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Swelling Behaviour of Bamboo (*Phyllostachys pubescens*)

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Abstract: Bamboo is a plant with various applications. As a natural, renewable material that exhibits good mechanical performance, it seems to be an interesting alternative to wood, which has become a scarce and expensive commodity. However, comprehensive knowledge of its properties is necessary to maximise its potential for various industrial purposes. The swelling behaviour of bamboo is one of the features that has not yet been sufficiently investigated. Therefore, in this research, we aimed to measure and analyse the swelling pressure and kinetics of bamboo blocks. The results show that similar to wood, the swelling kinetics of bamboo depend on its density: the denser the tissue, the higher the maximum swelling value recorded. The maximum tangential swelling measured was about 5%–6%, which is lower than the value for the most commonly used wood species. Swelling pressure ranged from 1.16 MPa to 1.39 MPa, depending on the bamboo density: the denser the sample, the shorter the time required to reach maximum swelling pressure. Like in wood, the smallest linear increase in size due to swelling was observed in the longitudinal direction (0.71%). However, opposite to wood, more pronounced swelling was recorded in the radial direction (over 7%) than in the tangential direction (nearly 6%). The results show that bamboo's swelling behaviour makes it a good material for use in variable humidity conditions, being more favourable than the unmodified wood of many species.

Keywords: bamboo; swelling; swelling pressure; moisture properties

Citation: Roszyk, E.; Kropaczewski, R.; Mania, P.; Broda, M. Swelling Behaviour of Bamboo (*Phyllostachys pubescens*). *Forests* **2024**, *15*, 118. https://doi.org/10.3390/f15010118

Academic Editor: Luis García Esteban

Received: 8 December 2023
Revised: 27 December 2023
Accepted: 5 January 2024
Published: 7 January 2024

1. Introduction

The current difficult wood market situation, resulting from various factors, including increasing demand, low supply, high prices, uncontrolled deforestation, and protests against industrial forest logging by pseudo-environmentalists, has created a need to search for alternative solutions—using different natural renewable materials—that will fit in with the trends of a sustainable economy and could at least partially replace wood and solve the problem of its deficit.

One such alternative is bamboo. Multiple bamboo genera and their corresponding species are typically evergreen perennial plants belonging to the subfamily Bambusoideae of the Poaceae grass family. They are widely distributed throughout tropical, subtropical, and mild-temperate regions, particularly in East and Southeast Asia [1,2]. Due to its high tolerance to lower temperatures, bamboo can also be successfully grown in different regions, including in Europe [3,4].

Bamboo is a plant with multiple applications, especially in the regions where they most commonly occur. The seeds and young shoots of some species serve as food; fresh leaves provide feed for livestock, while culms are used for manufacturing paper and everyday items such as shoes, baskets, pens, arrowheads, walking sticks, fishing poles, writing scrolls, furniture, and ornamental elements in gardens and serve as construction materials for building rafts, boats, pipes, bridges, scaffoldings, houses, rooves, and flooring [5–7].

The main advantages of bamboo that make it a potentially viable timber supplement for many industries are its fast growth (up to 30 cm per day for some species) and hard, strong, and flexible woody stems called culms. Culms are ringed and hollow between the nodes, ranging from 10 cm to over 40 m, depending on the species, and they have relatively high density and good mechanical performance [8,9]. However, their round and hollow geometry and structural inhomogeneity pose various manufacturing challenges that limit bamboo applications. To overcome these problems, bamboo is often processed to produce different composite materials with unified and improved durability and performance, including ply bamboo, laminated bamboo, bamboo scrimber, and bamboo-strand-based composites [10–13]. However, the high variability in density, permeability, chemical composition, and the resulting properties between different bamboo species restricts these composites from meeting the required quality and performance criteria for construction materials, thus limiting their applications. Therefore, more detailed knowledge of the properties of individual bamboo species and advanced industry practices are needed to allow this raw material to be more widely used for industrial purposes [9,12].

