

Chapter 3

Physical Properties of Calcutta Bamboo

3.1 Introduction

Dendrocalamus strictus is commonly recognized as Calcutta bamboo [1], but also known as male bamboo [2], and solid bamboo [3]. Calcutta bamboo is the most widely used bamboo in India [4], especially for the paper industry. It is also used in house construction, basket making, mats, furniture, agriculture implement and tools handles. It is the most common species of bamboo cited in the Indian forest and is available in every state in India [5]. This species is also found in Burma, Bangladesh and Thailand, as well as being cultivated in Malaysia, Indonesia, Sri Langka and southern parts of the United States [1, 6].

The suitability of Calcutta bamboo for structural composite products will be dependent upon its physical properties. The physical properties investigated are relative density (specific gravity), equilibrium moisture content and dimensional stability. Relative density is the most important single physical characteristic of woody material. The influence of moisture content and its effects to dimensional stability are studied as a basic concern when using any forest product [7]. Dimensions start to change as the moisture content changes below the fiber saturation point. Wood-based materials are closely related to the amount of water present. Thus, in order to satisfactorily use bamboo as a raw material for composite products, the physical properties of relative density and dimensional stability, and their relation with equilibrium moisture content are studied.

Physical Properties

Relative density (SG) is the weight of any given volume of a substance divided by the weight of an equal volume of water [9]. Relative density of *Dendrocalamus strictus* is determined using a water immersion method. The standard test methods for specific gravity of wood and wood-based materials is found in ASTM D 2395-93 [9]. Relative density for *D.strictus* is calculated using Equation 2.1 in Chapter 2.

Equilibrium moisture content (EMC) is defined as the moisture content that is in equilibrium with the temperature and relative humidity of the air [10,11]. EMC is an important in-service factor because wood, and other woody materials like bamboo, are subjected to long-term and short-term variation in surrounding relative humidity and temperature. Hence, this material is always undergoing changes in moisture content. In most cases, the changes are gradual and effect only the surface of the substrate when briefly exposed to moisture fluctuations. It is not usually desirable to use a material that experiences rapid moisture changes, because moisture affects the physical and mechanical properties of woody materials. Conditioning of bamboo to specific moisture contents can be carried out using the standard guide for moisture conditioning of wood and wood-based materials, ASTM D 4933-91 [12]. Moisture content is the mass of water in the substance expressed as a percentage of the oven-dry mass.

Dimensional stability pertains to shrinking and swelling of woody materials in response to changes in the bound water content. Shrinkage is approximately proportional to the amount of water loss from the cell wall. The introduction of water molecules into the cell wall results in swelling, although not

Physical Properties

completely reversible to the same degree. Bamboo is assumed to shrink and swell similar to wood, and therefore could be investigated using the standard methods of testing small clear specimens of timber, ASTM D 143-94 [13]. Shrinkage and swelling of bamboo in volume (V), longitudinal (L), radial (R) or tangential (T) directions are expressed by Equations 2.3 and 2.4 in Chapter 2.

This study has four main objectives. First, to measure the relative density of Calcutta bamboo and to compare this value at different heights along the culm, between nodes, and internodes. The second objective was to compare the shrinkage and swelling in the three orthogonal directions of bamboo, longitudinal, radial and tangential, as well as to compare the values at different locations along the length of the culm. The third objective was to correlate dimensional changes with relative density. Finally, the fourth objective was to measure the equilibrium moisture content at 20°C at various levels of relative humidity.

3.2 Experimental

3.2.1 Materials

Calcutta bamboo culms were purchased from Bamboo Rattan Works Inc., located in South Lakewood, New Jersey. The company imports bamboo from Southeast Asia, mainly from Burma. The average length of the culms was 18 ft. Standing culms of Calcutta bamboo are dark green in color. However the culms purchased were dark brown in color due to the smoke-drying process. The initial moisture content of the bamboo was about 10 to 11%.

Physical Properties

Upon arrival, the bamboo culms were measured for color, weight, culm length, number of internodes per culm, internode length at bottom, middle and top, internode diameter at bottom, middle and top, and the culm wall thickness at bottom, middle and top (Table 3.1). After these measurements, the culms were cut into 4 ft. long segments, and were placed in a conditioning chamber for several weeks. Moisture content was monitored until equilibrium was reached at temperature of 20°C, and relative humidity of 65%.

Table 3.1. Average culm characteristics of *Dendrocalamus strictus* specimens.

Property	
Color	Dark brown
Weight (lb.)	2.96
Culm length (ft)	18.0
Number of internodes per culm	36
Internode length (in)	
Bottom	2.16
Middle	7.39
Top	5.70
Internodes diameter (in)	
Bottom	1.30
Middle	1.02
Top	0.39
Culm wall thickness (in)	
Bottom	0.38
Middle	0.25
Top	0.14

3.2.2 Methods

The culms were carefully marked and labeled to identify the bottom to the top parts. The culms were divided into 4 parts, each 4 feet in length. Location 1 is the lower bottom part, location 2 is the upper bottom part, location 3 is the lower top part, and location 4 is the upper top part (Figure 3.1). Twenty culms were randomly selected from the thirty culms purchased. The culms were split half and used for physical property tests. The specimens for physical properties were selected randomly. The specimens were placed in the conditioning chamber before they were used for the experiments.

Relative Density

Specimens for relative density measurement were taken from the internodes following the scheme in Figure 3.1. Specimens from nodes were also taken. Comparisons of the relative density were made along the culm height. From each location, more than 50 specimens were taken for the measurement. The dimension for each location was impossible to standardize due to the changing dimension of the culm. Specimens used were irregular in shape. The method of water immersion served well in this situation. The bamboo skin was removed by using a hand spoke. Specimens were cut at least 1 in. long with variable thickness and width. Multiple comparison between the locations, and between the nodes and internodes, was carried out using statistical analysis of variance techniques.

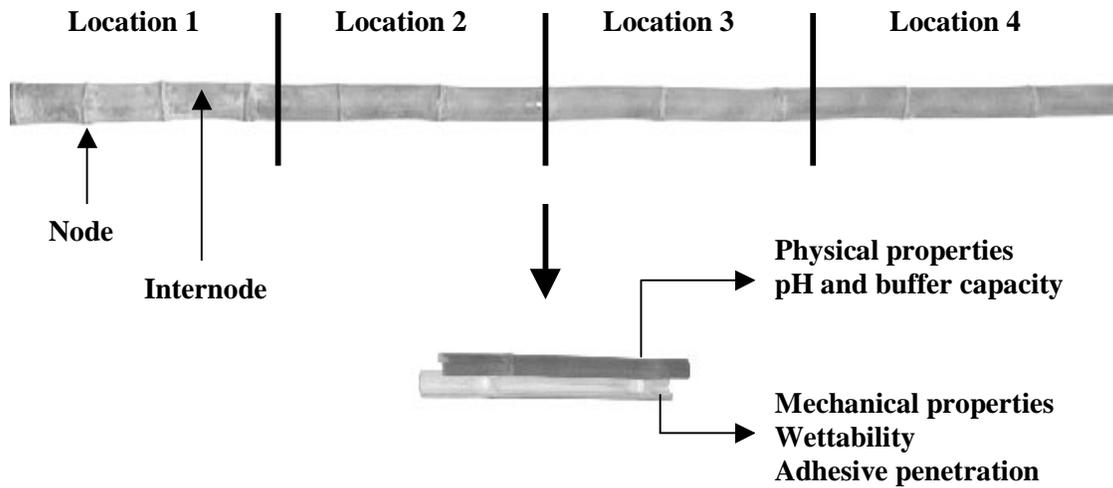


Figure 3.1. Sampling technique from *Dendrocalamus strictus* culm.

