Water adsorption properties of bamboo in the longitudinal direction

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Summary

Differences in the water adsorption properties of moso bamboo (*Phyllostachys pubescens*) were examined by analyzing isotherms. Hygroscopicity decreased from the bottom to the top of the culm, and this tendency was marked above about 80 % relative humidity. Results of alkali extraction and the analysis of bundle sheath distribution revealed that the distribution of hygroscopic saccharides, for example, hemicellulose and less-hygroscopic vascular bundles affects hygroscopicity, which varies depending on the position of the internode.

Introduction

Bamboo is a resource with an abundant growth increment that allows it to expand its territory very rapidly, which is often undesirable from a social standpoint. Bamboo can be harvested in 5 or 6 years, whereas other timber resources take decades to complete a planting-growing-harvesting cycle. Considering its rapid growth, bamboo has great potential as a bioresource in the middle-mountainous region.

We sought to describe the water adsorption properties with regard to the use of bamboo as a resource (Yamamoto et al. 2005) and found that bamboo has some interesting hygroscopic properties closely related to its higher-order structure. In addition, certain mechanical properties, which change depending on the position of the culm, were revealed. Those properties depended on the ingenious distribution of the vascular bundles, which keeps the bamboo culm standing. Detailed findings will be reported in our next paper.

Studies of reports of water influence on bamboo characteristics have been reported by Suzuki (1953) and Ota (1955) but relatively little is known about the water adsorption properties of bamboo . In this report, we focus on the differences in hygroscopisity in the logitudinal direction.

Experiments

Material and adsorption experiment

Bamboo samples were prepared from a six-year-old moso bamboo (*Phyllostachys pubescens*) culm harvested on October 2004, in Shimane Prefecture. Each internode of the bamboo culm was cut into 27 portions, and then the portions were designated as No. 1 to No. 27, starting from the bottom to the top of the culm. Among the 27 portions, 18 and 13 samples were selected randomly for the adsorption experiment and the NaOH-extraction experiment, respectively. Among them, there were 12 common samples, that were used for the analysis of the dependence of moisture content on weight loss with a 1 % NaOH aqueous solution. Block samples taken from the center of each internode had rectangular dimensions of 20 (L) × 5 (R) × 1 (T) (mm). Their waxy epidermides were removed after collection.

An adsorption experiment was conducted as follows. The block samples placed in weighing bottles were oven-dried at 105 ℃ for 24 h. Then the samples were conditioned to equilibrium moisture content in a closed container at 20 ℃ for over 3 weeks, in which the prescribed saturated solutions were placed. The ten kinds of solution used consisted of LiCl (11% RH), CH_3COOK (22% RH), $MgCl_2$ (33% RH), K_2CO_3 (43% RH), $Mg(NO_3)_2$ (53% RH), NH_4NO_3 (62% RH), NaCl (75% RH), $(NH_4)_2SO_4$ (80% RH), KNO_3 (92% RH), and K_2SO_4 (97% RH).

Alkali extraction treatment

To investigate the influence of extracts on hygroscopisity, each powder sample was subjected to an alkali extraction treatment. Powder samples were prepared from 13 different internodes to pass through a 60-mesh screen. About 1.7 g of absolute-dried samples was immersed in 100 ml of aqueous solution of 1 % NaOH for a total of 48 h. After extraction, samples were immersed in 150 ml of distilled water to remove alkali remaining in the bamboo substances. This procedure was performed twice a day for a total of 14 times. The samples were oven-dried at 105 ℃ for 24 h and we then calculated the weight loss due to extraction.

Image analysis of culm cross sections

A photograph of a cross section of each internode was taken with a CCD camera at a given magnification ratio, and the visual data were segmented. The digital data were processed with commercial analysis software （Quick Grain Standard: inotech Co. Ltd., Hiroshima, Japan）. We estimated the distribution of vascular bundles and calculated the number of vascular bundles per unit area for the block samples, which were divided into two parts in the radial direction (inner part and outer part). We further analyzed the dependence of the distribution of vascular bundles in both parts on the internode number.