Although several studies on bamboo structure, characteristics, performance, and processing methods have been conducted in the past two decades [14–19], not all of bamboo's properties have been well recognised. One of these properties is their moisture behaviour. Like other lignocellulosic materials, bamboo is hygroscopic, making it vulnerable to dimensional and mechanical changes under variable humidity conditions. It is already known that moisture absorption and desorption lead to the anisotropic swelling of bamboo, with greater deformations observed in the transverse direction than in the longitudinal direction [20,21]. Swelling and shrinkage in the radial direction differ between the external, middle, and internal bamboo layers, and dimensional changes in the radial and tangential directions differ between the nodes and internodes. It has also been recognised that oven-dried bamboo has a much lower moisture absorption capacity than the green form [21]. The absolute swelling of bamboo cell walls depends on the cell type, where the cell walls of fibre cells swell the most due to their maximal thickness. However, their relative swelling is the lowest because of the constraining of adjacent fibre cells [22]. Research on the swelling of bamboo blocks and separated fibres has also been conducted, broadening knowledge about bamboo's swelling mechanism [20,23]. Except for research on pure bamboo, extensive studies on the moisture behaviour of bamboo-based composites have been performed, enabling the determination of their properties under changeable moisture conditions, which is necessary before applying them as construction materials [24–29].

The swelling of lignocellulosic materials (including wood and bamboo) is an increase in their dimensions caused by increased bound water content [30]. Swelling pressure represents the stress required to completely prevent a material from swelling during its wetting; to put it differently, it is the maximum stress generated in a material during restrained swelling [31]. The swelling pressure generated in a material moistened from a completely dry state to the fibre saturation point is called "total swelling pressure" [32]. Swelling pressure is particularly great in wood when it is dry and entirely restrained before wetting [33]. It is believed that this phenomenon was employed by ancient Egyptians in quarrying. They would put dry wooden pegs in holes drilled in rock and then add water. The swelling pressure of wood helped split the block from a rock wall [34]. It is also used in joineries when the wooden parts are oven-dried before assembling, which makes the joint tighter and thus stronger as the wood swells, absorbing moisture from the air [35]. In general, however, swelling and swelling pressure have been recognised as a big concern from the perspective of the industrial use of lignocellulosic materials since they make the products dimensionally unstable under changeable moisture conditions and may cause damage to the surrounding constructions. A better understanding of the swelling behaviour and accompanying stresses and relaxations generated in a material is important from the practical perspective since they will help deter deformations and cracks, thus prolonging the service life of lignocellulosic materials and the products made from them. Swelling pressure is the experimentally determined index that describes the stress in wood caused by its moistening [36].

To the author's best knowledge, however, the swelling pressure of bamboo has not yet been sufficiently investigated. This parameter is significant for the safe use of bamboo as flooring and other construction materials and, in fact, in all cases where this material is exposed to variable moisture conditions. Therefore, to fill in the gap in our knowledge of bamboo properties, we aimed to analyse the swelling pressure of bamboo blocks and, more specifically, measure the stress that must be induced to inhibit the swelling of bamboo blocks. Additionally, swelling kinetics and total swelling rate were determined with regard to bamboo density. The results will aid in the comprehension of the swelling behaviour of bamboo and the development of safe techniques for drying and engineering this material for its sensible use in industrial practice as a sustainable alternative to wood.

2. Materials and Methods

2.1. Materials

The research material was Moso bamboo (*Phyllostachys pubescens*), a species commonly used for decking, flooring, wall covering, boards, beams, and worktops. It was bought from the Nomix Nong Minh Thai company in Ostrow Wielkopolski, Poland, and originated from Vietnam. Free of epidermis, samples for measurements were sourced from three different internodes (Figure 1). Their final dimensions were 8 × 22 × 30 mm in the radial (R), tangential (T), and longitudinal (L) anatomical directions, respectively.