Shrinkage and Swelling

Specimens for shrinkage and swelling measurement were also taken from the internodes following the sampling scheme illustrated in Figure 3.1. Comparisons of the dimensional stability were made along the culm height. From each location, more than 30 specimens were taken for the measurement. The dimensions of the specimens from different locations were impossible to standardize due to the tapering of bamboo from bottom to top. The culm wall thickness and the diameter is larger at the bottom compared to the top. Specimens prepared from location 1 are larger than specimens from location 2 and so forth. The bamboo skin was removed by using a hand spoke and cut into rectangular

Physical Properties

specimens of at least 1 in. long, with variable thickness and width. The shrinkage and swelling of each location, each section (internodes and nodes), and in the longitudinal, radial, tangential directions were measured. Shrinkage of the specimens was measured from 12% MC ($T= 20^{\circ}\text{C}$ and $\text{RH}=65\%$) to the oven dry condition. Swelling was measured from the oven dry condition to the wet condition by soaking the specimens in distilled water. The specimens used for the dimensional stability and relative density were cut from locations adjacent to each other. These specimens were used in the correlation study between the dimensional change and relative density. Multiple comparisons between the locations, between the nodes and internodes, and between the three orthogonal directions were carried out using statistical analysis of variance techniques.

Equilibrium Moisture Content

Specimens of equal dimension for EMC measurement were taken from the bottom location of the culm (1" by 0.5" by 0.2"). All specimens were cut from adjacent locations to eliminate bias. Two methods of conditioning were used, namely by means of an aqueous salt solution and a conditioning chamber. The specimens were exposed to five different moisture content conditions. Ten samples were placed in each condition. Three conditions utilized saturated salt solutions and the other two utilized the conditioning chamber. Table 3.2 lists the saturated salt solutions and the conditioning chamber RH and temperature control used in this study. The approximate EMC achievable by the same condition of Sitka spruce are also presented in Table 3.2 [14]. The apparatus and the procedure

Physical Properties

of conditioning followed the standard guide for moisture conditioning of wood and wood-based materials, ASTM D 4933-91 [12]. The apparatus used and the preparation of the aqueous solutions followed the standard practice for maintaining constant relative humidity by means of aqueous solution, ASTM E 104-85 [15].

Table 3.2. Methods of specimens conditioning.

Method [†] A or B	Chemical (Formula)	T °C ± 0.5 °C	RH%	EMC% of Sitka spruce
A	Lithium chloride (LiClH ₂ O)	20	15	3.5
A	Calcium chloride (CaCl ₂ ·6H ₂ O)	20	32.5	6.5
B	-	20	40	7.5
A	Sodium dichromate (Na ₂ Cr ₂ O ₇ ·2H ₂ O)	20	52	9.5
B	-	20	77	15.0

†- Method A is the saturated salt solution and method B is the conditioning chamber

Statistical Test

The model considered for the one-way analysis of variance is shown below:

$$y_{ij} = \mu + \alpha_i + \epsilon_{ij} \quad (3.5)$$

where:

y = observation (physical property)

μ = mean

α = treatment (effect of different location)

ε = error

One-way analysis of variance with post-hoc tests was performed on the relative density, dimensional stability at different locations, and dimensional

stability on the three orthogonal directions. The null hypothesis for the one-way ANOVA is shown below

$$H_0: \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$$

$$H_a: \text{At least one of the } \alpha \text{ differ from 0}$$

The null hypothesis was that different locations (locations 1 to 4) or different orthogonal direction (radial, tangential and longitudinal) have the same mean physical properties. If the H_0 is true then further tests do not need to be conducted. If H_0 is not true, then the corresponding alternative hypothesis is H_a , at least one of the mean physical properties differs from others. In this case the multiple comparison procedure, Tukey's studentized range (HSD) test was performed on the four culm locations and the three directions. The test procedure for comparing the physical properties between nodes and internodes was carried out using the two-sample t-test. The null hypothesis (H_0) was that the nodes and internodes have the same mean physical properties.

$$H_0: \mu_1 = \mu_2$$

$$H_a: \mu_1 \neq \mu_2$$

A simple linear regression was performed using the general linear models procedure. The predicted observation is represented by Equation 3.6:

$$y_i = \beta_0 + \beta_1 x_i \quad (3.6)$$

3.3 Results and Discussion

3.3.1 Relative Density

The average relative density in the oven-dry condition of Calcutta bamboo used in this study was 0.643. The average oven-dry density was 643 kg/m³ or 40.3 lb/ft³. Location 1 is associated with the bottom part and location 4 is associated with the top part (Figure 3.1). A section is designated as either a node or internode. The analysis of variance of density at different locations and section are presented in Table 3.3. The mean relative density of Calcutta bamboo at each location is presented in Table 3.4. The relative density of location 1 was 0.636, while location 2, location 3 and location 4 were 0.640, 0.651 and 0.644 respectively. The relative density increased from location 1 to location 3, but location 4 was slightly lower.

Table 3.3. Analysis of variance of relative density at different locations and section of *Dendrocalamus strictus* culms.

Source of variation	DF	Sum of squares	Mean square	F-value
Location	3	0.01	0.01	0.31 (NS)
Section	1	0.63	0.63	86.78 (HS)

(HS) indicates significance at the 1% level of probability

(NS) indicates not significant

The trend found by several studies [16,17] indicated an increase of relative density from bottom to the top. With the exception of location 4, the results of this study showed the same pattern. However from the analysis of variance performed (Table 3.3) there is no significant difference of the relative density between

Physical Properties

locations of the culm. In another words, there is no significant variability of the material in terms of mass of dry woody substance per volume along the culm. From a manufacturing point of view, the selection of Calcutta bamboo for utilization in composite materials on the basis of its relative density would not be affected by the location along the culm. Table 3.3 also shows the analysis of variance of the relative density between the nodes and internodes. From the two-sample t-test, it was found that there is a significant difference between the relative density of the nodes and the internodes. From Table 3.4, the mean relative density of the nodes was 0.785, compared to 0.643 of the relative density of internodes. Figure 3.2 presents the values in a graphical fashion.

