An Experimental Investigation of the Effects of Moisture Content on the Mechanical Properties of Bamboo and Cane

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Abstract-The natural strength and resilience of Bamboo and Cane make them effective, durable and inexpensive materials for construction. Bamboo and Cane have been recorded to have higher strength-to-weight ratio than even steel. Since the internodal regions are hollow, Bamboo and Cane are also lightweight, and the cylindrical geometry provides a high resistance to compressive axial loading and bending. Because Bamboo and Cane are fibrous, they gain and or loose moisture as temperature and humidity of the surroundings change. These changes have been observed to affect their weight, dimensions and strength (compressive, bending & tensile). In this study, Bamboo and Cane samples of varying moisture contents were subjected to increasing loads to the point of failure. The stress and deformation of the samples were recorded to analyze the impact of moisture content on their mechanical properties.

1. Introduction

Bamboo and Cane have been used for millennia in construction. Due to Bamboo and Cane's abundance and renewability, countries in East and South East Asia still heavily rely on Bamboo and Cane structures. Because of Bamboo and Cane's inherent strength and lightness (resulting from internodal cavities), they form very flexible building materials and offer reliable structural support. However, like many fibrous materials such as wood, Bamboo and Cane compromise their strength and rigidity when excessive moisture has been applied. Some of the basic properties that are affected by moisture content includes: weight, dimensions, strength (compressive, bending or tensile) and so on.

$$\textit{Moisture Content (MC\%)} = \frac{\textit{Weight of moist Bamboo/Cane} - \textit{Weight of oven dry Bamboo/Cane}}{\textit{Weight of oven dry Bamboo/Cane}} \times 100\% \quad \ldots(1a)$$

Bamboo and Cane can have extremely high moisture content compared to other wood species. The moisture content, calculated using equation (1a) above, of one culm of raw (unprocessed) Bamboo and Cane will vary from top to bottom, but more significantly, moisture content will be higher in the inner layers than in the outer layers of the Bamboo and Cane culm [1]. Moisture content for a given sample of Bamboo and Cane is defined as the weight of water in wood expressed as a percentage of the weight of Bamboo and Cane material (which is considered to be the oven dry weight of the sample). This content can range from 0% - 200%. Just like other fibrous materials, when Bamboo and Cane lose and gain moisture, they change, dimensionally. The anisotropic nature of Bamboo and Cane causes them to shrink at a different level, the greatest amount occurring in the direction of the growth rings (tangentially) and lowest occurring along the grain (longitudinally). These un-proportioned rates of shrinkage have a long-term effect causing Bamboo and Cane to deform as it dries. Processed Bamboo and Cane fiberboard, commonly used for flooring, absorb moisture in a more evenly-distributed manner similar to pine (also a building material commonly used in framing in residential structures). The distribution of moisture content in Bamboo and Cane specimens, dependent on the specimen type (raw or processed) along with other factors, may affect the normal and shear stress concentration gradients in the specimens. The distribution of moisture in Bamboo and Cane specimen exists in two forms; one- moisture filling the cell cavities and two-vapors chemically bound by hydrogen bonding to the cellulose of the Bamboo and Cane cell walls. Roh *et al* claimed that the mechanical properties of five-ply veneer-Bamboo zephyr composites decrease significantly with moisture content above 12% (a common MC in laboratory conditions) [2]. Since both raw and processed Bamboo and Cane are widely used in construction, it is thus important to test a variety of Bamboo and Cane specimens for analysis of variances in their mechanical properties.

In this research, Bamboo and Cane specimens were prepared to represent the characteristics of raw Bamboo and Cane (with and without the node), processed Bamboo and Cane (parallel and perpendicular grain direction), and dry and wet samples of each of the four previous classifications. These specimens were subjected to axial compressive testing, and the applied load and deformation of the specimen were recorded. The affect of moisture content on the mechanical properties of Bamboo and Cane became evident through this experimental investigation.

2. Experimental Investigation

2.1. Experimental Procedure

Given the fibrous characteristic of any wood species, both compression tests parallel and perpendicular to grain growth are necessary to obtain relevant data on the material's mechanical properties. Testing procedures and Bamboo and Cane specimen preparation followed the ASTM D 143 standards (Standard Methods of Testing Wood) [3]. The Tinius-Olson Universal Testing Machine (serial # 208314), as seen in Figure 1, was used to conduct axial compressive testing according to these ASTM standards. The dimensions of the representative samples are listed in Table 1.