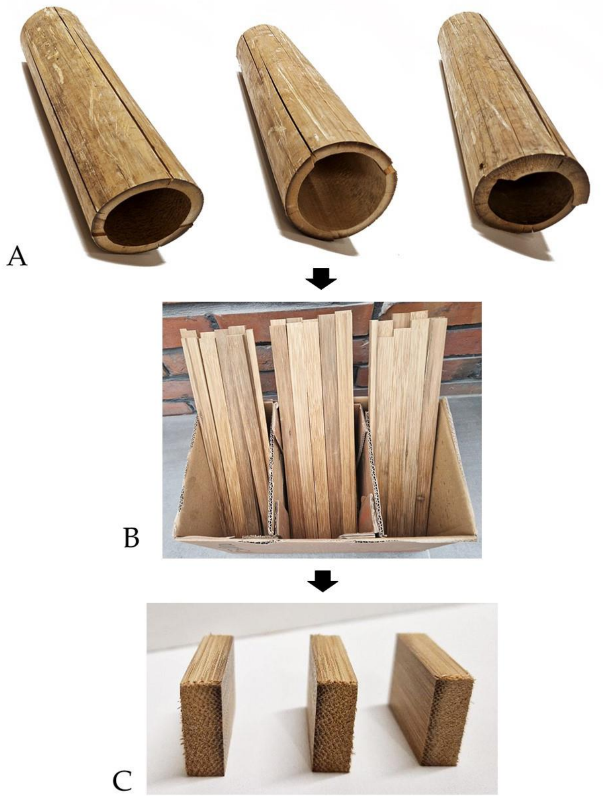

Figure 1. A scheme showing research material: (**A**) three bamboo internodes, (**B**) slats cut from bamboo internodes, and (**C**) final samples used in the research.

2.2. Methods

2.2.1. Density and Moisture Content Measurements

The density of bamboo samples was determined using a stereometric method following ISO 13061-2 [37]. Bamboo blocks were conditioned for two weeks at a temperature of 23 ± 2 °C and air relative humidity of 35 ± 3%. Then, their dimensions were measured with a digital calliper (±0.01 mm), and their mass was determined using an analytical balance (Sartorius GmbH, Göttingen, Germany) with an accuracy of 0.001 g. Density was calculated as the ratio of bamboo sample mass to its volume.

The moisture content of conditioned bamboo blocks was determined using a standard oven-drying method. Bamboo blocks were oven-dried at a temperature of 103 ± 2 °C, and their mass was measured as described above. Moisture content was calculated as the ratio of the mass of water (the difference between the mass of a sample after conditioning and in a completely dry state) to the mass of a dry sample.

All bamboo samples for swelling measurements were oven-dried at 103 ± 2 °C until attaining a constant weight, and their mass, dimensions, and density were determined.

2.2.2. Swelling Kinetics

Bamboo swelling was measured in the tangential direction using oven-dried blocks. Their dimensions were reduced compared to normative samples due to the hollow, tubular structure of bamboo culms. Measurements in the radial direction were no longer conducted due to the fact that the length of the block in this direction (8 mm) was too small to measure with sufficient accuracy. Swelling in the longitudinal direction was not measured since moisture-induced deformations in this direction for wood and other lignocellulosic materials are negligibly low.

Three sets of samples differing in density were prepared (about 380 kg m^{-3}, 450 kg m^{-3}, and 540 kg m^{-3}, respectively). Each bamboo block was placed in a support stand equipped with a flatbed micrometre such that measurements could be conducted in the tangential direction (Figure 2). Each stand with a sample was placed in water, and at this moment, the measurement started. The indications of micrometres were recorded at specified intervals. The degree of bamboo swelling for each interval was calculated according to Equation (1):

$$\alpha = \frac{\Delta l}{l_0} \times 100, \quad (1)$$

where α is the degree of swelling, Δl is the increase in sample dimensions in the measured direction, and l_0 denotes the initial dimensions of a completely dry sample in the direction of measured swelling.

Figure 2. A picture of equipment used for the measurement of swelling kinetics.

The swelling process was recorded until the increase in sample dimensions in the tangential direction had stabilised. Ten samples from each density group were measured.