The relative density of several bamboo species are given in Table 2A and 3A of Appendix A. The relative density of giant timber bamboo (*Phyllostachys bambusoides*) is 0.48 (oven-dry), while some bamboo like Mitenga (*Bambusa longispiculata*) shows very high relative density, about 0.91. In comparison to other timber species used for composite materials, Calcutta bamboo exhibits a high relative density. Yellow-poplar and Douglas-fir and are some example of the timber species used by the wood- based composite industries. The relative density based on 12% MC of these species are 0.42 and 0.48 respectively. Table 3B of Appendix B presents the relative density of several timber species.

Relative density is an important factor because it affects the material behavior, especially the physical and mechanical properties. In the wood-based composite material, relative density of the species is a strong factor that affects board properties. The species that are commonly used for composite material lies

Physical Properties

below 0.5. Generally, board physical (except swelling) and mechanical properties are improved, but there are limitations. Heavy composite material is hard to work with and transportation cost may increase. High specific gravity of the materials can prevent intimate contact between the particle in the mat during pressing. High pressure has to be applied and failure of the material can cause weaknesses in the products. The industries commonly used wood species that are in the range between 0.3 and 0.5 for their composite products. An increase of 0.15 to 0.2 above the species gravity is common. Relative density of Calcutta bamboo was higher than the range recommended for wood composite products. Thus, if composite material from Calcutta bamboo is to be produced the increase in relative density have to be minimized.

Table 3.4. Mean relative density of *Dendrocalamus strictus*.

Relative density of different culm internodes location			
Location 1	Location 2	Location 3	Location 4
0.636 (0.056)	0.640 (0.067)	0.651 (0.103)	0.644 (0.107)
Relative density of nodes and internodes			
Nodes		Internodes*	
0.785 (0.087)		0.643 (0.086)	

Number in parenthesis associate to standard deviation.

Relative density based on dry mass and dry volume

* The mean internodes value of all locations

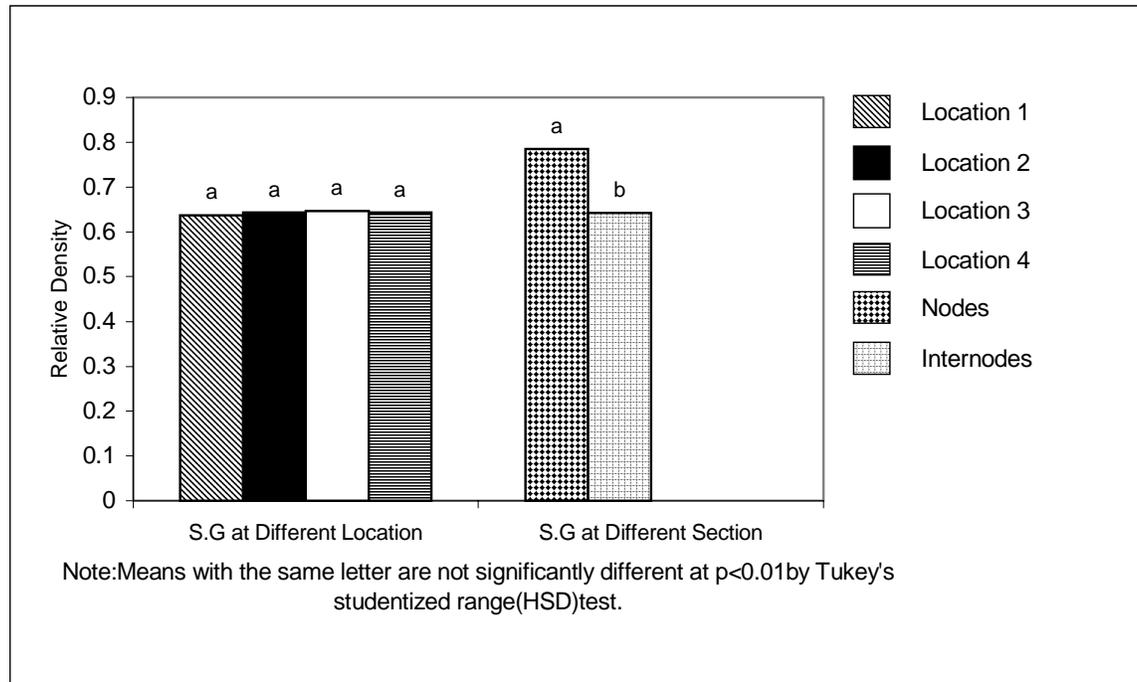


Figure 3.2. Relative density of *Dendrocalamus strictus* at different culm location and section.

3.3.2 Shrinkage and Swelling

The mean dimensional stability of Calcutta bamboo is shown in Table 3.6. The internode radial shrinkage was 2.5%, 3.1%, 3.2% and 3.7% for location 1 to 4 respectively. From the ANOVA shown in Table 3.5, there were significant differences in radial shrinkage. Figure 3.3 illustrates the shrinkage for different internode locations in the culm. Radial shrinkage in locations 1 and 4 are significantly different from locations 2 and 3, while locations 2 and 3 are not significantly different from each other. Tangential and longitudinal shrinkage shows no significant difference along the entire culm. Tangential shrinkage in locations 1 to 4 are 2.9%, 3.7%, 3.2% and 3.3% respectively, while longitudinal

Table 3.5. Summary of analysis of variance of dimensional stability by different location, direction and section of *Dendrocalamus strictus* culms.

Source of variation	DF	Sum of squares	Mean square	F-value
Location:				
Radial shrinkage	3	26.64	8.88	11.98 (HS)
Tangential shrinkage	3	10.90	3.63	2.85 (NS)
Longitudinal shrinkage	3	0.02	0.01	0.70 (NS)
Location:				
Radial swelling	3	4111.69	1370.57	7.96 (HS)
Tangential swelling	3	1987.20	662.40	4.84 (HS)
Longitudinal swelling	3	0.30	0.10	1.20 (NS)
Direction:				
Shrinkage	2	724.44	362.22	387.96 (HS)
Swelling	2	36247.74	18123.87	155.89 (HS)
Section:				
Shrinkage	3	252.86	84.28	79.97 (HS)
Swelling	3	986.85	328.95	1.92 (NS)

(HS) indicates significance at the 1% level of probability

(NS) indicates not significant

Section is associated to internode and node

shrinkage in location 1 to 4 are 0.43%, 0.16%, 0.17% and 0.19% respectively.

The ANOVA in Table 3.5, shows that there were significant differences between locations 1 to 4 for radial and tangential swelling. Figure 3.4 illustrates the swelling of Calcutta bamboo for each location in the culm. Radial swelling in location 1 is significantly different from locations 2, 3 and 4. Location 2, 3 and 4

Table 3.6: Mean dimensional stability of *Dendrocalamus strictus* separated by different culm location , section and direction.