Figure 1: *Tinius Olson Universal Testing Machine (serial # 208314)*

The compressive load was applied to each of the eight specimens continuously throughout the test at a rate of approximately 0.3048 mm/min. The constant load was applied to the point of visible failure of the specimens, and the displacements of the specimens were recorded at specific intervals of the applied compressive forces.

The Tinius Olson Universal Testing Machine was calibrated in English units, but all measurements and data were converted to SI units. The displacements of each specimen were recorded at approximately every 200 lbs (0.89 kN) of force applied. The Tinius Olson Universal Testing Machine allowed for displacement to be converted to micro-strain. Micro-strain was converted to strain which represents the change in length as a ratio to original length and thus remain the same when converted to SI units.

2.2. Computational Analysis

Based on the recorded force and strain, all mechanical properties could be calculated, and the results for each of the eight samples are represented in Figures 2-9 or Tables1(a,b). Equation 1 was used to calculate engineering stress for each interval of applied force over the original cross-sectional area of the sample.

$$\sigma = \frac{F}{A_0} \quad (1)$$

Equation 2 represents how engineering strain can be calculated from displacement and the original length of the sample.

$$\epsilon = \frac{\ell - \ell_0}{\ell_0} \quad (2)$$

However, the Tinius Olson Universal Testing Machine's computer had already provided the micro-strain at each measured interval which was multiplied by a factor of 10^{-6} to obtain strain.

Stress versus strain curves for each sample provides visual inconsistencies between samples in Figures 2-9 and allowed for the determination of some important mechanical properties for each sample, such as σ_y (yield stress) and σ_s (compressive strength). Equation 3 (derived from Hooke's Law) was used to compute the Young's moduli, which represents the ratio of stress strain up until the linear elastic limit.

$$\mathrm{E} = \frac{\sigma}{\varepsilon} \quad (3)$$

Equation 4 yields the elastic energy for each sample and is merely half the yield stress of the sample.

$$eE = \frac{\sigma_y}{2} \quad (4)$$

Equation 5 resembles the modulus of resilience (or elastic energy over yield strain).

$$U_r = \frac{eE}{\varepsilon_y} \quad (5)$$

2.3. Results

2.3.1. Summary of Significant Results

Table 1 provides an overview of the properties deduced from each of the Bamboo and Cane samples. The first column denotes the sample numbers (corresponding to Figures 2 – 9). The second and third columns provide the length and cross-sectional area. The fourth, fifth, and sixth columns compare the differences in wet and dry weights (where 0% means no additional moisture content was added to the assumed 12% standard moisture content of the samples). The seventh column indicates whether the sample was processed or raw Bamboo and Cane and the direction of the grain. The next relevant columns respectively list yield strain, yield stress, compressive strength, elastic energy, modulus of resilience, and finally Young's Modulus

Table 1a: Summary of key results for overall sample comparison.

S#	L (mm)	C.S.A (mm^2)	Dry Wt. (gm)	Final Wt. (gm)	%Wt. of H_2O	Type
1	44.25	217.03	5.21	5.21	0.00	Processed/ perpendicular
2	44.20	217.03	5.57	7.34	24.01	Processed/ perpendicular
3	58.93	217.03	8.25	8.25	0.00	Processed/ parallel
4	58.93	217.03	8.57	11.02	22.25	Processed/ parallel
5	50.80	239.50	8.24	8.24	0.00	Raw/no node
6	50.80	239.50	8.64	9.95	13.17	Raw/no node
7	50.80	334.51	10.28	10.28	0.00	Raw/node
8	50.80	334.51	9.15	10.33	11.40	Raw/node

Table 1b: Summary of key results for overall sample comparison.

S #	ε_y (mm/mm)	σ_y (MPa)	σ_x (MPa)	eE (MPa)	U_r (MPa)	E (MPa)
1	0.001588	4.10	49.19	2.05	1290.66	6971.33
2	0.014483	28.69	35.70	14.35	990.61	1485.94
3	0.001702	4.10	32.34	2.05	1204.21	2441.42
4	0.003328	4.10	25.70	2.05	615.86	96.02
5	0.001925	8.20	27.24	4.10	2129.42	3791.99
6	0.001748	8.20	16.40	4.10	2345.05	3733.28
7	0.009981	28.96	32.98	14.48	1451.00	3059.06
8	0.003798	16.40	24.59	8.20	2158.58	2051.62

From the graphs in Figures 2-9, it can be observed that the wet sample seems to represent a more ductile material than the dry samples.