2.2.3. Swelling Pressure

Bamboo total swelling pressure was measured on oven-dried blocks in the tangential direction (with the same sample dimensions as in the experiment described above) using a prototype device designed for this purpose (Figure 3) [38]. The stand (1 in Figure 3) of the device consists of two frames (2 and 3 in Figure 3) that were slidable in relation to each other, where shifting of the lower frame (3 in Figure 3) is controlled by an adjusting screw (5 in Figure 3). The upper frame (2 in Figure 3) is coupled with a bow dynamometer (4 in Figure 3) used for the measurement of swelling force and connected to a crossbar with a dial micrometre fixed to it (6 in Figure 3). A container (7 in Figure 3) with a sample (8 in Figure 3) is located on the bottom shelf of the upper frame (2 in Figure 3). The weight of the upper frame was counterbalanced by weights (9 in Figure 3) to avoid tensile forces in an unloaded dynamometer. The device enabled the measurement of the total force needed to counteract the linear swelling of the analysed material during its wetting. Before the experiment started, each sample was preloaded to eliminate contact deformations. The measurement began when the sample in the container was flooded with water. At this moment, the sample started to swell, and the piston resting on the sample was pushed upwards so that it protruded from the vessel. As a result, the top frame was lowered by a distance equivalent to the swelling indicated by the dial micrometre. After initial swelling of about 0.002 mm had occurred, the bottom frame was lowered using the adjusting screw. In this way, the swelling was compensated by compression, and the indicating needle of the dial micrometre returned to its initial position. The bow dynamometer indicated the force required to compensate for swelling at a given moment. The procedure was repeated until maximum swelling pressure was obtained, i.e., until the recorded value stabilised or decreased.

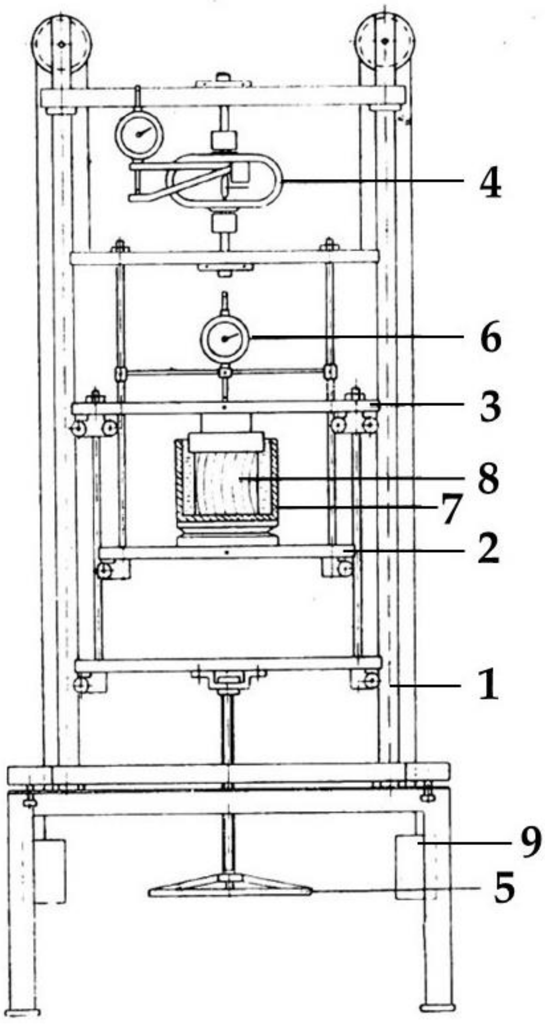

Figure 3. A scheme depicting the equipment used for the measurement of swelling pressure; 1—a stand, 2 and 3—slidable frames, 4—dynamometer, 5—adjusting screw, 6—dial micrometre, 7—container filled with water, 8—sample, and 9—weights.

Swelling pressure was calculated based on Equation (2):

$$\sigma cp = \frac{P}{A'}, \quad (2)$$

where σcp is the total swelling pressure (MPa), P is the value of swelling force measured (N), and A' is the cross-sectional area of the sample in a completely dry state before measurement. Ten samples from each density group were measured.