Results and Discussion

Isotherms for three different internodes shown in Figure 1 are typical for bamboo, which exhibited a sigmoid formation as reported previously. Figure 1 suggests that differences in adsoprtion properties exist among internodes and that hygroscopisity increases from the top to the bottom of the culm.

Figure 2 shows moisture content plotted against the internode number under various relative humidity (RH) conditions. Figure 2 indicates that the dependence of moisture content on internode number is minimal at lower RH; however, curves for the lower internodes (near the bottom of the culm) shows a higher moisture content above about 80 % RH, especially at 97 % RH. This implies that differences in hygroscopisity in length are more remarkable at higher RH.

Powder samples were subsequently extracted with a 1 % NaOH aqueous solution to investigate the chemical composition of each internode. Figure 3 indicates that the NaOH solution extract decreases with increasing internode number. Noncrystalline regions of cellulose and a variable hemicellulose tissue in bamboo have higher hygroscopisity. Figures 2 and 3 show that the water adsorption properties in the longitudinal direction differ primarily by the chemical composition. Relationships between the extract and moisture content at 75 % and 97 % RH are shown in Figure 4. It is obvious from Figure 4 that the moisture content increases in proportion to the amount of extract and that the tendency is noticeable at higher RH.

Nakano (2003) and Nakano *et al.* (2006) noted that the fine structure of cell walls influences the hygroscopicity of wood and bamboo. The wood cell wall consists mainly of three layers, S1, S2, and S3, in which helically wound microfibrils are embedded at different angles in an amorphous region consisting of lignin and hemicellulose. In the S1 and S3 layers, microfibrils in wall lamellae oriented transversely and microfibrils in the S2 layer are oriented longitudinally. Using the thermodynamic analysis, Nakano (2003) found that the S1 and S3 layers resist swelling at lower hygroscopicity. Similar results were obtained for bamboo. The bamboo substance consists of vascular bundles and parenchyma, and each vascular bundle consists of a bundle sheath, vessel, and phloem. The bundle sheath consists of sclerenchyma cells, which have a structural role. Sclerenchyma cells exhibit a multilayer structure with alternating layers of even-numbered layers, in which microfibrils are oriented transversely, and odd-numbered layers, in which microfibrils are oriented longitudinally (Parameswaran and Liese 1976, Liese 1987). This multilayer structure inhibits swelling. In contrast, parenchyma cells are flexible and swelling can occur.

Considering the effect of the ultrastructure on hygroscopic properties, we postylated that the hygroscopicity of each internode could be evaluated based on the distribution of vascular bundles. As noted above, the amount of water adsorbed is expected to decrease when the number of vascular bundles per unit area increases. The fact that the moisture content of the outer parts with a higher vascular bundle density is lower than that of the inner parts supports this evaluation (Nakano et al. 2006). Figure 5 shows the relationship between the number of vascular bundles per unit area and the internode number. The vascular bundle density of both the inner and outer parts increases with increasing internode number. The relationship between the amount of extract and vascular bundle density is shown in Figure 6. The amount of alkaline extract decreases proportionally with increasing vascular bundle density.

From these results, we confirmed that differences in the longitudinal direction shown in Figures 1 and 2 are attributable to differences in chemical composition and ultrastructure of each internode. Thus, hygroscopic substances such as hemicellulose and the rate of parenchyma cells, which contain a great deal of hygroscopic substances, both decrease with increasing internode number. Hygroscopicity is further influenced by sclerenchyma cells consisting of bundle sheaths that restrain swelling because of their multilayered structure. How much the two factors influence the hygroscopicity of the internode was not determined conclusively by the present study.

