Equilibrium Moisture Content and Sorption Isotherms determination for different conditions of relative humidity and temperature in the bamboo guadua Angustifolia Kunth

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Abstract. The physical and mechanical properties of bamboo guadua \textit{Angustifolia Kunth} are decisive parameters for accurate structural design in this material. It is also necessary to take into account all the variables that affect the mechanical properties of stiffness and strength of bamboo, including the moisture content of the material. Certainly, this measure depends on where the building is carried out, because the temperature and relative humidity have a direct effect on the moisture content of the material under study. Given the diversity of weathers of Colombia, it has established a range of temperature and relative humidity, which can describe these environmental conditions. With the method developed, it was possible to obtain some moisture content measurements from the material exposed to those conditions, in a certain period of time. Subsequently, with these values, sorption isotherms from bamboo guadua \textit{Angustifolia Kunth} were calculated. The procedure was carried out using representative samples including knot or without knot, and from different parts of bamboo in height. The sample’s measures were 10 cm long, 2 cm wide and the thickness of each section itself. These samples were brought to a constant climate chamber with the ability to simulate specific conditions of temperature and relative humidity. At the time that each of the samples were stabilized with changes less than 0.01gr in weight, it was determined that they had reached the equilibrium moisture content with environment exposed; with the data obtained from each classification the average moisture content of each test was calculated, after that, with this data the construction of sorption isotherms from bamboo guadua \textit{Angustifolia Kunth} was initiated with the first points.

Introduction

The use of unconventional materials in construction has taken great strength in recent years; it has passed from using conventional materials such as concrete and steel, to look different functional alternatives in the field of construction. One material that has attracted most attention in Colombia is the bamboo guadua \textit{Angustifolia Kunth}, because it has physical and mechanical properties beneficial for the construction of structures and it generates minimal environmental impact, dealing to be listed as a sustainable material [2].

In the Colombian seismic-resistant building code from 2010 (NSR 10) [9] the bamboo \textit{Angustifolia Kunth} was included as one of the main structural materials, which can be used in structures up to two stories high. In that document, different parameters have been specified for the design of structures in bamboo; however, these data do not correspond specifically to research conducted with bamboo, but in
some cases correspond to data from structural timber, because on that material has been made more research in the field of structural engineering.

It has been found that in despite of the similarities between these two materials, physical, mechanical and structural behavior is not the same, so it is necessary to extend the knowledge in data that corresponds specifically to the bamboo, in order to make designs and constructions much more adjusted to the actual behavior that can have this material. Within those parameters is the equilibrium moisture content of the bamboo guadua *Angustifolia Kunth*, which corresponds to the moisture content reached when the material is exposed during a period of time to specific environmental conditions. The moisture content of the bamboo, as in wood, affects its physical and mechanical properties since the amount of water contained into the material modifies the stiffness and strength [4]. Given that Colombia is a country with a great diversity of weathers (Different conditions of relative humidity and temperature), and moreover, that the bamboo for being a hygroscopic material has the ability to absorb moisture from the environment, it is necessary to determine how varying the moisture content of the material, when it is exposed to different conditions of relative humidity and temperature. Therefore, you must know sorption isotherms of the material, in order to determine the moisture content to be presented in different cities and may determine how to vary the stiffness and strength due to the effect of moisture content.

According to the NSR 10, all the bamboo guadua designated for the construction of structures should be dried to a moisture content (MC %), as close as possible to the equilibrium moisture content (EMC) in the environment of the area where it will be installed. The standard also states that to identify the equilibrium moisture content of bamboo, the table G.D.1 in page G-151 should be used [9], which shows sorption isotherms (Figure 1), however, it has noted that the values presented in Figure 1 correspond specifically to values of EMC in timber, as previous research has found that these moisture contents differ considerably with the bamboo [5]. By taking different values of EMC in the material, incorrect settings can be made when the strength and stiffness of bamboo are changed due to the involvement of MC, driving away structural designs from the real behavior of the structure, because the increase in the moisture content of bamboo produces a decrease in the strength and the stiffness. Table 1 shows the effect of moisture content on this material in the different stresses to which it is subjected a structure, for example when the equilibrium moisture content is equal to 18%, the bending stress is affected by multiplying the allowable stress by 0.74.

