A Self-defined Index for Hygrothermal Performance-Oriented Development of Bamboo and Its Test Method

Zujian Huang¹,²,*, Yimin Sun¹,²,³

¹. School of Architecture, South China University of Technology, Guangzhou 510640, China;
². State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China;
³. Guangdong Research Center of Sustainable Architecture and Urban Design Engineering Technology, Guangzhou 510640, China

*huangzuj@scut.edu.cn

Abstract. In the manufacturing process of the mechanical performance-oriented bamboo products, the bulk density is often used as an important control index since it has significant correlation with the mechanical properties. However, the development of bamboo for building envelope is supposed to be hygrothermal performance-oriented, which may require a different control index. In this study, 6 typical bamboo products are selected as the research objects. Based on the material parameter requirements of the building envelope coupled heat and moisture process model, 6 test items for hygrothermal properties and 2 test items for basic properties, including the dry bulk density (ρ_d) and a self-defined ‘open porosity of liquid water (Φ_l)’, are carried out. Correlation analyses between the tested hygrothermal properties and the basic properties show that, macroscopically both moisture and heat transport properties show stronger correlation with Φ_l than that with ρ_d. Taking the correlation coefficient (r) and the statistical significance (sig) as indicators, the correlations between the hygrothermal properties and Φ_l are, respectively, 107.23%–140.00% and 1.44%–11.94% of that between the hygrothermal properties and ρ_d. The phenomenon proves that Φ_l is potential to be a better control index for the development of hygrothermal performance-oriented bamboo. Based on this, a method including 6 operation steps to test the Φ_l is introduced.

1. Introduction

Bamboo is a fast-growing plant, distributed in the low latitudes in Asia Pacific, America and Africa, and is widely used in the local traditional constructions. Nowadays, the promotion of ‘building with bamboo’ has multiple potentials such as the high-value utilization of the bamboo resource and sustainable development of the building industry. Under the background of industrialization of the bamboo forest resources, a variety of bamboo products have been developed, including the plybamboo (bamboo plywood), bamboo particle board, bamboo oriented strand board, bamboo laminated lumber, bamboo scrimber, etc. [1] which are used in the load-bearing structural elements such as beams and columns, as well as in the non-load-bearing building envelope elements such as the walls and floors, etc.

The mechanical strength of certain materials largely depends on the solid part, which results in a significant correlation between the mechanical properties and the bulk density. Therefore, for a long period, bulk density is commonly used as a manufacturing indicator for the control and strength
prediction of those mechanical performance-oriented building materials, including the wood/bamboo-based panels [2]. Other than this, those materials used in building envelope is oriented by hygrothermal performance. As a fundamental work, the material tests on bamboo for different property parameters have been widely carried out.

1.1. Overview of the bamboo properties studies
The material parameters have important impacts on the performance of building envelope, such as the heat and moisture flows through the exterior wall, the indoor environment and the building energy consumption [4]. Previous studies on hygrothermal properties of bamboo mostly focus on raw bamboo, measuring the specific heat capacity, thermal conductivity, sorption isotherm and water vapor transmission resistance factors, etc. [4]

The Moso bamboo (*Phyllostachys pubescens*), a common bamboo species, is often used as the test object in these studies. The tests on the specific heat capacity of Moso bamboo result in various values from 1.7 to 2.3 kJ/(kg·K) [4] at 40°C by the differential scanning calorimetry method. The raw bamboo is proved to be significantly non-homogenous in terms of the thermal properties in the longitudinal, radial and tangential directions. The thermal diffusivity of Moso bamboo in longitudinal direction, as well as the thermal conductivity of Moso laminated board and bamboo veneer board have also been measured [5].

The sorption isotherm of bamboo blocks, bamboo powder, parenchyma cells and chemically macerated fibers are tested by different scholars, and the comparison results show similar laws that the hygroscopic capability are, in descending order, the parenchyma cells, the bamboo fibers, the bamboo powder and the bamboo blocks [6]. Different values have been measured from the samples taken from different parts of a bamboo wall. For the liquid water-related properties, the capillary saturated moisture contents are 572, 479 and 385 kg/m³, respectively, for the exterior, middle and interior parts of the bamboo culm wall, and the corresponding liquid water absorption coefficients are 0.014, 0.008 and 0.0019 kg/(m²·s⁰.⁵) [4]. The dry cup test on the water vapor diffusion resistance factor shows the values in the radial and tangential directions range from 30 to 57 [4].