2.3.2 Processed – Perpendicular to Grain

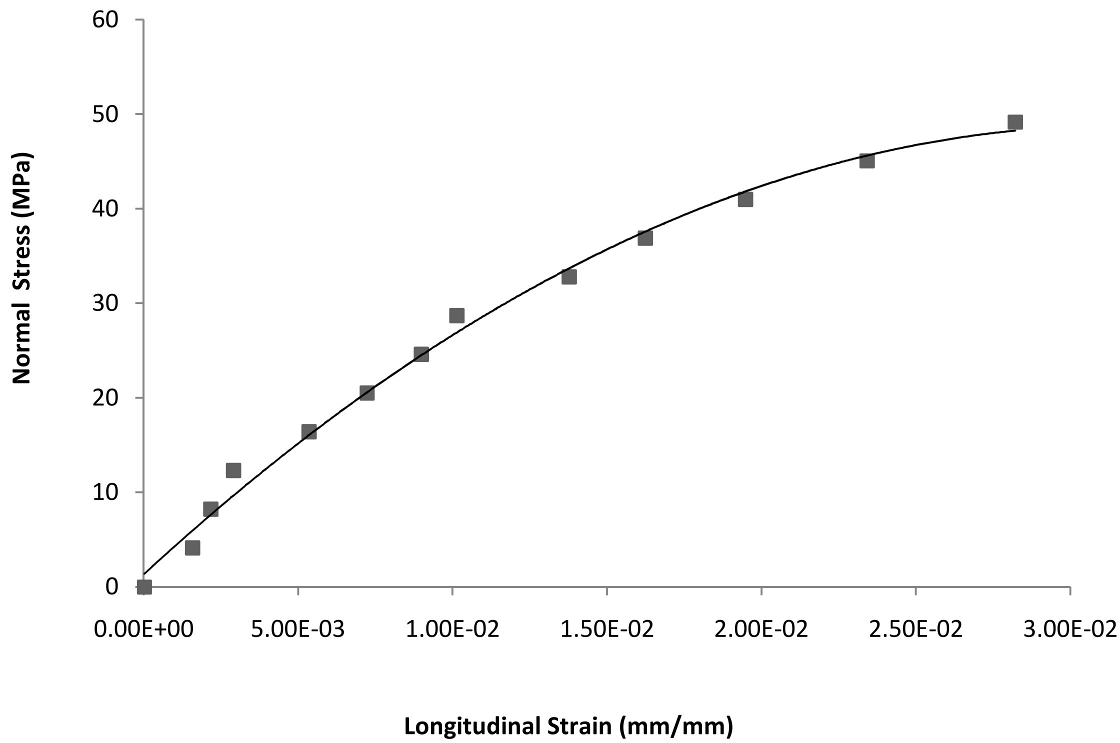

Figure 2: Sample #1 (Dry)

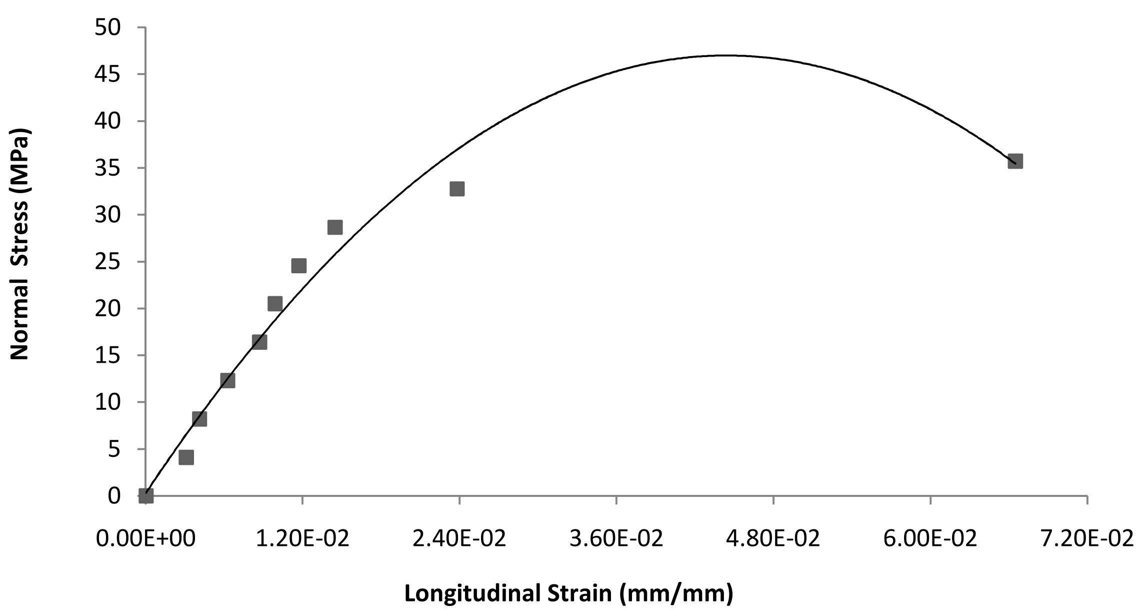

Figure 3: Sample #2 (Wet)

