

# Magnetic Suspension Balance for Measurement of Sorption Isotherm of Tectona Grandis Wood Species (Building Material) In The Republic of Benin

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## ABSTRACT

Wood, when used as engineering and building material, requires a perfect understanding of its heat and mass transfer properties. The device presented in this work is used for establishing sorption isotherms curve of Teak (*Tectona grandis*) from adsorption/desorption cycles. The experimental set up is built around a magnetic suspension balance, which is able to achieve accurate mass measurements over a wide range of temperature and relative humidity. Sorption isotherms of teak have been experimentally found at 50°C by using a moist air generator over a range of relative humidity from 0% up to 95 %. The experimental data have been fitted by a GAB(Guggenheim-Anderson-de Boer) model. This model enables the representation of whole sorption isotherms with the Mean Absolute Percentage Deviation (MAPD) about 3.8% in adsorption and 1.8 % in desorption for teak wood and a better estimation of the equilibrium moisture content corresponding to monolayer saturation. The hydrothermal properties results obtained in this study are suitable for a proper use of teak wood in construction or for modelling purposes.

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## Introduction

One of the main objectives of building is to protect occupants from climate excesses (hot, cold) by creating satisfactory microclimatic conditions that are favorable to the performance of various activities [1]. However, in developing countries such as Benin, building materials are often expensive, especially when most of the materials have to be imported. On the other hand, the use of expensive and inappropriate materials is improper in the tropical regions. This situation obliges people to resort to locally cheap and widely available materials such as timber. Indeed, timber is available locally throughout every country in Africa and has always been widely used as a building material for temporary and permanent buildings. Wood has the advantages of relative tooling costs compared to those for competitive materials, a high strength to weight ratio, an excellent insulation and unique aesthetic properties [2]. Teak plantations in Benin currently cover almost 50000 ha. The species has been planted in the country for more than 50 years and is considerable socio-economic importance because it offers employment opportunities and provides foreign currency. Private plantations in southern Benin have been established at increasing rate in the last thirty years [3]. Wood being a hygroscopic material, its various physical properties such as mass, dimensions and density as well as its mechanical properties is affected by its moisture content [4]. That is why moisture movement is of great interest in wood processing and uses. Thus, the investigation of wood adsorption and desorption is very useful in understanding

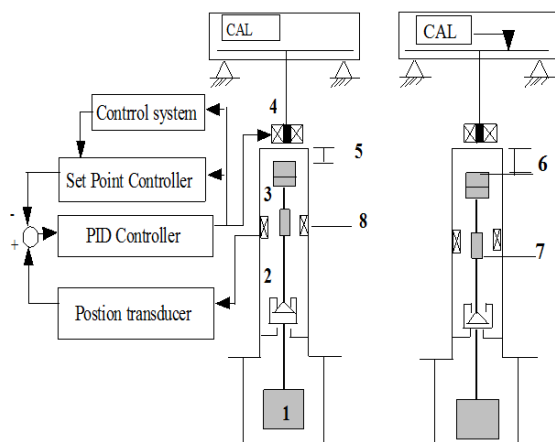
the effect of environmental conditions on the moist storage of building materials. Moreover, most buildings absorb water vapor from the environment until equilibrium conditions are achieved. This manner can be described by isotherm sorption curves over a humidity range between 0 and 95% relative humidity [5]. Many authors have published results about sorption isotherms of various products [6]-[7]-[8] but very little information is available about sorption isotherms of tropical woods. That is why this work intends to investigate the water adsorption and desorption isotherms of teak wood used as building material. Results are presented at the end of this paper for teak samples at 50°C for stepwise changes of relative humidity in the range 0% to 95%. A gravimetric method for small specimens that measures the sorption isotherm of teak wood species is also described.

## Experimental

### Magnetic suspension balance

A schematic representation of the device used is depicted in Fig 1. The balance and the electromagnet are completely disconnected from the measuring cell in order to avoid disturbance that may be generated by high temperature and pressure. The balance and the upper part of electromagnet are in an ambient environment while the lower part of the electromagnet is in the measuring chamber and is at the experimental temperature. Two different vertical positions of the suspension magnet can be chosen, which correspond to two different measuring positions: the zero point (6) which corresponds

to an unloaded balance, allows a tarring and calibration of the balance at any time while at the measuring point (5), the sample is lifted up and its weight is taken.