2.2.4. Total Swelling Rate

The total swelling rate was calculated as a percentage increase in sample dimensions in a given direction from an oven-dried state to a completely wet state. Bamboo samples similar to those used in the previous experiments were oven-dried at a temperature of 103 ± 2 °C, and their masses and linear dimensions were measured as described above. They were placed in a beaker filled with distilled water at room temperature and secured to prevent them from coming up to the surface. The samples were soaked for a time previously determined during the measurement of linear swelling kinetics. The linear dimensions of completely swollen samples were measured in the same places where they were measured in an oven-dried state, and their masses in a wet state were recorded. Fifty samples were used in this experiment.

2.2.5. Statistics

STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA) was used to statistically analyse the obtained experimental data. An analysis of variance (one-way ANOVA), followed by the post hoc Tukey's honest significance test, was applied to find means that were significantly different from each other.

3. Results and Discussion

3.1. Bamboo Density and Moisture Content

The densities of the bamboo samples used in this study were diverse (Table 1). The lowest value recorded for the oven-dried samples was 385 kg m^{-3}, and the highest was 545 kg m^{-3}, while for air-dried specimens with a moisture content of about 8%, the lowest value was 403 kg m^{-3}, and the highest was 568 kg m^{-3}.

Table 1. The mean values of bamboo density (ρ) in an oven- and air-dried state for three different internodes.

Bamboo	Oven-Dried			Air-Dried		
	Min	Mean	Max	Min	Mean	Max
	(kg × m^{-3})					
Internode 1	385	437 ^{a}	472	403	457 ^{a}	493
Internode 2	429	471 ^{b}	545	444	494 ^{b}	568
Internode 3	412	472 ^{b}	535	433	492 ^{b}	561

^{a,b} different superscripts denote a statistically significant ($p < 0.05$) difference between mean values ($n = 10$ for each set of samples) according to Tukey's honest significant difference test.

Although the measured variability in bamboo density may seem surprising, this feature is characteristic of bamboo and results from its anatomical structure. Bamboo tissue mainly consists of vascular bundles composed of hollow vessels enclosed by fibrous sclerenchyma cells and surrounded by parenchyma cells. The volume fraction of vascular bundles increases radially towards the outer part of the culm and, more gradually, along the height of the culm from bottom to top. This is accompanied by an increased solid fraction in the bundles due to reduced vessel diameter. All these phenomena lead to a pronounced density gradient in both the radial and longitudinal directions in the bamboo culm, with lower density in the internal parts than in the external layers [39–41]. The density spread of bamboo internodes in the longitudinal direction reported by Huang et al. [41] ranged from 323 kg m^{-3} to 1334 kg m^{-3}.

Due to the density variability of the research material, the planned experiments in this study were performed on three groups of bamboo samples, namely, those with low, medium, and high density (average density values for each sample group were statistically different; they are given in Table 2).

Table 2. The mean values of bamboo density (ρ) in an oven- and air-dried state for three different groups of densities: low, medium, and high; *SD*—standard deviation; *CV*—variation coefficient.

Bamboo	Oven-Dried			Air-Dried		
	ρ (kg × m^{-3})	*SD*	*CV* (%)	ρ (kg × m^{-3})	*SD*	*CV* (%)
Low-density	385 ^{a}	25.4	6.6	399 ^{a}	25.2	6.3
Medium-density	455 ^{b}	28.3	6.2	471 ^{b}	34.0	7.2
High-density	540 ^{c}	37.1	6.9	564 ^{c}	38.3	6.8

^{a,b,c} different superscripts denote a statistically significant ($p < 0.05$) difference between mean values ($n = 10$ for each set of samples) according to Tukey's honest significant difference test.

3.2. Linear Swelling Kinetics of Bamboo

The kinetics of bamboo linear swelling in the tangential direction are presented in Figure 2. In the initial phase, the bamboo samples swelled fast, and after about 16 h, the swelling rate significantly decreased. The time of bamboo swelling until reaching relatively constant dimensions was 73.5 h. In wood, swelling kinetics are not only affected by anatomical direction but also strongly depend on wood density [42]. A similar correlation can be observed for bamboo samples, where the highest swelling values were recorded for the densest samples and lower values were observed for medium- and low-density blocks (Figure 4).