Internodes/ radial							
Location 1		Location 2		Location 3		Location 4	
Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling
2.5 (0.75)	13.8 (8.41)	3.1 (0.64)	24.3 (11.69)	3.2 (0.68)	24.0 (13.25)	3.7 (1.25)	28.7 (17.88)
Internodes/ tangential							
Location 1		Location 2		Location 3		Location 4	
Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling
2.9 (1.07)	14.6 (9.03)	3.7 (1.21)	20.5 (8.59)	3.2 (1.05)	16.3 (9.25)	3.3 (1.19)	24.7 (17.71)
Internodes/ longitudinal							
Location 1		Location 2		Location 3		Location 4	
Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling	Shrin- kage	Swel- ling
0.43 (1.41)	0.64 (0.32)	0.16 (0.10)	0.51 (0.33)	0.17 (0.09)	0.60 (0.28)	0.19 (0.08)	0.59 (0.20)
Nodes							
Radial shrinkage		Radial swelling		Tangential shrinkage		Tangential swelling	
2.85 (2.89)		18.68 (13.70)		0.71 (1.58)		20.59 (11.60)	
Internodes*							
Radial shrinkage	Radial swelling	Tangential shrinkage	Tangential swelling	Long. shrinkage	Long. swelling		
3.08 (0.96)	22.44 (14.1)	3.25 (1.15)	18.84 (12.21)	0.18 (0.09)	0.59 (0.29)		

Dimensional changes in percent(%)

Number in parenthesis is the standard deviation.

Shrinkage measured from 9.4% MC to oven-dry condition

Swelling measured from oven-dry to wet condition (average 63% mc)

*Mean value of all internode specimens.

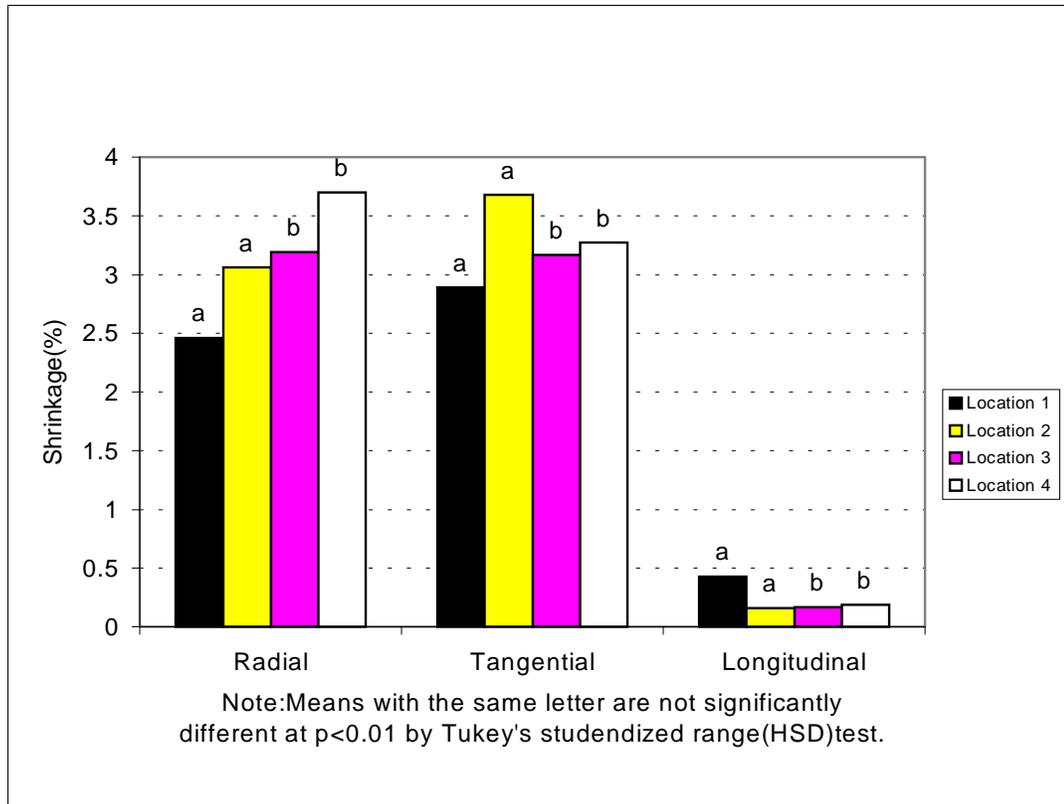


Figure 3.3. Dimensional shrinkage of *Dendrocalamus strictus* for different internode location and direction of the culm.

are not significantly different from one another. The tangential swelling also exhibits differences. From Figure 3.4, tangential swelling in locations 1, 2 and 3 shows no significant difference from one another, but tangential swelling in location 1 is significantly different from location 4. On the other hand, there is no significant difference in the tangential swelling in locations 2, 3 and 4. Similar to longitudinal shrinkage, there is no significant difference for longitudinal swelling in the locations. Moreover, both the shrinkage and swelling in the longitudinal direction have small values compared to the radial and tangential directions.