**Figure1:** Schematic representation of the Magnetic Suspension Balance. 1, sample; 2, measuring load decoupling; 3, permanent magnet; 4, electromagnet; 5, measuring point; 6, zero point; 7, sensor core; 8, sensor coil

#### Temperature and relative humidity control

The temperature sensor for measuring the actual temperature was calibrated. Water temperature is controlled within  $0.01^{\circ}\text{C}$ . The stability of the air conditions was tested over several days and monitored using a Pt1000 temperature sensor. The standard deviation of air temperature is equal to  $\pm 0.05^{\circ}\text{C}$ . During the test presented here, the temperature was set at  $50^{\circ}\text{C}$ .

The relative humidity was controlled by mixing dry and saturated air with two mass flow meters. To obtain saturated air, a double-layered saturator chamber, 110/180mm diameter, 835mm high, was also designed and built using stainless steel. The input of dry air is divided into two flows, each one being measured and controlled. The saturated air and dry air flows are then mixed into a test chamber [9]-[10].

#### Computer control

A PC was used to control all the elements of the experimental device in Fig. 2 (mass flow regulators and cryothermostat) and record the experimental data (temperature; relative humidity) via a data acquisition device (Hewlett-Packard HP 34970A).



**Figure 2:** Pictures of experimental mechanism (a) in position of measurement (b). 1: mass flow controllers; 2: Saturator; 3: Balance; 4: sample; 5: Double-walled tubes system

The sample mass is also recorded by the PC, directly from the electronic balance. The software, developed in Visual Basic, was also used to control the position of the magnetic coupling in order to avoid the balance shift by tarring at regular time intervals.

#### Sample preparation

The samples were taken from teak (*Tectona grandis*) species, a tropical wood species commonly found in southern Benin. The specimens used to determine the sorption isotherms were very fine teak wood cut with a microtome blade to obtain samples on each board with dimensions approximately  $20 \times 20 \text{ mm}$ . The sample used here is a 1-mm-thick section of teak wood, either in longitudinal or tangential direction. The lateral faces of the sample were insulated by applying two coats of an epoxy resin to avoid penetration and leakage of water vapour at the lateral faces during measurements [11] (Figure. 3). We have repeated each experiment on each specimen for confirmation. Thus, five experiments have been done on three sample teak species in tangential and longitudinal direction. Comstock and Côté[12] had used two or more specimens and average values were presented. Kouchadé[13] had determined the mass diffusion coefficients of African tropical woods using indirect method from electrical resistant measurements in unsteady state with thickness equal to 5mm reported according to radial and tangential directions in desorption and adsorption phase. He had used two to five specimens by species and orthotropic direction and average value is recorded. It is important to note that to plot a sorption isotherm curve it takes five relative humidity levels in our case. However, the equilibrium of a 1 mm thick sample cut in the longitudinal direction takes on average 15 hours against 24 hours for the tangential direction for a relative humidity step. This limits the measurements on a large number of samples but the quality of the experimental device makes the measurements reliable.



**Figure 3:** Teak sample

#### Sorption isotherm fitting

Sorption isotherms of a material have been described by various mathematical models with two or more parameters. Nevertheless, models with more than three parameters lead to difficult uses and physical interpretation. The model presented by Brunauer and al.[14] known as "BET model", and its modified version from Guggenheim-Anderson-de Boer (GAB) as described by Bizot [15], have been successfully used by many authors

for modelling sorption isotherms. These models include parameters which have physical meaning.

In this study, the GAB model was used to model the sorption isotherms. The term GAB model comes from the names Guggenheim, Anderson and De Boer, who independently derived the equation in 1966, 1946 and 1953, respectively [16]-[17]. This model has many advantages over the others, such as having a viable theoretical background since it is a refinement of Langmuir and BET theories of physical absorption.

It postulates that the state of sorbet molecules in the second layer is identical to the one in superior layers, but different from those of the liquid state. These authors introduced a second sorption stage of the molecules of sorbets that was differentiated as a good sorbet. This isotherm necessarily contains a third constant,  $k$ , which measures the difference of the chemical potential standard between the molecules of this second stage and those of the pure liquid state.