Bamboo wall, as the main part for industrial utilization, has been studied by scholars from disciplines of botany, material science and bamboo-based panels production, etc. for the microstructure, surface morphology, density distribution, pore structure, cracking characteristics, etc. [7,8] The density distribution observation by computer tomography scanning shows that the bulk density of Moso bamboo nodes and internodes is in the range 600-800 kg/m³ [4]. When taking the bamboo-based panels into account, the bulk density of bamboo products is from 650 to 1290 kg/m³, which is substantially higher than timber products that are generally in the range 400-800 kg/m³. An observation on the pore structure of bamboo culms by backscattered electron scanning and computerized tomography shows that the average porosity of Moso bamboo internode is between 44.9% and 63.4% [4].

1.2. Hypothesis and motivation of this study
In the heat and moisture process model of building envelope, a variety of parameters that characterize the materials' properties are involved, which can generally be classified as the basic properties, hygric properties and thermal properties. The hygric and thermal properties can be further divided into parameters characterizing the storage and transfer properties. The tests on hygrothermal properties is extremely slow, which take months or even years to obtain the complete results. Therefore, finding a basic physical property indicator that is easy to obtain and can accurately predict those hygrothermal properties is of importance [3].

Basic properties can be categorized into two groups: the skeletal features that characterize the solid sections and the pore features that characterize the internal space. For most physical properties related to the heat and moisture process, except the thermal storage property (specific heat capacity) that is depending on the chemical composition, the storage locations and transport channels of the moisture (including liquid and gaseous water) as well as a part of the heat transport occurs in the internal space. Therefore, it can be considered that using bulk density to predict the hygric and thermal properties would have inevitable limitations.
As a plant fiber-based organic material, bamboo has a complex pore structure, so it is not feasible to be described on a microscopic level. ‘Porosity’, as an index to describe the ratio of the internal space to the whole volume, is relatively easy to obtain. However, the pores within bamboo are in two statues, namely the open pores and closed pores, the latter of which is isolated from the outside, so that moisture absorption and desorption processes hardly occur there. However, in general testing process, the obtained ‘porosity’ includes both the open pores and closed pores.

‘Open porosity’ is used to describe the part of space where moisture storage and transport can occur. However, the results measured by general vacuum saturation experiments include both liquid water and gaseous water in total amount, which cannot be distinguished. Although the latter has a smaller mass proportion, there is a difference in the initial moisture content, ie, the gaseous water content, between various bamboo samples, which is normally in the range 8%-15% [9,10]. This causes errors to the test results and prevents the test method from forming a uniform standard.

The aim of this study is to propose a method to test the volume of the open pores and exclude the interference of the initial gaseous water content, and verify its possibility to be a new index for the hygrothermal performance-oriented development of bamboo.

2. Material and method

2.1. Test object
Based on the investigation of literature, material manufacturers and the classification of representative bamboo products, 6 kinds of test samples are selected, including the flattened bamboo panel (FB), plybamboo (BMB), bamboo particleboard (BPB), bamboo oriented strand board (BOSB), bamboo laminated lumber (BSB) and bamboo scrimber (BFB). Among these samples, FB represents the raw bamboo that is flattened without applying glue, and the rest are bamboo-based panels. (figure1)

![Figure 1. Photos of the material samples.](image)

2.2 Test method

2.2.1 Hygrothermal properties. To obtain the necessary hygrothermal properties, six test items are carried out, including the sorption test for the moisture storage properties; capillary absorption test,
water vapor transmission test and drying test for the moisture transport properties; thermal analysis for the heat storage properties, and thermal conductivity test for the heat transport properties. (table 1)