Figure 1. Sorption isotherms (for timber and bamboo) proposed by the NSR 10.

![Sorption isotherms](image)

Source: NSR 10 Table G.D.1 sorption isotherms, translated into English
Table 1. Modification factors by moisture content proposed in the NSR 10.

<table>
<thead>
<tr>
<th>stress</th>
<th>CH ≤ 12%</th>
<th>CH ≤ 13%</th>
<th>CH ≤ 14%</th>
<th>CH ≤ 15%</th>
<th>CH ≤ 16%</th>
<th>CH ≤ 17%</th>
<th>CH ≤ 18%</th>
<th>CH ≤ 19%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>1,0</td>
<td>0,96</td>
<td>0,91</td>
<td>0,87</td>
<td>0,83</td>
<td>0,79</td>
<td>0,74</td>
<td>0,70</td>
</tr>
<tr>
<td>Traction</td>
<td>1,0</td>
<td>0,97</td>
<td>0,94</td>
<td>0,91</td>
<td>0,89</td>
<td>0,86</td>
<td>0,83</td>
<td>0,80</td>
</tr>
<tr>
<td>Fc</td>
<td>1,0</td>
<td>0,96</td>
<td>0,91</td>
<td>0,87</td>
<td>0,83</td>
<td>0,79</td>
<td>0,74</td>
<td>0,70</td>
</tr>
<tr>
<td>Fp</td>
<td>1,0</td>
<td>0,97</td>
<td>0,94</td>
<td>0,91</td>
<td>0,89</td>
<td>0,86</td>
<td>0,83</td>
<td>0,80</td>
</tr>
<tr>
<td>Shear</td>
<td>1,0</td>
<td>0,97</td>
<td>0,94</td>
<td>0,91</td>
<td>0,89</td>
<td>0,86</td>
<td>0,83</td>
<td>0,80</td>
</tr>
<tr>
<td>modulus of elasticity</td>
<td>1,0</td>
<td>0,99</td>
<td>0,97</td>
<td>0,96</td>
<td>0,94</td>
<td>0,91</td>
<td>0,90</td>
<td></td>
</tr>
</tbody>
</table>

E 0.5
E 0.05
E min

Source: NSR 10 Table G.12.7-5.

Given the need of obtaining real values specifically for bamboo guadua *Angustifolia Kunth*, the appropriate methodology for the construction of sorption isotherms was determined, and experimentation began resulting in the first points to identify the equilibrium moisture content of the material for different conditions of relative humidity and temperature.

**Materials and Methods**

**Materials.** For the experimentation, mature bamboo guadua *Angustifolia Kunth* was used, with four years average aged, with each one of specifications given in NTC 5301 which indicates the preservation and drying of the culm of bamboo guadua *Angustifolia Kunth* [6]. Specimens were used with 10 cm height, 2 cm width and thickness of each section itself. The bamboo has sections in height with different features, so for this research the most used parts in construction were used (Bottom, middle and upper part), which are from ground level to about 20 meters high; Distilled water is also used with PH 6-8; a marker for the identification of specimens; latex gloves for the handling of the specimens; and a brush to remove particles outside the culm.

**Equipment.** The experimental phase of this project was taken with a constant climate chamber PPH 110 (Memmert) which simulates conditions of relative humidity and temperature controlled a scale with 0.001g accuracy, and an oven to carry out the drying of the specimens.

