was quite different from B_{endo}, the effect of the difference on the recovery was canceled by controlling the ratio of the span and thickness at a constant level. As shown in Fig. 4, the amounts of recovery from deformation for thinly sliced specimens (B_1 and B_4) were considerably larger than that for B_{endo}. The specimen of B_{endo} had a clear mechanical gradient due to its structure. Hence, this result suggests that

Table 1. Residual set and oven-dry density for bamboo specimens with different proportions of bast fibers and parenchyma cells

Specimen	Oven-dry density (g/cm^3)	Set ratio (%)
B_1	0.38	63.01
B_2	0.43	65.93
B_3	0.61	62.90
B_4	0.88	61.25
B_5	0.92	62.24
B_{epi} [a]	0.71	64.17
B_{endo} [b]	0.71	73.62

[a] Specimens loaded on epidermis side
[b] Specimens loaded on endodermis side

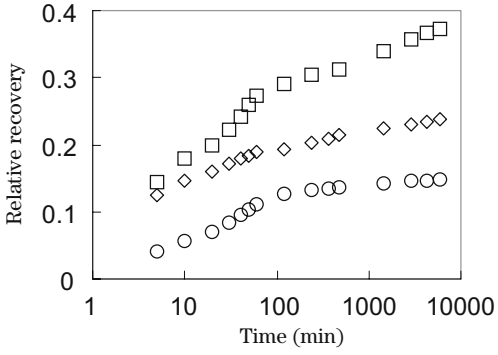

Fig. 4. Recovery from deformation with time for parenchyma-cell-rich specimen B_1 and bast-fiber-rich specimen B_4. *Diamonds*, B_1; *squares*, B_4; *circles*, B_{endo}

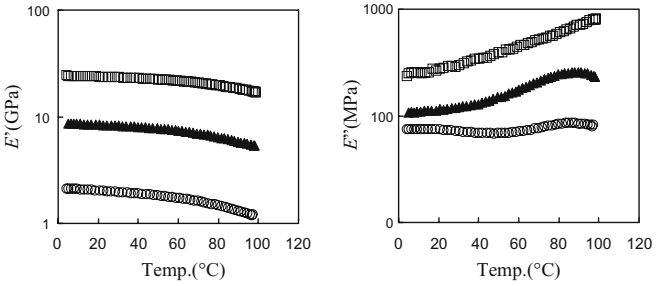

Fig. 5. Temperature dispersion of E' (*left*) and E'' (*right*) for bamboo (bast-fiber-rich specimen B_{fib} and parenchyma-cell-rich specimen B_{par}) and wood at 0.05 Hz. *Squares*, B_{fib}; *circles*, B_{par}; *triangles*, wood

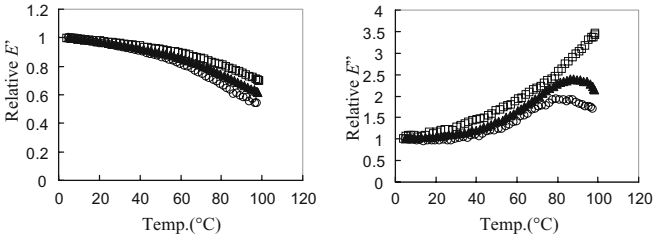

Fig. 6. Relative E' (*left*) and E'' (*right*) for bamboo (bast-fiber-rich specimen B_{fib} and parenchyma-cell-rich specimen B_{par}) and wood at 0.05 Hz. The values are relative to the value at 5°C. *Squares*, B_{fib}; *circles*, B_{par}; *triangles*, wood

the mechanical gradient induces some effects on restraining the recovery from deformation. Furthermore, a clear difference in recovery was seen between B_1 and B_4, which have substantial differences in their proportions of bast fibers and parenchyma cells. From this result, it is obvious that the proportion of bast fibers and parenchyma cells influences the recovery behavior, although no clear effect of their proportions on set measured immediately after cooling was found. As shown in previous reports, there is a close relationship between the thermal softening of lignin and cooling set. Hence, it is important to clarify the thermal-softening properties and chemical composition of bast-fiber-rich and parenchyma-cell-rich specimens.