2.3.3. Processed – Parallel to Grain

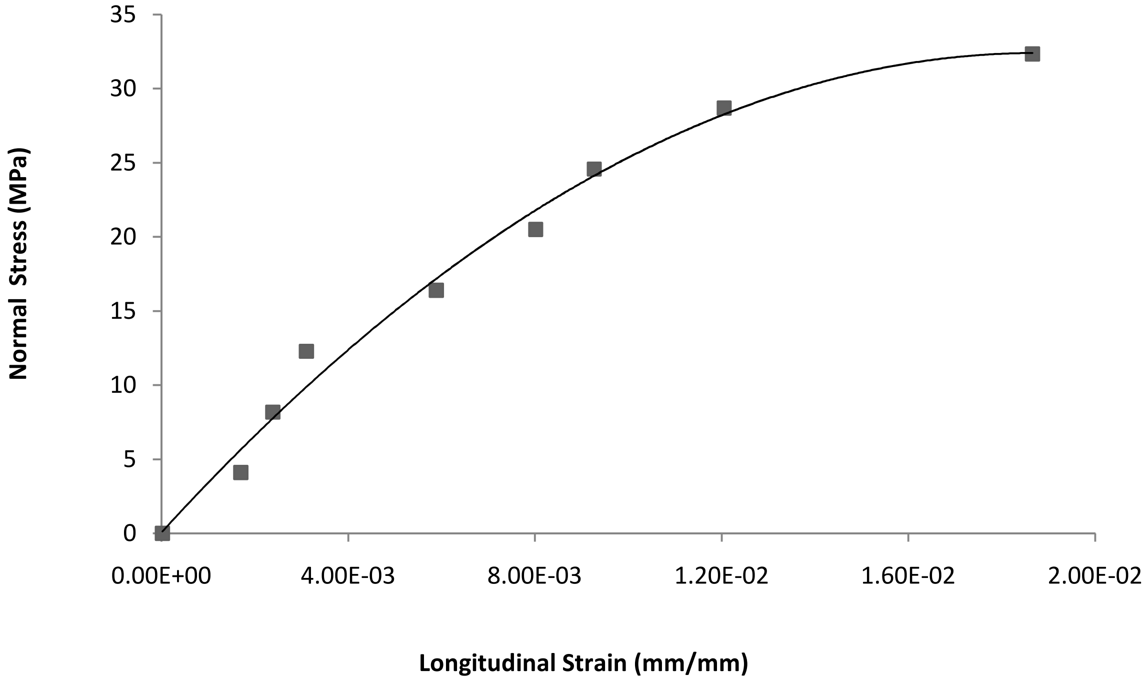

Figure 4: Sample #3 (Dry)