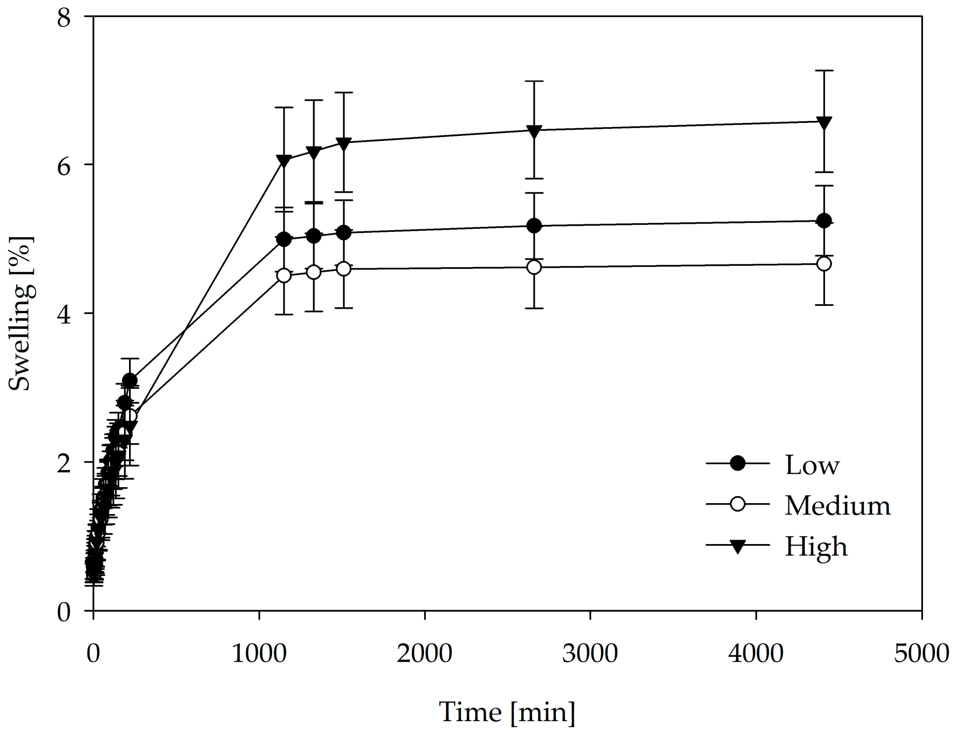

Figure 4. Kinetics of linear swelling in the tangential direction measured for three different density groups of bamboo blocks: low, medium, and high; error bars represent the standard deviation.

Generally, the measured values of maximum tangential swelling of bamboo tissue were relatively low, around 5%–6% (Figure 4). For comparison, the maximum tangential swelling of the untreated oven-dried wood samples with a density similar to medium-density bamboo was 8.8% for Sitka spruce (*Picea sitchensis* (Bong.), with an oven-dried density of 400 kg m^{-3});

9% for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco, with an oven-dried density of 480 kg m^{-3}); and 8.9% for quaking aspen (*Populus tremuloides*, with an oven-dried density of 480 kg m^{-3}) after 100 days [43] versus nearly 5% for bamboo. For denser wood, it was 10.9% for Norway spruce (*Picea abies* L. Karst., with an oven-dried density of 520 kg m^{-3}), 8.7% for Scots pine (*Pinus sylvestris* L., with an oven-dried density of 570 kg m^{-3}), 13.1% for European beech (*Fagus sylvatica* L., with an oven-dried density of 690 kg m^{-3} and an average density of 680 kg m^{-3}), and 9.6% for English oak (*Quercus robur* L., with an oven-dried density of 670 kg m^{-3} and an average density 690 kg m^{-3}) after 24 h [42] and 10% for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco, with an oven-dried density of 580 kg m^{-3}), 10.6% for sugar maple (*Acer saccharum* Marsh., with an oven-dried density of 680 kg m^{-3}) after 100 days [43] versus about 6.5% for the densest bamboo measured. Increased wood density generally promotes more pronounced moisture-induced wood deformations due to an increased number of sorption sites. However, high extractive content and the presence of reaction wood constitute an exception to this general rule [44,45].