Dynamic viscoelastic properties and chemical composition

Figure 5 shows the temperature dispersion curves of E' for B_{par}, B_{fib}, and wood. The E' for B_{par} and B_{fib} at 20°C was 2.0 and 25 GPa, respectively. With regard to Young's modulus of bast fibers and parenchyma cells in bamboo, Chuma et al.[16] showed that the mechanical properties could be evaluated by the measurement of specific gravity using the rule of the mixture existing between the volume fraction of bundle sheath and Young's modulus in air-dried conditions. They determined the Young's modulus of parenchyma and bundle sheath in moso bamboo as 0.26 and 48 GPa, respectively.[16] There are several other reports of Young's modulus for moso bamboo, and the values are quite different in each report.[17–19] In addition, the difference in Young's modulus between madake bamboo used in this study and moso bamboo should also be noted.[19] Thus, it is difficult to determine from the results of dynamic viscoelastic measurements how accurately the parenchyma cells and bast fibers are separated. However, the distinct differences in Young's modulus and oven-dry density for B_{par} and B_{fib} measured in this study suggest that B_{fib} and B_{par} were mainly composed of bast fibers and parenchyma cells, respectively, although some amount of bast fibers and parenchyma cells were included in B_{par} and $B_{fib,}$ respectively.

To compare the differences in the thermal-softening behavior more clearly, the temperature dispersion curves standardized by E' and E'' at 5°C for each specimen are shown in Fig. 6. A steep decrease in E' was shown above 60°C for all specimens. While the peak temperature of E'' for B_{par} and wood were seen around 82°C and 95°C, respectively, no clear peak was found for B_{fib} in this temperature range.

According to previous reports,[20–22] mechanical relaxation in this temperature range was considered to be caused by thermal softening due to micro-Brownian motion of lignin. Furuta et al.[23] investigated anisotropy for the thermal-softening properties of water-saturated wood, and they showed that the peak of tan δ for longitudinal specimen was not observed in the temperature range of 10° to 95°C at 0.05 Hz by a forced-vibration method. However, the peak was at about 80°C for specimens with a grain angle of 20° and more. They interpreted the difference in peak temperature of tan δ as suggesting the contribution of cell wall structure, such as the arrangement of microfibrils, to the thermal-softening properties of water-swollen wood.

According to reports by Olsson and Salmen[24] and Furuta et al.,[25] the condensation degree of lignin also influences the thermal-softening temperature. From these reports, it can be considered that differences in E'' between wood and bamboo were attributable to the degree of condensation of lignin or higher-order structure. Furthermore, it is clear that the peak temperature of E'' for bamboo changes with the proportion of parenchyma cells or bast fibers.

The difference in cell wall structure between parenchyma cells and bast fiber in bamboo was reported by Parameswaran and Liese[10] and Tono and Ono.[11] According to these reports, bast fibers have alternating lamellae, broad ones with microfibrils oriented at an angle of 2°–5° to the longitudinal axis and narrow ones with microfibrils at an angle of 85°–90°. The distribution of lignin in the cell wall was reported by Parameswaran and Liese.[10] They suggested qualitative and quantitative differences in lignin between broad lamellae and narrow lamellae from the result of ultraviolet microspectrophotometry. On the other hand, the secondary wall of parenchyma cells has a polylamellate structure consisting of up to 20 lamellae with alternating orientations. The direction of microfibrils in the broad lamellae follows a slight bow-like pattern and merges into narrow lamellae, while lignin of the cell wall layers has a distribution corresponding to the orientation of the fibril with higher lignin content in the narrower lamellae.