**Table 1.** Hygrothermal properties test items and the operation methods.

| Category          | Test items                                | Target value                                      | Reference of the operation methods |
|-------------------|-------------------------------------------|---------------------------------------------------|------------------------------------|
| Hygric properties | 1. Sorption test                           | 20°C isothermal adsorption and desorption curve   | The ISO standard: ISO 12571:2012, and the American standard: ASTM-04a(2016) [11,12] |
|                   | 2. Capillary absorption test               | Water absorption coefficient; Capillary saturated moisture content | The ISO standard: ISO 15148:2002(E) [13] |
|                   | 3. Water vapor transmission test           | Water vapor transfer coefficient                   | The ISO standard: ISO 12572:2001(E), and the American standard: ASTM E 96/E 96M-2005 [14,15], in which the water vapor transfer coefficient of still air $\delta_{\text{air}}$ [kg/(m·s·Pa)] at a certain temperature $T$ and pressure $p$ refers from [16] |
|                   | 4. Drying test                             | Drying curve; Drying rate curve                   | The test method from Fraunhofer IBP (accredited by the DIN EN ISO/IEC 17025) |
| Thermal properties| 5. Thermal analysis                        | Specific heat capacity                             | The ISO standard: ISO 11357-4-2005 [17] |
|                   | 6. Thermal conductivity test              | Thermal conductivity                              | The ISO standard: ISO 8302-1991 [18] |

2.2.2 *Open porosity of liquid water.* The study proposes a method for testing the self-defined index, called the ‘open porosity of liquid water’, for bamboo, which mainly includes the following steps: specimen preparing, specimen drying, dry specimen weighing, specimen vacuum saturating (air pumping, water injecting, and water immersing), vacuum saturated specimen weighing, and the data processing. (figure 2)

![Figure 2](imageURL)

**Figure 2.** The test flow chart of the ‘open porosity of liquid water.'
3. Result analysis

3.1 Test results
The test results include the dry bulk density ($\rho_d$) and open porosity of liquid water ($\Phi_l$) that characterize the basic properties of the test samples; the 20°C isothermal adsorption and desorption curve and the capillary saturated moisture content, water absorption coefficient, water vapor transfer coefficient and the drying rate curve that characterize the hygric properties; the specific heat capacity, 24h thermal storage coefficient and the thermal conductivity that characterize the thermal properties. (table 2, 3)

Table 2. Test results of the basic properties.

| Test items                  | Target value                                      | Abbreviation | Test and calculation results |
|-----------------------------|---------------------------------------------------|--------------|----------------------------|
| 1. Bulk density test        | Dry bulk density $\rho_d$ [kg/m$^3$]               |              | FB  666.38 776.21 623.32 895.02 563.81 1108.77 |
| 2. Open porosity test       | Open porosity of liquid water $\Phi_l$ [-]         |              | BF  52.24 49.58 63.17 42.32 53.97 17.36 |

Table 3. Test results of the hygrothermal properties.

| Test items                  | Target value                                      | Abbreviation | Test and calculation results |
|-----------------------------|---------------------------------------------------|--------------|----------------------------|
| 1. Sorption test            | 20°C isothermal sorption curve $w_{RH=50%}$ [kg/m$^3$] |              | FB  31.07 39.20 36.89 46.07 30.44 28.17 |
| 2 Capillary absorption test | Water absorption coefficient $A_{cap}$ [E$^{04}$ kg/(m$^2$·s$^{0.5}$)] |              | BB  74.06 38.71 447.78 59.15 78.74 8.73 |
|                            | Capillary saturated moisture content $w_{cap}$ [kg/m$^3$] |              | BS  326.41 221.44 521.95 342.68 317.21 165.93 |
| 3. Water vapor transmission test | Water vapor transfer coefficient $\delta_{RH=50%}$ [E$^{13}$ kg/(m·s·Pa)] |              | BS  27.81 19.28 93.28 7.23 27.99 4.37 |
| 4. Drying test              | Drying rate ($T$=23°C, $RH=50\%$) $U_{d12%-65%}$ [E$^{07}$ kg/(m$^2$·s)] |              | BS  135.15 18.32 126.46 38.01 60.20 10.14 |
| 5. Thermal analysis         | Specific heat capacity $c$ [J/(kg·K)]              |              | BS  1796 2020 1760 1663 1960 1550 |
|                            | 24h thermal storage coefficient $S_{24h}$ [W/(m$^2$·K)] |              | BS  5.93 8.57 4.87 6.94 6.63 8.68 |
| 6. Thermal conductivity test | Thermal conductivity $\lambda$ [W/(m·K)]           |              | BS  0.1088 0.1733 0.0801 0.1197 0.1475 0.1625 |