Based on the results obtained, it can be stated that lower bamboo swelling makes it a better-suited material for use in variable humidity conditions than untreated wood of similar density. Lower swelling values will be sufficient to help adjust individual elements in applications such as flooring or terraces without causing bumps, and, presumably, lower shrinkage when compared to untreated wood of a similar density will prevent the elements from cracking and distortions, enabling longer and safe usage of finished products made of bamboo.

3.3. Bamboo Swelling Pressure

The values of swelling pressure for the bamboo samples in the tangential direction are presented in Figure 5. They differed depending on the bamboo block density, increasing as density increased, reaching maximum values of 1.39 MPa for the densest sample, 1.35 MPa for the medium-density block, and 1.16 MPa for the lowest-density sample. Additionally, a dependence of the time taken to achieve maximum swelling pressure on bamboo density was observed: the samples with the lowest density reached their maximum swelling pressure after 160 min, and those with medium density reached this value after 190 min, while the densest blocks only reached this value after 340 min.

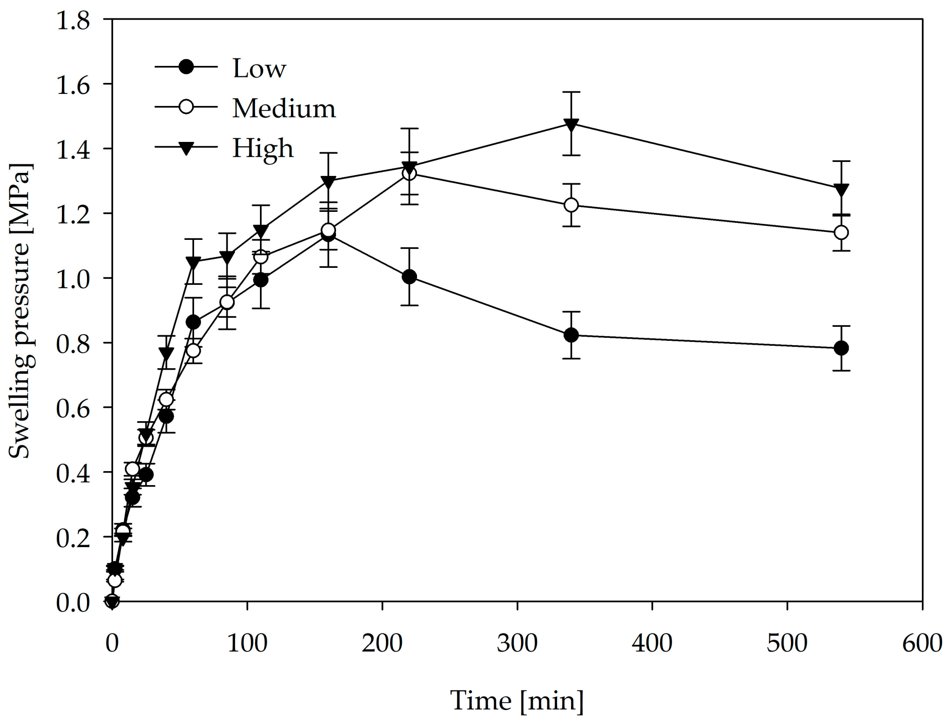

Figure 5. Swelling pressure graph for three different density groups of bamboo blocks: low, medium, and high. Measurements were conducted in the tangential direction; error bars represent the standard deviation.