To investigate the hygroscopic properties of each internode in detail, isotherms were analyzed based on the Hailwood and Horrobin theory with three constants. In this theory, K_1 and K_2 are equilibrium constants in the reaction of dissolved water and anhydrous polymer to form hydrous polymer, and in denoteing dissolved water as being the external water vapor, respectively. W is defined as the molecular weight of the polymer substance per sorption site. Then K_1K_2 and 1/W can be expressed as equilibrium constants in a reaction of the external water vapor and anhydrous polymer to form a hydrous polymer, and the number of sorption sites per gram of bamboo substance, respectively. Figure 7 shows the dependence of K_1K_2 and 1/W on the position of the culm. Figure 7 indicates that 1/W has little dependence on the internode number, while K_1K_2 increases from the top to the bottom of the culm. This result also implies that hygroscopicity of the culm increases with increasing in internode number, corroborating the results discussed above.

Conclusions

We investigated the difference in water adsorption properties in the longitudinal direction of moso bamboo (*Phyllostachys pubescens*). We cut each internode of a bamboo culm into 27 portions and examined the adsorption properties. We found that hygroscopicity increased with increasing internode number. Moreover, this tendency was strong above 80 % RH, but not at lower RH. Results of alkali extraction and analysis of vascular bundle distributions revealed that the distribution of hygroscopic saccharides like hemicellulose and less-hygroscopic bundle sheaths, affected hygroscopicity, which varied depending on the level of the internode.

Because bamboo grows rapidly, the chemical composition and ultrastructure of the cell wall varies by age. These experiments were applied to bamboos at the age of six years. Further studies on the difference among ages are expected.

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Captions

Fig. 1. Typical isotherm curves of various internode samples in the longitudinal direction.

Fig. 2. Relationship between moisture content and internode number by relative humidity.

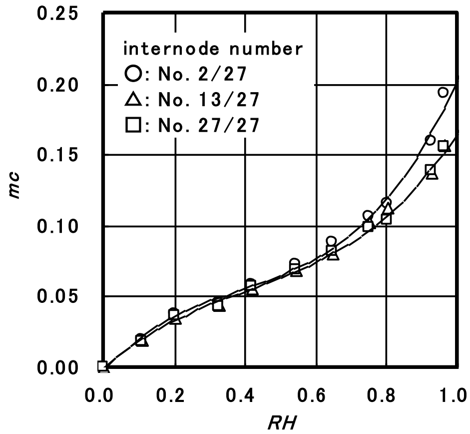
Fig. 3. Relationship between internode number and weight loss by extraction with a 1 % NaOH aqueous solution.

Fig. 4. Dependence of moisture content on weight loss with a 1 % NaOH aqueous solution.

Fig. 5. Relationship between the internode number ordered from the root of the bamboo and the number of vascular bundles per mm^2.

Fig. 6. Relationship between weight loss by extraction and the number of vascular bundles per mm^2.

Fig. 7. Relationship between internode number and K_1K_2 and 1/W. Note: K_1K_2 and 1/W are parameters of the Hailwood and Horrobin theory.



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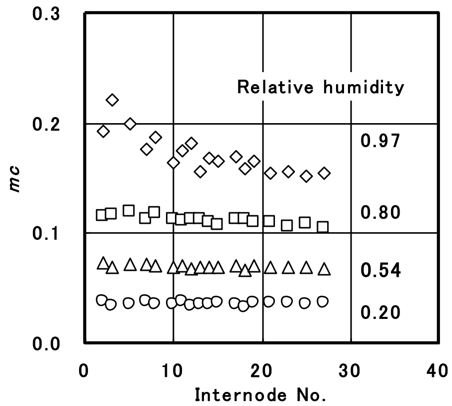

Fig. 2. Relationship between moisture content and internode number by relative humidity.

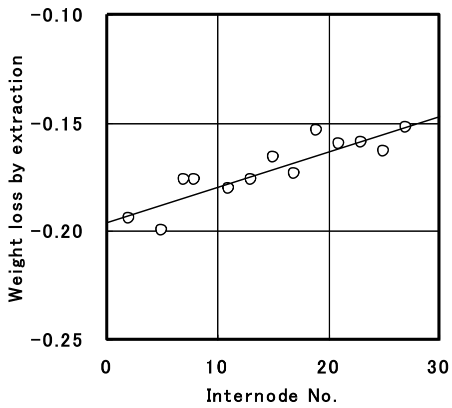

Fig. 3. Relationship between internode number and weight loss by extraction with a 1 % NaOH aqueous solution.