3.2. Correlation analysis
Correlation analyses of the test results are carried out between the basic properties ($\rho_d$, $\Phi_l$) and the hygrothermal properties. Results show that the correlation between the $\Phi_l$ and the hygrothermal properties is stronger than that between the $\rho_d$ and the hygrothermal properties, which proves that the $\Phi_l$ would be a better indicator to predict the hygrothermal properties of bamboo. The comparison results could be expressed as the ratio of the correlation coefficient ($r$) and the statistical significance...
of the two groups. The correlation strength is proportional to the $r$ value and inversely proportional to the $\text{sig}$ value.

The correlation between the hygrothermal properties with $\Phi_l$ is, respectively, 107%-140% ($r$) and 1.4%-11.9% ($\text{sig}$), of the correlation between the hygrothermal properties and $\rho_d$. Compared with the dry bulk density, the correlation strength of the open porosity of liquid water has been significantly improved. (table 4)

| Items | Correlation index | $w_{\text{cap}}$ | $\delta$ | $A_{\text{cap}}$ | $U$ | $c$ | $\lambda$ |
|-------|------------------|-----------------|---------|-----------------|-----|-----|--------|
| $\rho_d$ | correlation coefficient ($r$) | 0.6740 | 0.6745 | 0.9002 | 0.7891 | 0.4857 | -0.5925 |
| | statistical significance ($\text{sig}$) | 0.002159 | 1.4681E-7 | 3.5973E-7 | 1.0776E-8 | 0.328723 | 0.009565 |
| $\Phi_l$ | correlation coefficient ($r$) | -0.5361 | -0.6014 | -0.8249 | -0.7359 | -0.6000 | 0.4232 |
| | statistical significance ($\text{sig}$) | 0.021829 | 0.000006 | 0.000025 | 3.1545E-7 | 0.0208000 | 0.080111 |
| $r-\Phi_l/\rho_d$ | correlation coefficient ($r$) | 125.72% | 112.15% | 109.13% | 107.23% | - | 140.00% |
| | statistical significance ($\text{sig}$) | 9.89% | 2.45% | 1.44% | 3.42% | - | 11.94% |
| number of samples (N) | 18 | 48 | 18 | 36 | - | 18 |

Note: since the $c$ depends on the chemical composition of the material, it is excluded from the correlation analysis.

4. Conclusion

1) The ‘open porosity of liquid water ($\Phi_l$)’ proposed in this study is potential to be a basic property control index for the hygrothermal performance-oriented development of bamboo. As a simplified indicator, $\Phi_l$ is easy to measure, and costs much shorter time than the testing of hygrothermal properties. For the application of bamboo in building envelope, due to the significant correlation between the $\Phi_l$ and the hygrothermal properties, it can provide an efficient and accurate prediction for the selection of material products in practical engineering. For the production of bamboo products, $\Phi_l$ is potential to be a hygrothermal performance-oriented production control index.

2) The test procedure for $\Phi_l$.

A method proposed in this study for testing the $\Phi_l$ of bamboo includes the following steps: 1) Specimen preparing: make a plurality of specimens (suggested to be 6 pieces) of standard size; 2) Specimen drying: dry the specimens from the step 1 to obtain dry specimen; 3) Dry specimen weighing: weigh the specimens and record the weight of the dry specimens; 4) Specimen vacuum saturating: place the dry specimens into the sink in the vacuum chamber, close the door of the chamber, pump out the air from the chamber and the specimen, then start inject water into the sink and keep the specimens immersed in water to obtain the vacuum saturated specimens; 5) Vacuum saturated specimen weighing: weigh the specimens and record the weight of the vacuum saturated specimens; 6) Data processing.

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