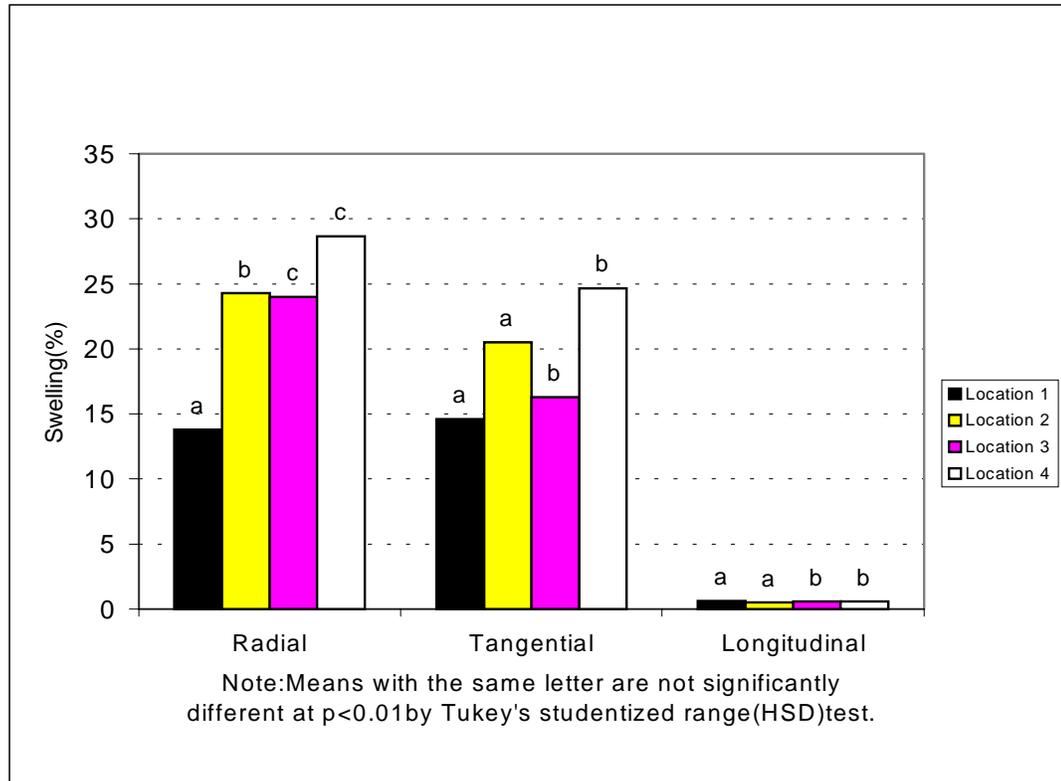


Figure 3.4. Swelling of *Dendrocalamus strictus* by internode location and direction of the culm.

The dimensional stability behavior shown by bamboo occurs in timber as well. This behavior occurs in timber because the orientation of most of the microfibrils (S2 layer) are aligned parallel to the longitudinal axis. The explanation of this behavior can also be applied to bamboo. According to the study of the anatomical structure by Parameswaran [18], there are two types of microfibril orientation in bamboo, the narrow lamellae showing fibrillar angle of $80 - 90^\circ$ to the axis and the broader ones with fibrillar angle almost parallel to the axis. Although the fibers in bamboo demonstrated polylamellate

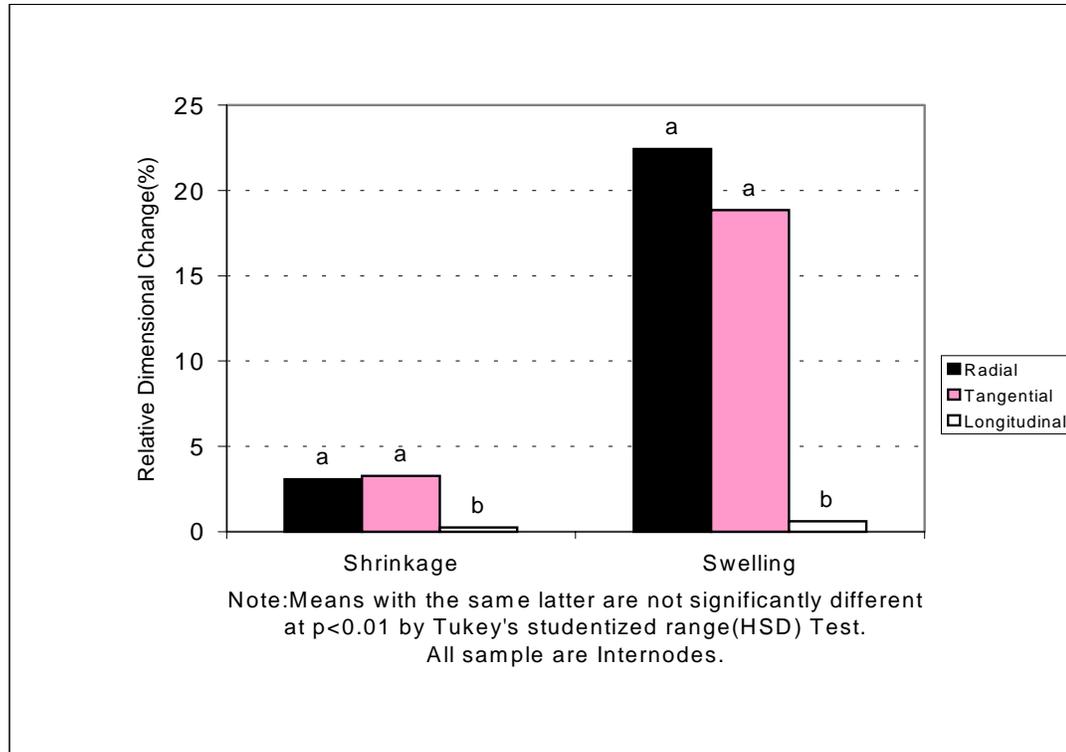


Figure 3.5. Dimensional stability of internodes of *Dendrocalamus strictus* by direction in the culm. Shrinkage is from 9.4% to oven-dry moisture content. Swelling is from oven-dry to saturated moisture content.

nature (8 lamellae compare to 3 lamellae in wood (S1, S2 and S3)), the broad fibril layer which are parallel to the axis is greater when compared to the narrow lamellae.

The dimensional stability in the three orthogonal directions was also compared. Only internode values were used in this comparison. The mean radial, tangential and longitudinal shrinkage of Calcutta bamboo was 3.08%, 3.25% and

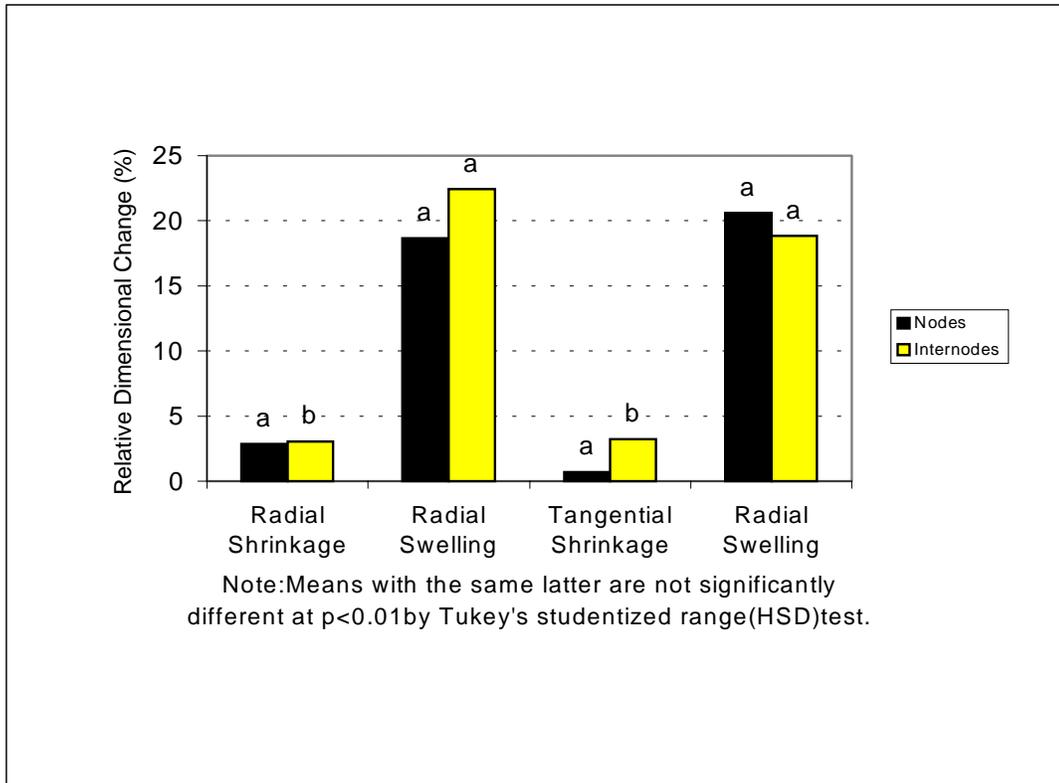


Figure 3.6. Dimensional stability of *Dendrocalamus strictus* for different culm section (internodes and nodes).