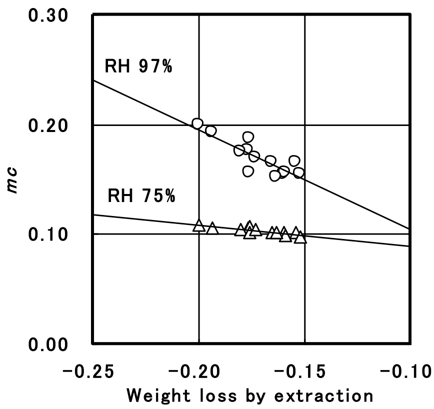

Fig. 4. Dependence of moisture content on weight loss with a 1 % NaOH aqueous solution.

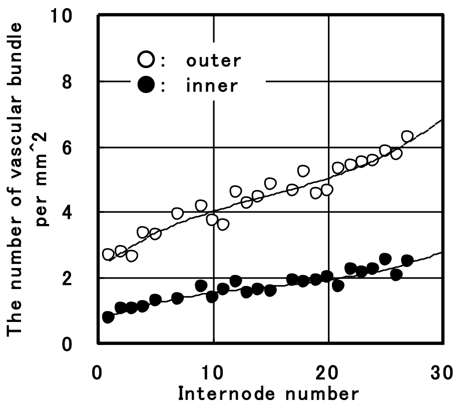

Fig. 5. Relationship between the internode number ordered from the root of the bamboo and the number of vascular bundles per mm^2.

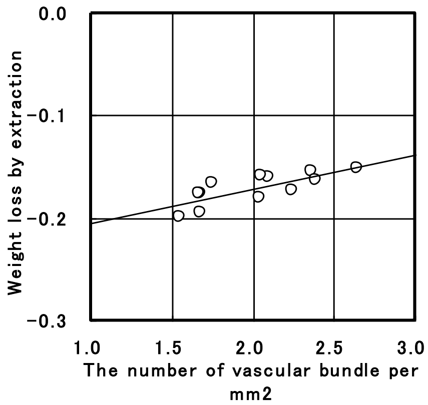

Fig. 6. Relationship between weight loss by extraction and the number of vascular bundles per mm^2.

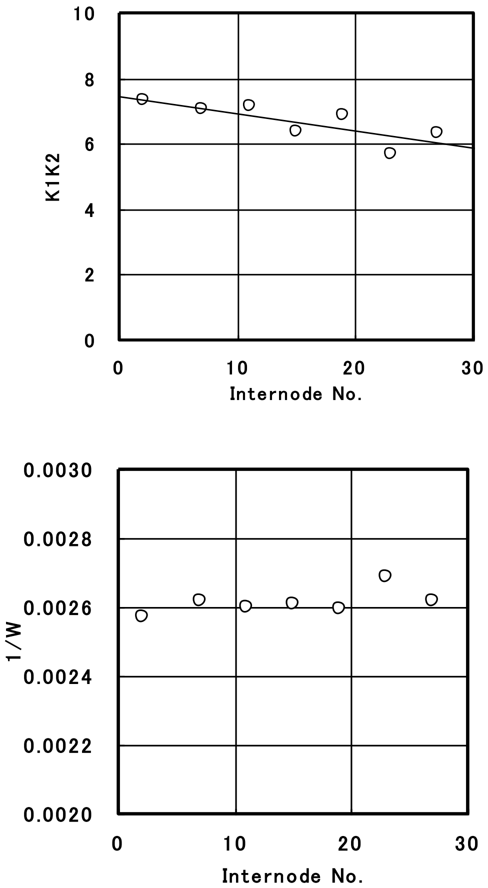

Fig. 7. Relationship between internode number and K_1K_2 and 1/W. Note: K_1K_2 and 1/W are parameters of the Hailwood and Horrobin theory.