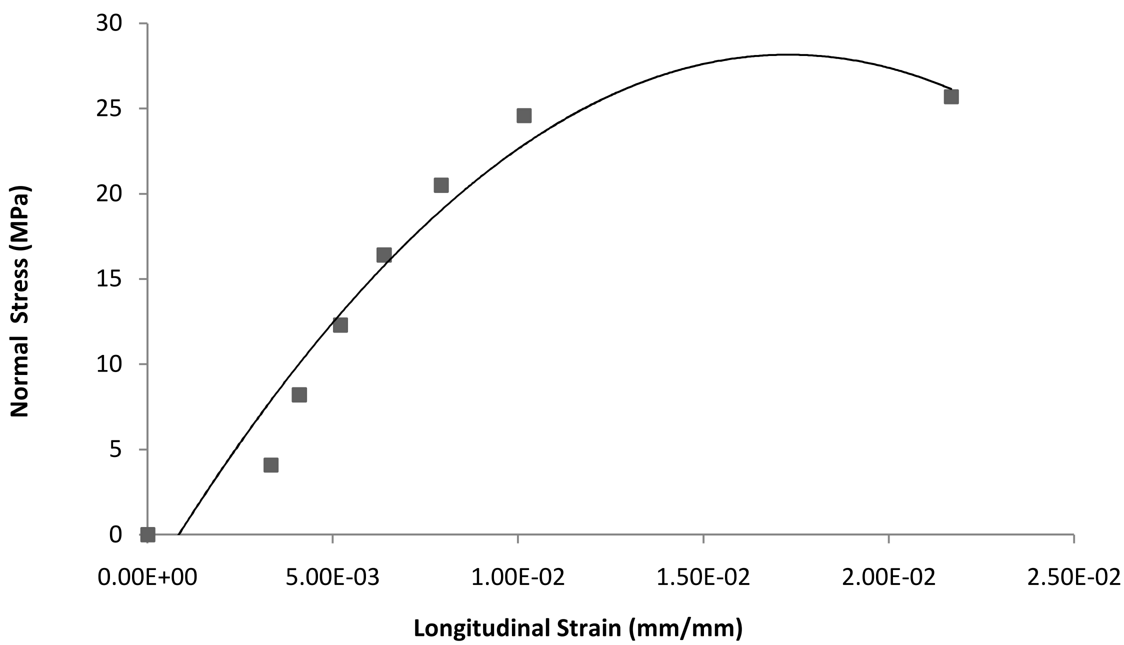

Figure 5: Sample #4 (Wet)

2.3.4. Raw – No Node

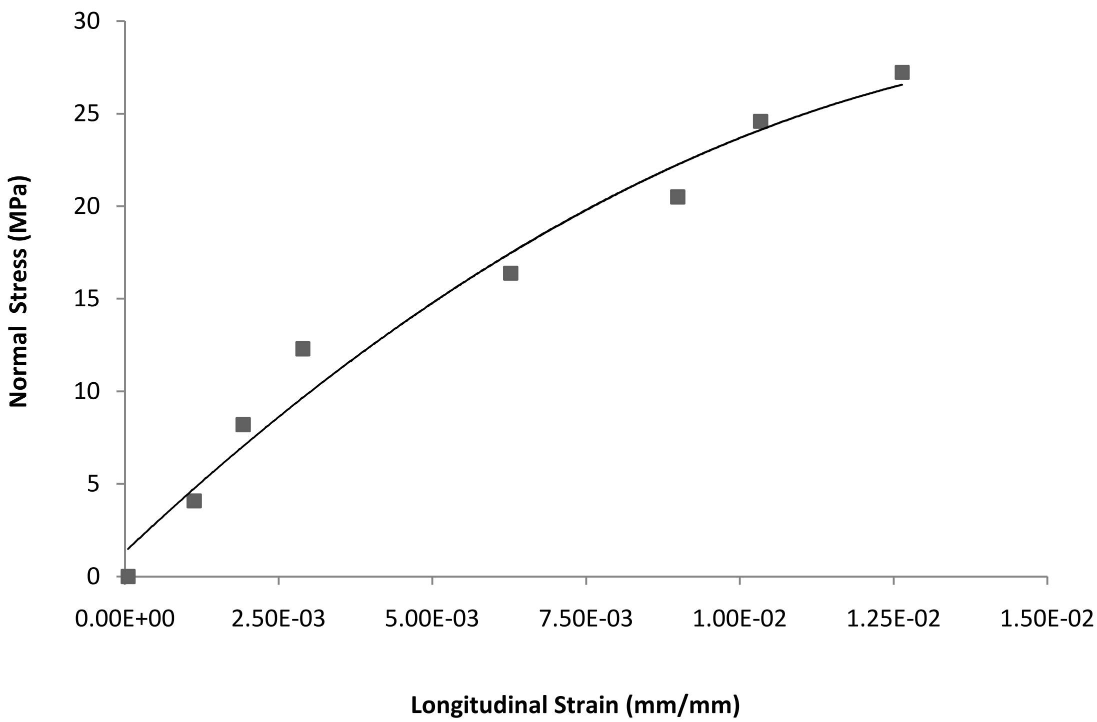

Figure 6: Sample #5 (Dry)