**Methodology.** The developed methodology was established on the basis of previous studies that are related to this research, like the ones made by Jorge Augusto Montoya in Colombia [3] to determine the sorption isotherms of bamboo species *Phyllostachys Pubescens Mazel*, plus another study performed in Argentina in UNNE University [8], which had as its objective the construction of sorption isotherms for wood. However, the research with most impact in this methodology was made in Colombia by Andrés Garay Tangarife [1] which was aimed at creating an applicable methodology for the experimental phase in the construction of sorption isotherms of bamboo guadua *Angustifolia Kunth*.

Thus, it was established that for the experimental phase of this project 12 samples would be used for each part of the bamboo (Bottom, middle and upper part), of which 6 samples with knot and other 6 samples knotless were taken. It was determined that these specimens would be exposed to relative humidities between 35% and 90% (labeled from A through F) and given temperatures between 10 ° C and 40 ° C, typical ranges for different weather conditions presented in Colombia. For the first experiment the combination of 90% relative humidity and 40 ° C temperature was carried out in order
to establish the most critical conditions for constant climate chamber. It is worth noting that other combinations will be used for the following research on this topic. The identification of these specimens was performed according to the Table 2.

Table 2. Sample identification based on the different variables analyzed.

<table>
<thead>
<tr>
<th>Relative humidity in percentage</th>
<th>Corresponding identification</th>
<th>Temperature</th>
<th>Corresponding identification</th>
<th>Part of bamboo in height</th>
<th>Corresponding identification</th>
<th>Consecutive number</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>A</td>
<td>10°C</td>
<td>T1</td>
<td>Bottom part with knot</td>
<td>C</td>
<td>1</td>
</tr>
<tr>
<td>50%</td>
<td>B</td>
<td>20°C</td>
<td>T2</td>
<td>Bottom part without knot</td>
<td>C-SN</td>
<td>2</td>
</tr>
<tr>
<td>60%</td>
<td>C</td>
<td>30°C</td>
<td>T3</td>
<td>Middle part with knot</td>
<td>B</td>
<td>3</td>
</tr>
<tr>
<td>70%</td>
<td>D</td>
<td>40°C</td>
<td>T4</td>
<td>Middle part without knot</td>
<td>B-SN</td>
<td>4</td>
</tr>
<tr>
<td>80%</td>
<td>E</td>
<td></td>
<td></td>
<td>Upper part with knot</td>
<td>SB</td>
<td>5</td>
</tr>
<tr>
<td>90%</td>
<td>F</td>
<td></td>
<td></td>
<td>Upper part without knot</td>
<td>SB-SN</td>
<td>6</td>
</tr>
</tbody>
</table>

Own source

The 36 samples that were used in each test were cleaned and removed particles that may detach during the procedure in order to avoid mistakes in the measure. Then, the initial weighing was carried out for each specimen or sample used in this phase of experimentation. Following the procedure, the samples were introduced into the machine that simulates conditions of temperature and humidity controlled. Subsequently, the machine is programmed for the desired temperature and relative humidity. Daily weighing was performed (in days) to controlling the absorption of each sample, a representative sample of each group with the same characteristics was taking. When the analyzed sample had a lower variation in weight 0.01g overnight, it could determine the weights had stabilized and that the samples used had reached equilibrium moisture for the environmental conditions previously established. To determine the moisture values was carried out the procedure explained in the Colombian Technical Standard NTC 5525 [7], which stipulates the test methods to determine the physical and mechanical properties of bamboo guadua Angustifolia Kunth.

Results and discussion

First experiment. The test was conducted with conditions of 90% of relative humidity and 40 °C of temperature. In figure 2, the humidity change of each specimen with respect to days these were maintained in constant climate chamber, while reached the equilibrium moisture content is observed. It can be seen that the specimen has a significant loss of moisture from the first day until the ninth day, from this time, the specimens stop to lose moisture dramatically, until it can stabilize their weight slowly.