Thus, it can be considered that the interpretation of the differences between wood and bamboo mentioned above is also applicable to the difference in thermal-softening prop-

Table 2. Chemical composition of the parenchyma-cell-rich specimen B_1 and the bast-fiber-rich specimen B_4

Sample	Extracts (%)[a]		Main constituents (%)[b]		
	Hot water	Ethanol–benzene	Holocellulose	α-Cellulose	Lignin
B_1	9.2	3.6	81.1	45.7	24.6
B_4	6.0	2.3	79.5	51.1	27.3

[a] Based on oven-dry weight
[b] Based on oven-dry weight after extraction

erties between parenchyma cells and bast fibers. It is obvious that parenchyma cells and bast fiber have different thermal-softening properties in this temperature range.

The chemical compositions in parenchyma-cell-rich specimen B_1 and bast-fiber-rich specimen B_4 are shown in Table 2. It should be noted that the samples used for this analysis were not absolutely separated into parenchyma cells and bundle sheaths. Comparing B_1 with B_4, α-cellulose was slightly more abundant in B_4, and a small difference in lignin content was detected. Hemicellulose (alkali soluble) in B_1 was slightly more abundant than in B_4. More details about these results are discussed in the following section in relation to the results of residual set, recovery with time, and dynamic viscoelastic measurements.

Discussion

As seen in the residual set measurement, no clear difference in set ratio between parenchyma-cell-rich specimen B_1 and bast-fiber-rich specimen B_4 was found. This result suggests that set measured immediately after cooling is not affected by the difference in the proportion of parenchyma cells and bast fibers. In the previous report,[5] a close relationship between cooling set and thermal softening of lignin was found by investigations on the temperature dependence in thermal recovery of cooling set. In addition, as shown in the determination of the chemical composition of B_1 and B_4, there was no remarkable difference in lignin content between them, and interestingly the largest set ratio was found for B_{endo}. This may be attributable to the relatively larger mechanical gradients caused by the structure of bamboo in B_{endo} than the thinly sliced specimens B_1–B_5.

The difference in hemicellulose content should be noted. It is known that hemicellulose is in a rubbery state at room temperature because it shows mechanical relaxation around –40°C for water-swollen wood.[26] Hence, it is possible to deduce that the dynamic viscoelastic properties around room temperature are influenced by hemicellulose content. Because the recovery from deformation with time was measured at 20°C, the differences in hemicellulose content should also influence the recovery behavior of the samples. However, recovery from the deformation for B_{fib} was larger than that of B_{par} despite the lower hemicellulose content in B_4.

Differences in the quality of the lignin, such as the degree of condensation, were also presumed between parenchyma cells and bast fibers from the dynamic viscoelastic measurements. These suggest that the degree of thermal softening, such as the state of molecular motion at maximum temperature before cooling, is different between parenchyma cells and bast fibers although they were heated and cooled in the same temperature range. Thus, it can be deduced that specimen B_4 was cooled without fully surpassing the thermal-softening temperature in the heating process when compared with B_1. Furthermore, as described above, the differences in higher-order structure and α-cellulose contents between parenchyma cells and bast fibers could also be related to the current results. Hence, although the results of cooling set immediately after cooling are almost the same for all of the specimens at first glance, recovery from the deformation with time varied with the proportion of parenchyma cells and bast fibers in the specimen.

Conclusions

To clarify the effects of tissue and structure on cooling set, bamboo specimens with different proportions of parenchyma cells and bast fibers were investigated with regard to characteristics such as dynamic viscoelastic properties, chemical composition, and recovery from the deformation with time. While no clear effect of the proportion of parenchyma cells and bast fibers on residual set was found, the relative recovery from deformation with time for bast-fiber-rich specimen was larger than that of parenchyma-cell-rich specimen. Only a small difference in lignin content was seen between them. However, the peak temperature of E'' found for B_{par}, which was attributable to micro-Brownian motion of lignin, was obviously lower than that for B_{fib}. This was considered to be due to differences in the degree of condensation of lignin and/or higher-order structure.

From these results, it was deduced that bast-fiber-rich specimen being cellulose rich and having a higher peak temperature for the thermal-softening of lignin, which induce insufficient thermal-softening in the range of 20° to 90°C, caused a larger recovery from the deformation with time.

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