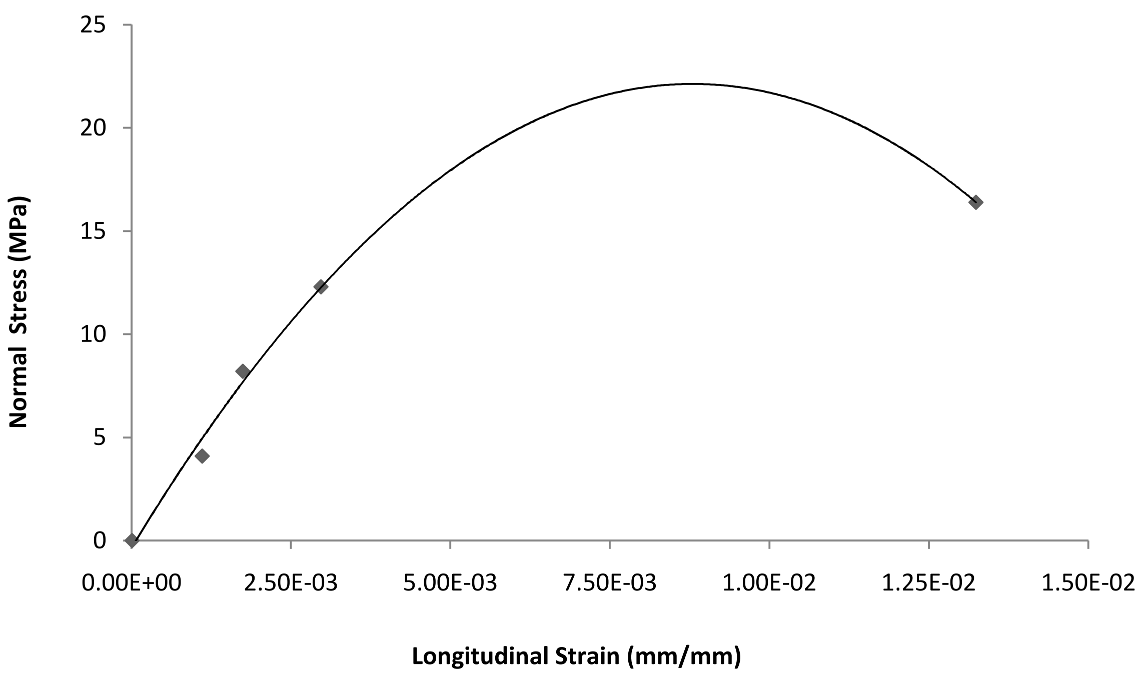

Figure 7: Sample #6 (Wet)

2.3.5.   Raw - Node

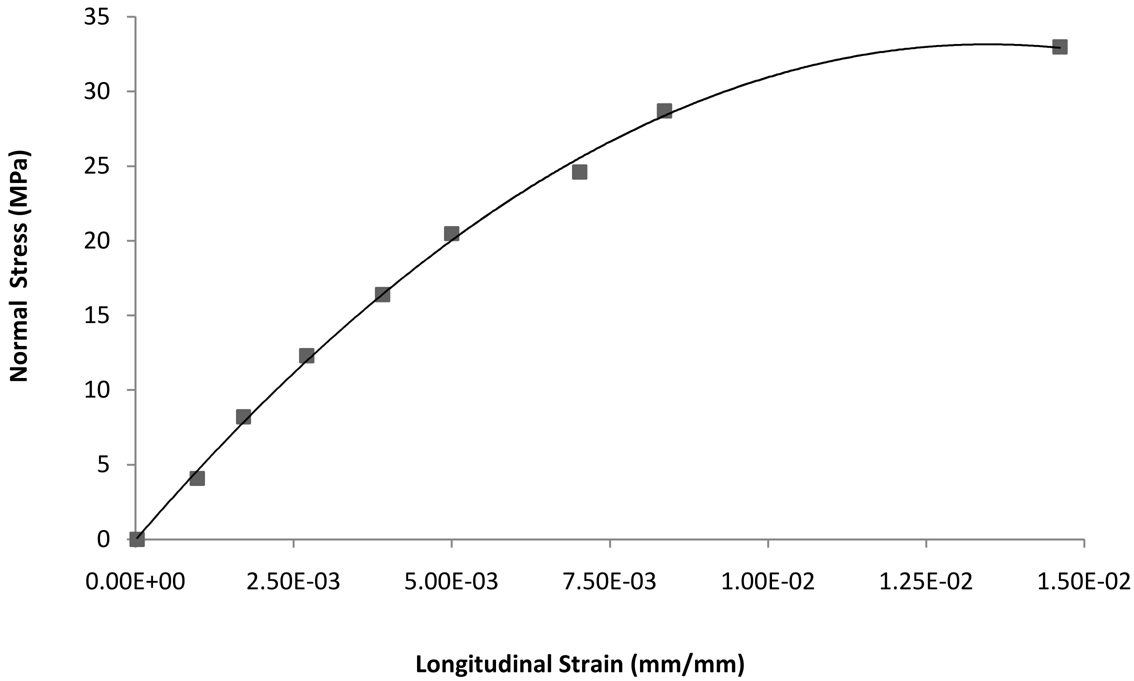

Figure 8: Sample #7 (Dry)