The comparison of bamboo swelling pressure with that of wood is complicated because the information about the maximum swelling pressure of wood in the literature is scarce. Additionally, the results obtained depend on the measurement method used: the values of swelling pressure determined from the time course of a wood sample's hygro-mechanical creep [46,47] are higher than those measured with the method proposed by Perkitny [32,48], where due to cyclic loading, the stresses in wood undergo gradual relaxations, so the swelling pressure values measured are lower than the actual total pressure developed in the material. For example, the maximum swelling pressure measured in the tangential direction for ash wood (*Fraxinus excelsior* L.) was 4.18 MPa after 18 h [36], and this value was only 1.35 MPa for Scots pine wood [49], but the measurement methods used were different. It can be stated, however, that bamboo's relatively low total swelling pressure makes it useful for applications in variable humidity conditions.

3.4. Bamboo Total Swelling Rate

The mean values of total linear swelling in all three anatomical directions, along with volumetric swelling for the three density groups of bamboo, are presented in Table 3. The only statistically significant difference between the density groups can be observed for medium-density bamboo in the radial direction and the high-density samples in the longitudinal direction. Similar to wood, the smallest increase in bamboo sample size due to swelling was observed in the longitudinal direction, reaching an average value of 0.71%. In the tangential direction, the swelling was much higher, nearly 6%, while in the radial direction, it was as much as over 7%. In wood, greater moisture-induced deformations are observed in the tangential direction compared to the radial direction [50]. Since the measurements were performed on 50 bamboo samples and the relationships between swelling in the tangential to radial directions were similar, the results obtained seem reliable. However, the tangential dimensions of the samples were much larger than the radial dimensions, which may have affected the results. Another possible explanation consists of the differences in the anatomical structure between bamboo and wood. Wood tissue has medullary rays in its structure. These rays are made of parenchyma cells and are responsible for the radial transportation of water, minerals, and other organic substances from a tree's centre to the periphery [51]. It is known that the presence of rays reduces dimensional changes in the radial direction because the rays are more dimensionally stable along their length than the surrounding axial tissue. They act like reinforcing bars, and the wider the rays and the greater their number, the lower the wood swelling and shrinkage in the radial direction [52]. Bamboo tissue does not have structures such as rays [53], presumably making its swelling behaviour in the tangential and radial directions different from that of wood. Nevertheless, the observed phenomenon requires further, more detailed studies.

Table 3. The mean values of bamboo swelling in three anatomical directions and volumetric swelling for three different groups of densities.

Bamboo	Tangential	Radial	Longitudinal	Volume
			[%]	
Low-density	5.864 ^{a}	6.680 ^{a}	0.667 ^{a}	13.691 ^{a}
Medium-density	5.809 ^{a}	7.505 ^{b}	0.634 ^{a}	14.473 ^{a}
High-density	5.956 ^{a}	7.022 ^{a}	0.803 ^{b}	14.307 ^{a}

^{a,b} different superscripts denote a statistically significant ($p < 0.05$) difference between mean values ($n = 10$ for each set of samples) according to Tukey's honest significant difference test.

4. Conclusions

Our research on bamboo's swelling behaviour revealed that, like in wood, bamboo swelling and swelling pressure measured in the tangential direction depend on a sample's density. However, the values measured for bamboo were lower than those determined for wood of an analogous density. Similar to wood, the lowest degree of linear swelling was observed in the longitudinal direction. Interestingly, opposite to wood, radial swelling was greater than tangential swelling, which may be a result of the anatomical differences between bamboo and wood (the presence of rays in the latter) or the different radial and tangential dimensions of the samples used in this research. Bamboo swelling pressure in the tangential direction was relatively low, comparable to that for Scots pine. The lower the bamboo density, the lower the swelling pressure value measured and the time required to achieve maximum swelling pressure.

The results obtained show that the swelling behaviour of bamboo is better or comparable to that of wood, and from this perspective, bamboo culms, at least the parts with lower and medium density (in the analysed range between 385 and 540 kg m^{-3}), seem to be a good material for use in variable humidity conditions, more favourable than the unmodified wood of many species.

Author Contributions: Conceptualisation, E.R. and M.B.; methodology, E.R. and M.B.; formal analysis, M.B. and E.R.; investigation, R.K. and M.B.; writing—original draft preparation, M.B., E.R. and P.M.; writing—review and editing, M.B., E.R., R.K. and P.M.; visualisation, P.M.; supervision, E.R. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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