0.18% respectively when all locations are considered. The ANOVA in Table 3.5 shows that there were significant differences between the different directions.

Figure 3.5 illustrates the differences between the three directions. Radial and tangential shrinkage are not significantly different from one another, but the longitudinal shrinkage was significantly lower than the other two directions. The mean radial, tangential and longitudinal swelling of Calcutta bamboo was 22.4%,

18.8% and 0.6% respectively when all locations were considered. All directional swelling mean values were significantly different from one another.

The analysis of variance shown in Table 3.5 indicates that there were differences in shrinkage between radial nodes and internodes. Radial and tangential shrinkage mean values at the nodes were 2.9% and 0.71% respectively. Radial and tangential swelling mean values between the nodes and internodes were 19% and 20% respectively. They were not significantly different. Longitudinal shrinkage and swelling at the nodes were not measured since the changes are very small, and can be neglected.

3.3.3 Effect of Relative Density on Shrinkage and Swelling

Simple linear regression analysis with the general linear model procedure was performed on the relative density and dimensional changes. The shrinkage was observed from 9.4% moisture content to oven-dry condition, while swelling was observed from oven-dry to the wet condition. The coefficient of determination (R^2) and ANOVA of the linear regression are presented in Table 3.7. The procedure indicates that there was a weak relationship between dimensional changes and relative density.

Table 3.7. Coefficient of determination (R^2) and analysis of variance for the linear association between dimensional changes and relative density.

Correlation to relative density	Number of specimens	Sum of squares	F-value	R^2
Radial shrinkage	128	5.4226	7.28 (HS)	0.055
Tangential shrinkage	130	40.3715	26.83 (HS)	0.173
Longitudinal shrinkage	130	0.1607	21.90 (HS)	0.146
Radial swelling	133	525.7858	2.74 (NS)	0.021
Tangential swelling	132	794.5168	5.33 (HS)	0.039
Longitudinal swelling	133	0.0194	0.21 (NS)	0.001

(HS) indicates there is a significant relationship

(NS) indicates there is no significant relationship

All the correlation are significant at the 1% level of probability

The shrinkage and swelling of Calcutta bamboo was not significantly different between radial and tangential direction. This is in contrast with timber, where shrinkage and swelling are greater on the tangential direction. This result is consistent with the dimensional stability of other bamboo species. The explanation for this behavior is that bamboo have a different anatomical structure compared to timber. Bamboo lacks radially-oriented cells and growth rings like wood. Thus, the dimensional movement is similar in the two directions.

From Table 3B of Appendix B, the radial and tangential shrinkage (and swelling) from green to oven-dry condition of yellow-poplar is 4.6% and 8.2%, respectively. The shrinkage and swelling of Calcutta bamboo is large in comparison to yellow-poplar. Thus, Calcutta bamboo has lower dimensional

stability compared to wood. This is not a desirable behavior, and could become a factor that hinders the application of Calcutta bamboo for composite materials.

3.3.4 Equilibrium Moisture Content

The equilibrium moisture content of Calcutta bamboo was determined under five moisture conditions. The initial moisture content of the specimens under all conditions was approximately 12%. Figures 3.9 to 3.13 illustrate the changes of the moisture content over 39 days. Table 3.8 presents the EMC values for Calcutta bamboo at different environmental conditions. The EMC values for Sitka spruce are also presented in Table 3.8 for comparison [10]. In the first condition (20°C and 15% RH), the EMC of Calcutta bamboo is 4.2%, while EMC for Sitka spruce is 3.5%. As shown in Figure 3.9, the EMC was achieved in 18 to 20 days under the first condition.

Table 3.8. Equilibrium moisture content of *Dendrocalamus strictus* and *Picea sitchensis* (Sitka spruce) under five moisture conditions.

Condi- tion	At 20°C with Relative humidity (%)	Moisture content(%)	
		Calcutta bamboo	Sitka spruce
1	15.0	4.2	3.5
2	32.5	6.4	6.5
3	40.0	7.6	7.5
4	60.0	9.5	9.5
5	77.0	-	15.0

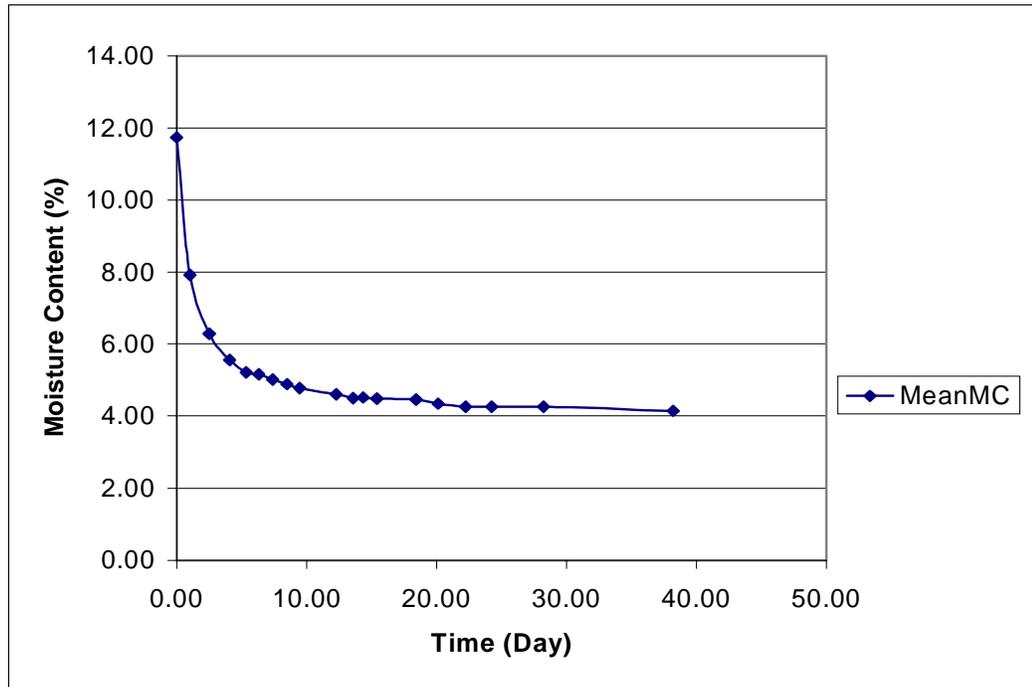


Figure 3.7. Moisture content change versus time for *Dendrocalamus strictus* at conditions of 20°C and 15% relative humidity.