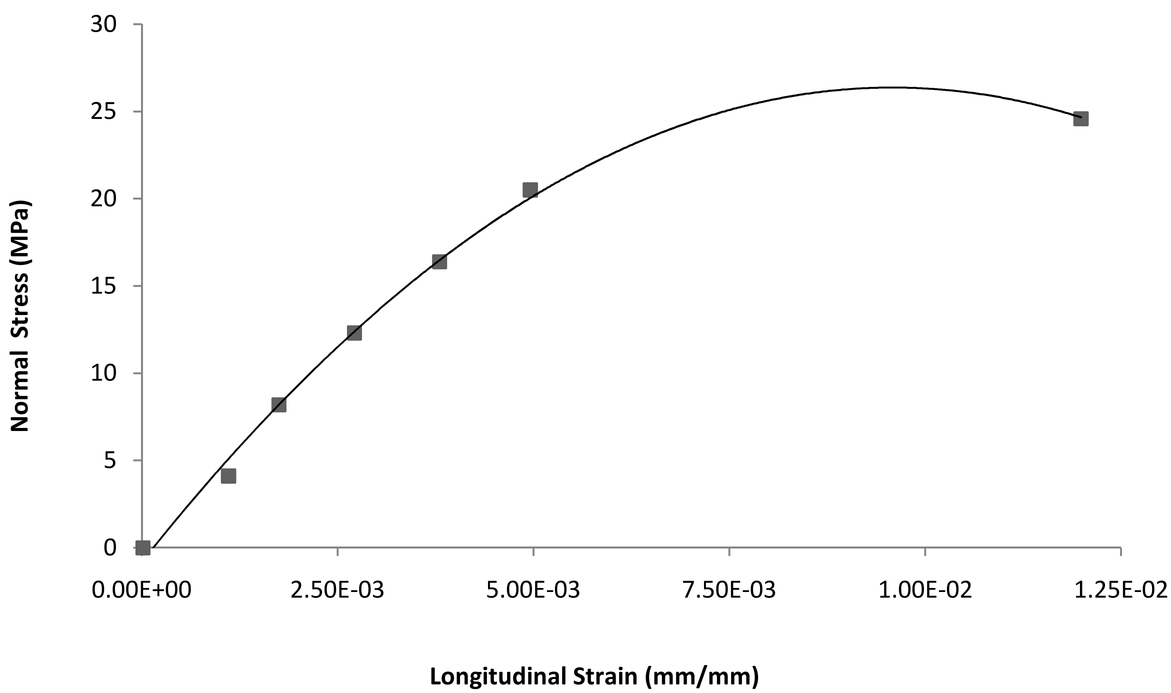

Figure 9: Sample #8 (Wet)

3. Discussion of Results

The moisture content (MC) of samples 2 and 4 seemed to have significant impact on certain essential mechanical properties. Samples 1-4 consisted of processed Bamboo and Cane (fiberboard), and perpendicular-grained samples 2 and 4 were subjected to extra moisture content (approx. 20-25% MC), whereas parallel-grained samples 1 and 3 were dry (disregarding ambient moisture). The wet samples 2 and 4 showed a drastic reduction in elastic modulus; a reduction over 75% was observed for both samples. Sample 2, compared to sample 1, proved to have a 78% reduction (96.02 MPa vs. 2441.42 MPa respectively), and similarly sample 4 compared to sample 3 had a 96% reduction (1485.94 MPa vs. 6971.33 MPa respectively). The raw Bamboo and Cane responded much less significantly to the moisture content. The moistened, node-free sample 6 had a less than 2% reduction in the elastic modulus over the dry, node-free sample number 5 (3733.28 MPa vs. 3791.99 MPa respectively). The nodal samples 7 and 8 indicated a 33% variation in the elastic modulus due to moisture content (2051.62 MPa vs. 3059.06 MPa respectively). The samples with additional moisture content thus had less of a tendency to resist deformation under compressive stress.

Compressive strength of the Bamboo and Cane samples also suffered due to added moisture content. Sample 1 (dry) had a compressive strength σ_s of 49.19 MPa, whereas sample 2's σ_s was recorded at 35.7 MPa, leaving a 27% reduction in the Bamboo and cane and Cane's strength due to excessive MC. Samples 3 and 4 had similar results, where the reduction in σ_s was over 20% (32.34 MPa vs. 25.7 MPa respectively). The raw samples showed similar but more defined results (as opposed to trend comparison in the elastic moduli). The reduction in strength due to MC for samples 5 and 6 proved to be nearly 40% (27.24 MPa vs. 16.4 MPa respectively) and 43% for samples 7 and 8 (32.98 MPa vs. 24.59 MPa respectively).