Likewise, it was established that the Guadua Agustifolia Kunth, must be brought to the place where they will perform the construction, at least 2-3 weeks before starting the work, and as a result, the material will reach the equilibrium moisture content with the specific environmental conditions of the place where it will remain, that after making the drying process, according to the procedure defined in the NTC 5301 [6].
In Figure 3 it can be seen the equilibrium moisture content in each of the specimens tested in the first experiment. This data shows that between specimens with knot and knotless, there is an insignificant variation for both specimens subjected to the same conditions of temperature and relative humidity.

For the combination of 90% humidity and 40 °C temperature, it is obtained that the average of equilibrium moisture content of bamboo guadua *Angustifolia Kunth* is 22.95%, value that differs from the indicated by sorption isotherms that the seismic resistant Colombian building code proposed in the attachment G.D [9], since as presented in Figure 1, to these same conditions, the equilibrium moisture content would be about 19%, four points below the experimental result. Thus it is evident that sorption isotherms of timber does not apply for the guadua *Angustifolia Kunth*, in addition, it was also found
that the table for the correction factor for moisture content, does not provide values for moisture contents above 19%.

**Subsequent experiments.** To continue building the sorption isotherm for 40°C temperature, a variation of the relative humidity from 80% to 60% was performed.

Following the same procedure applied for the first group of samples, these were introduced to the constant climate chamber, with the difference that thanks to the previous experiment, it was planned that in the first week is given an important weight variation, for this reason, since the second week, the daily weighing of samples was performed until the weight changes overnight were less than 0.01 g.

The values of equilibrium moisture content of each sample to 40°C and relative humidity of 80%, 70% and 60%, are presented in Figure 4, 5 and 6 respectively.

**Figure 4.** Equilibrium moisture content variation in culms with knot and without knot, for temperature of 40°C and relative humidity of 80%.

For the second combination with 80% of relative humidity and 40°C of temperature, an equilibrium moisture content of 17.4% was obtained for the Guadua *Angustifolia Kunth*. This value also varies with respect to the data given in the seismic-resistant Colombian building code [9], since according to the sorption isotherms of the Figure 1, the equilibrium moisture content proposed for these conditions is approximately 15%, it means 2.4 points lower than the obtained data experimentally. These data allow us to identify the variation in the correction factor for allowable stresses by moisture content. For example, if an approximate equilibrium moisture content obtained experimentally is 17%, a significant difference can be seen, since the correction factor for compression parallel to the fiber for a 15% of moisture content is 0.87, while for 17% of moisture content the corresponding coefficient is 0.79. Overall, the importance of having specific data for bamboo Guadua *Angustifolia Kunth*, in order to avoid mistakes in the calculation of allowable stresses needed for the structural design is evident.
Figure 5. Equilibrium moisture content variation in culms with knot and without knot, for temperature of 40 °C and relative humidity of 70%.

Figure 6. Equilibrium moisture content variation in culms with knot and without knot, for temperature of 40 °C and relative humidity of 60%.

Sorption isotherms. In Figure 7, results obtained from the experiments described above are shown. This isotherm shows the equilibrium moisture content of bamboo guadua *Angustifolia Kunth* for the analyzed environmental conditions (temperature 40 °C and relative humidities from 60% to 90%).
Conclusions
Sorption isotherms of timber are not applicable for the bamboo guadua *Angustifolia Kunth*, since these materials absorb moisture from the environment in which they are located in very different ways.

Further research is needed regarding correction factors in allowable stresses for moisture content due to the equilibrium moisture content of bamboo *Angustifolia Kunth* exceeds 19%, under conditions of high relative humidity and low temperatures.

When a structure of bamboo is going to be built, it is necessary that the material used in construction is located in the site, at least three weeks before starting the work, in order that it may reach the EMC with the environment which is going to be exposed.

The variation in the EMC of bamboo, substantially affects the correction factors in strength of the material, as for example to the value of 80% in relative humidity and environmental temperature of 40° C, the correction factors in strength varies by 8% compared to the factor previously found.

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