Condition 2 (20°C and 32.5% RH) produced an EMC of 6.4%. In the same condition, EMC for Sitka spruce is 6.5%. As shown in Figure 3.10, the EMC was achieved within 20 to 25 days. This is not as anticipated because it usually takes a longer time to achieve lower moisture content. The size used for all conditioning is approximately 1" by 0.5" by 0.2" and the specimens were taken from adjacent sections of the culm. The only explanation for this anomaly is that there was still variability in the specimens although certain standard procedures were followed. A larger sample size should be used in the future investigation in order to minimize variability.

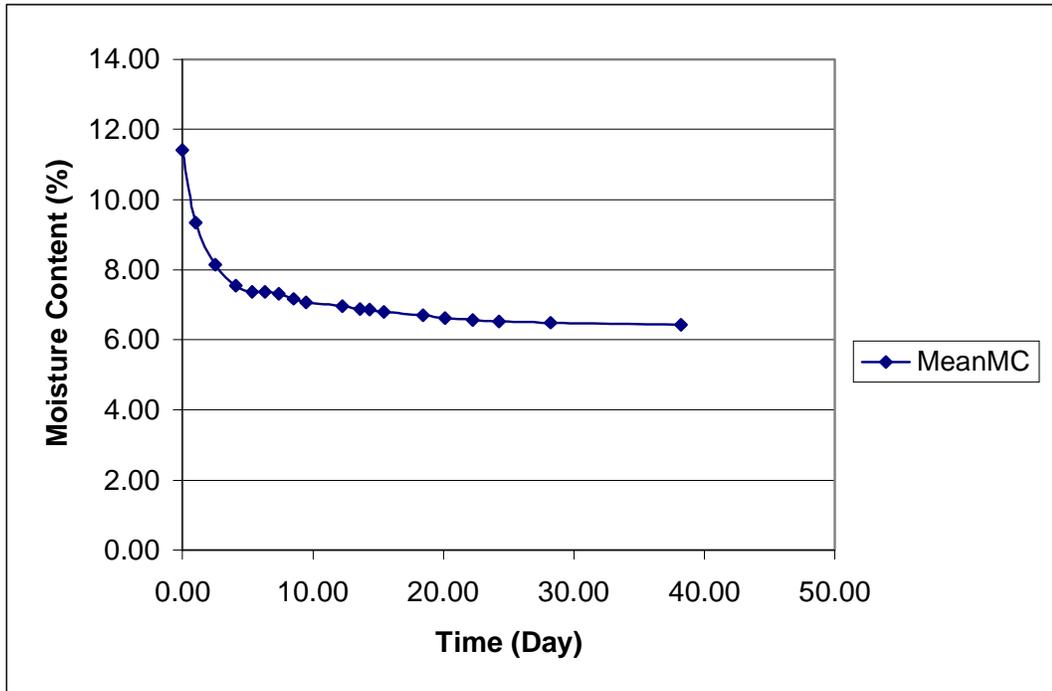


Figure 3.8. Moisture content change versus time for *Dendrocalamus strictus* at conditions of 20°C and 32.5% relative humidity.

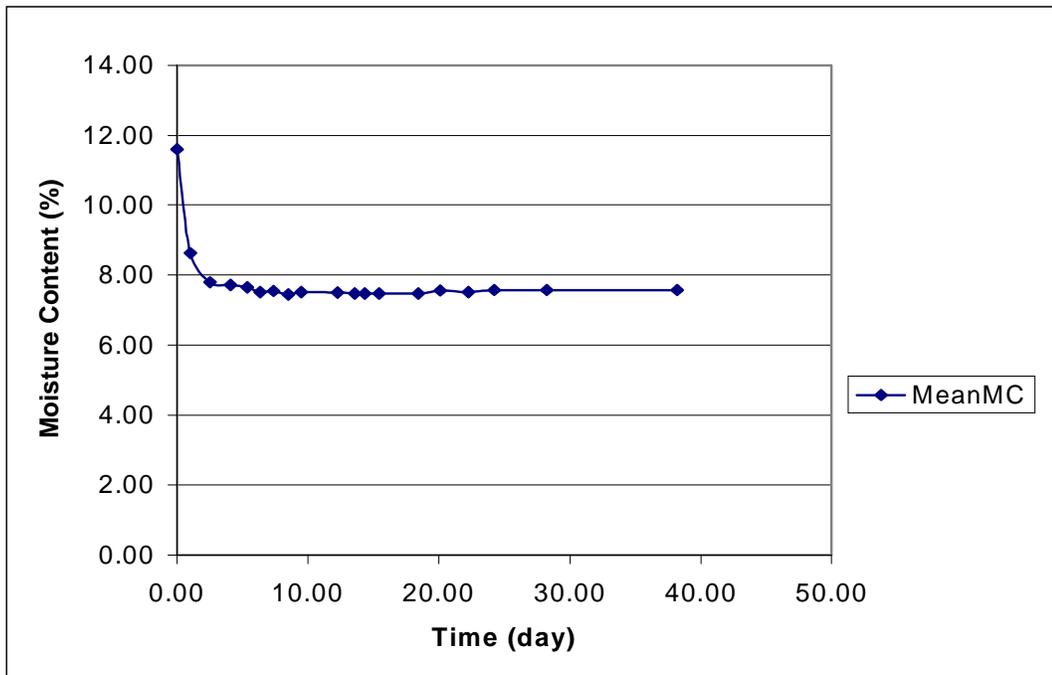


Figure 3.9. Moisture content change versus time for *Dendrocalamus strictus* at conditions of 20°C and 40% relative humidity.