If Bamboo and Cane, subjected to moisture contents in excess of what was analyzed in this investigation, were to be tested, the assumption may be made that the mechanical properties of that Bamboo and Cane set would be adversely affected in a manner congruent with the aforementioned discussions. However, it has become evident from recent studies that Bamboo and Cane may serve well as a concrete reinforcement (like rebar), even when subjected to high moisture contents, contrary to previous assumptions [4].

4. Conclusion

Bamboo and Cane will continue to serve as prominent engineering materials in many Asian countries. The awareness of the effect of moisture content on Bamboo and Cane's mechanical properties and the understanding of Bamboo and Cane's limitations as structural support will save lives and help avoid property damage. New and innovative techniques to enhance the strength and resilience of Bamboo and Cane (even in the presence of excessive moisture) are well on their way into the twenty-first century. Research is being conducted on Bamboo and Cane fiber reinforced polyester composites and Bamboo and Cane/vinyl ester composites [5, 6, 7]. The results of this experimental investigation on the effect of moisture content on the mechanical properties of Bamboo and Cane will hopefully provide supplementary information to the research and development of safer and more effective utilization and implementation of Bamboo and Cane in engineering.

References

1. L. Xiaobo, "Physical, chemical, and mechanical properties of Bamboo and cane and Cane and its utilization potential for fiberboard manufacturing," Thesis. pp. 27-30
2. J. K. Roh and J. B. Ra, "Effect of moisture content and density on the mechanical properties of veneer-Bamboo and cane and Cane zephyr composites," Forest Products Journal. Article No. 10395
3. ASTM. "Standard Methods for Testing Small Clear Specimens of Timber," ASTM D143-94. West Conshohocken, PA. Forest Products Journal. 26(11): 51-56.
4. H. C. Lima, F. L. Willrich, N. P. Barbosa, M. A. Rosa, and B. S. Cunha, "Durability analysis of Bamboo and cane and Cane as concrete reinforcement," Materials and Structures, vol. 41, no. 5, pp. 981-989, 2008.
5. K. J. Wong, "Fracture characterization of short Bamboo and cane and Cane fiber reinforced polyester composites," ScienceDirect, vol. 31, no. 9, pp. 4147-4154, 2010.
6. H. Chen, M. Miao, and X. Ding, "Influence of moisture absorption on the interfacial strength of Bamboo and cane and Cane/vinyl ester composites," ScienceDirect, vol. 40, no. 12, pp. 2013-2019, 2009.
7. K. Okubo, T. Fujii, and Y. Yamamoto, "Development of Bamboo and cane and Cane-based polymer composites and their mechanical properties," ScienceDirect, vol.35, no. 3, pp. 377-383, 2002.
8. Acceptance Criteria For Structural Bamboo and cane and Cane. *AC162,* 2000. Whittier, CA. ICBO Evaluation Services, Inc. Pages 2-5.
9. Arce-Villalobos, Oscar. *Mechanical Properties of Bamboo and cane and Cane*. 10 Sept 2002. Accessed 18 Nov 2010. http://www.bambus.com/new/eng/reports/mechanical_properties/referat2.html>.
10. ASTM. *Standard Methods for Testing Small Clear Specimens of Timber.* ASTM D143-94. West Conshohocken, PA. Forest Products Journal. 26(11): 51-56.
11. Chudnoff, M. *Tropical Timbers of the World.* Agricultural Handbook, 1987. Washington DC: US Department of Agriculture. Pages 13–20.
12. Fracture Properties of Bamboo and cane and Cane. *Composites Part B: Engineering.* Volume 32, Issue 5, 2001, Pages 451-459.
13. Gerhards, C.C. *Effect of Moisture Content and Temperature on the Mechanical Properties of Wood: An Analysis of Immediate Effects.* Wood and Fiber. 14(1): 4-36.
14. Green, David. Winandy, Jerrold. Kretschmann, David. *Wood Handbook: Wood as an*

Engineering Material, 1999. Madison, WI: USDA Forest Service. Pages 4-1 – 4-45

15. Kretschmann, D.E., and Bendtsen, B.A. *Ultimate Tensile Stress and Modulus of Elasticity of Fast-grown Plantation Loblolly Pine Lumber*. Wood and Fiber Science, 1992. 24(2): 189-203.
16. Mallory, M.P., and Cramer, S. *Fracture Mechanics: A Tool for Predicting Wood Component Strength.* Forrest Products Journal, 1987. 37(7/8): 39-47.
17. Okhio, C. B., Waning, J., Mekonnen, Y. T., Journal of Selected Areas in Biomaterials, Cyberjournals, December 2010.