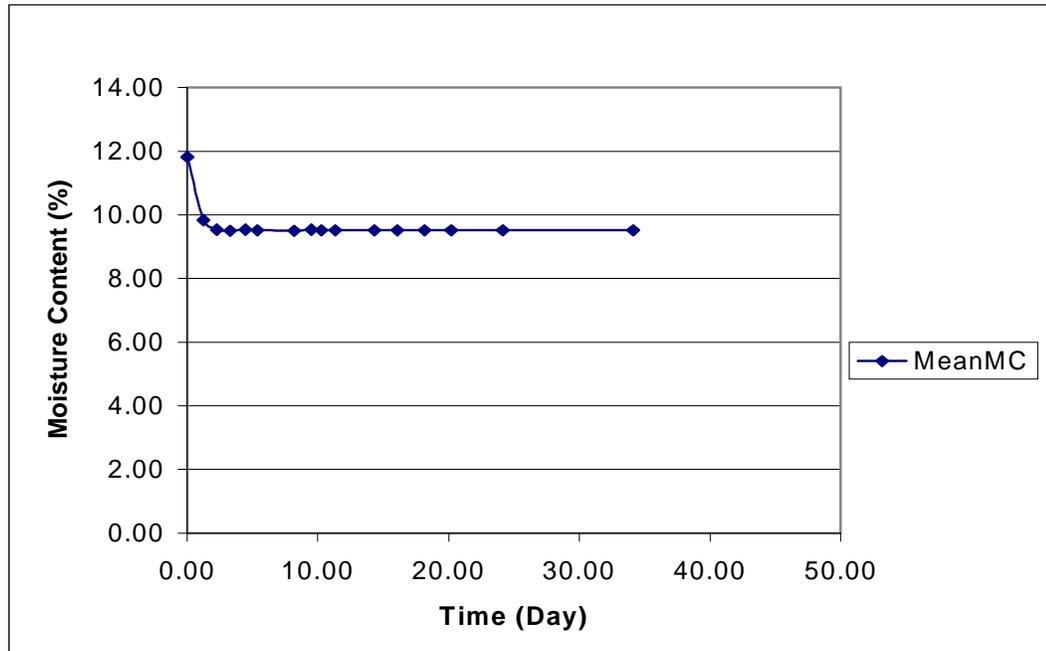


Figure 3.10. Moisture content change versus time for *Dendrocalamus strictus* at condition of 20°C and 60% relative humidity.

The EMC value in the third (20°C and 40% RH), and fourth (20°C and 60% RH) condition were 7.6% and 9.5% respectively, which was achieved in less than 5 days (Figure 3.11 and 3.12).

The EMC in the fifth condition shown in Figure 3.13 (20°C and 77% RH) could not be achieved due to the growth of fungi on the specimens. Eventually the moisture content increased above 15% for Calcutta bamboo, which is the EMC achievable by Sitka spruce. Bamboo that was conditioned under 20°C and 65% RH was not attacked by fungi. The average moisture content in this condition was 11 to 12%. Above this condition, bamboo, under prolonged exposure will start to be deteriorated by fungi. Higher temperature (above 55°C) should be used in the

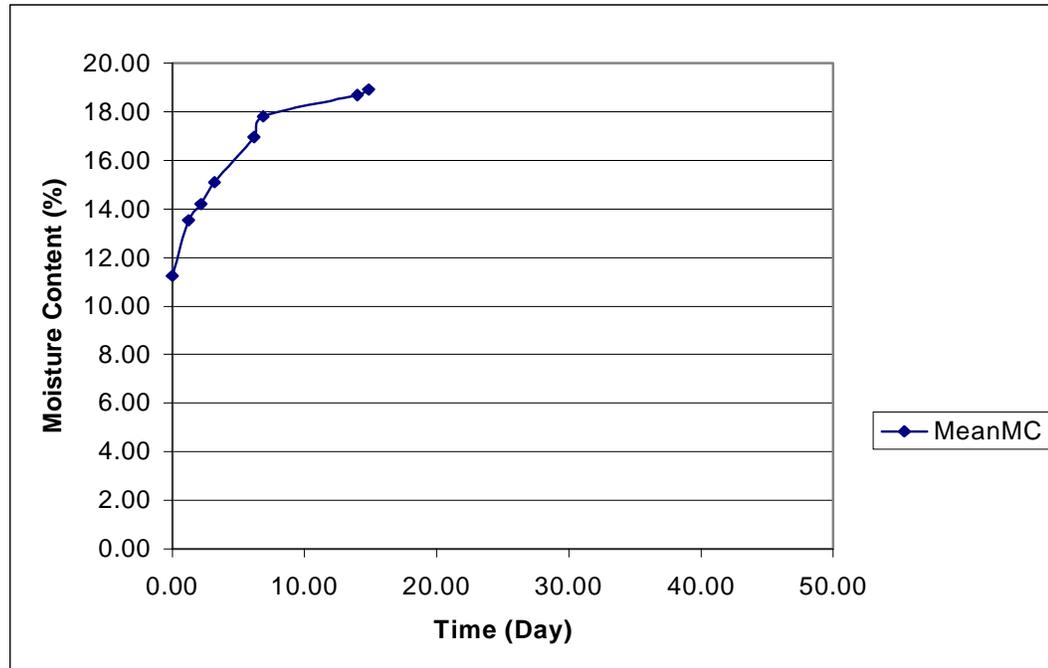


Figure 3.11. Moisture content change versus time of *Dendrocalamus strictus* at condition of 20°C and 77% relative humidity.

future to condition bamboo to higher than 12% moisture content. A chemical treatment could be used to overcome the fungi problem, as long as the chemical did not effect the EMC value.

The EMC values for Calcutta bamboo were close to Sitka spruce. The isotherm curves of Sitka spruce are used throughout much of the world for estimating the EMC of timber. In general this initial study on the EMC of Calcutta bamboo shows that the patterns are very similar to wood, and the data for Sitka spruce could be used for describing the bamboo-moisture relationship.

However, it appears that there is a potential for fungal activity above 15% moisture content. This is a problem that has been reported by others [4,6,14].

3.4 Conclusions

Selected physical properties of Calcutta bamboo have been analyzed. Relative density of the entire culm was determined to not significantly change along the length, although there are significant differences in relative density between nodes and internodes. From a practical point of view, this is a desirable factor because more bamboo woody material can be recovered for products. The dimensional stability of Calcutta bamboo was also measured in different location along the length of the culm, as well as in different directions, nodes and internodes. The mean radial shrinkage and swelling in Calcutta bamboo is not statistically different from tangential shrinkage and swelling. Longitudinal shrinkage and swelling are very small and are significantly different when compared to the other directions. There was a weak correlation between relative density and dimensional stability. Lastly, equilibrium moisture content of Calcutta bamboo was measured. It was found that bamboo and wood share common behavior when exposed to different environmental conditions. Environmental conditions generate losses and gains of moisture, which in term cause shrinking and swelling of Calcutta bamboo.

The density and the swelling values are much larger than the wood species commonly used in structural wood composites. This will impact the applications of Calcutta bamboo to specifically high-density composites or composite, which

Physical Properties

have the same density as the raw material. A laminated product or product that need not have extensive compression to press them together would be suitable for Calcutta bamboo.

Calcutta bamboo and bamboo as a whole, are high in sugar content. It is prone to microorganism attack, such as fungi and mold because its natural durability is low. A standard practice for bamboo is that it needs preservative treatment to increase its durability against these degradation agents. Due to this property, fungal growth was noted when the moisture content was raised to a higher level. This behavior could be a big problem if not treated. Thus Calcutta bamboo especially for the exterior structural composite application should be applied with chemical treatment in the future.

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Physical Properties

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