In the 1990s, the GAB model was adapted from food science, and soon, it became at least as frequently applied for modelling the sorption isotherm of wood as the H-H model [18]-[19]. The GAB model assumed binding water molecules on to sorption sites and forming a monomolecular layer of the primary sorbed water. The molecules of the sorbed water were converted into the secondary sorption sites, and the additional water formed a multilayer. It was assumed that water in the multilayer was less strongly sorbed than in the monolayer, and it also varied in its thermodynamic properties as compared with liquid water.

The sorption isotherm is evaluated from the final equilibrium mass value in each measurement step [20]. The sorption isotherm is given by the experimental couples ( $H_r$ ,  $X_r$ ). The Equilibrium Moisture Content is given by the following formula:

$$X_r = 100 \times \frac{m_{eq} - m_d}{m_d} \quad (1)$$

Where,  $m_{eq}$ : sample equilibrium mass (kg) ; and  $m_d$ : sample oven dry mass (kg).

The GAB model enables a representation of sorption isotherms for the whole values of relative humidity [19]. Its mathematical expression is the following:

$$X_r (\%) = \frac{X_m H_r C K \times 100}{(100 - H_r K)(100 + H_r C K - H_r K)} \quad (2)$$

$X_r$ : Equilibrium moisture content ( $\text{kg.kg}^{-1}$ );  $X_m$ : moisture content corresponding to monolayer ( $\text{kg.kg}^{-1}$ );  $H_r$ : The relative humidity of the surrounding air (%);  $C$ : constant of the GAB model linked to monolayer sorption heat;  $K$ : constant of the GAB model linked to multilayer's sorption heat.

It can also be indicated that  $C$  and  $K$  are the absorption constants, which are related to the energies of interaction between the first and the further sorbed molecules at individual sorption sites. They can be theoretically expressed as

$$C = c_0 \exp\left(\frac{H_0 - H_n}{RT}\right) \quad (3)$$

$$K = k_0 \exp\left(\frac{H_n - H_t}{RT}\right) \quad (4)$$

Where  $c_0$  and  $k_0$  are the entropic accommodation factors;  $H_0$ ,  $H_n$ , and  $H_t$  are the molar sorption enthalpies of the monolayer, the multilayer on top of the monolayer, and the bulk liquid, respectively.  $R$  is the ideal gas constant and  $T$  is the absolute temperature.

Figure 6 represents the experimental absorption and desorption isotherms at temperature about 50°C for teak sample in tangential direction. The parameters of GAB model are collected in Table I, along with values of the mean relative percentage deviation. The constants  $X_m$ ,  $C$ , and  $K$  of the GAB model depend on wood characteristics. All these constants are estimated from experimental results. To estimate the parameters, the non-linear least squares method was used to build the objective function  $F_{ob}$  (5) and the downhill- Simplex method [21] was used to minimize the objective function calculated by (5) between the experimental equilibrium moisture contents ( $X_{exp}$ ) and the values calculated ( $X_f$ ) by equation 2.

$$F_{ob} = \sqrt{\sum_{i=1}^n \left( \frac{X_{exp} - X_f}{n} \right)^2} \quad (5)$$

Where  $n$  is the number of measurements.

## Results and Discussion

### Experimental procedure and sorption kinetic

Unsteady-state measurements involved recording the weight change of a sample after an abrupt change in the external relative humidity. To do this, it was necessary to initially equilibrate the wood at a given relative humidity (0 % RH in this work) and then expose the specimen to higher relative humidity [22]. Absorption of moisture was conducted with the same sample, by increasing stepwise the RH of the surrounding atmosphere up to 95 %. Each step represents a RH increase of 18 % up to 72%. Between each step, the time is chosen so that the absorption equilibrium can be attained (Fig. 4). The mass changes of the sample were recorded over time until equilibrium is reached. Desorption is performed using the same protocol, from 95% RH down to 0% RH. Fluctuations of the mass, temperature and relative humidity were respectively 0.2 mg, 0.02°C and 0.03 %. The complete set of experimental data is presented in Fig. 4 and 5.

In the case of absorption (Fig. 4), the temperature curve was plotted versus time and proves that the temperature is very stable during the absorption process. This trend is the same in the desorption process (Fig. 5). The relative humidity curve obtained from the ratio of dry air and saturated air streams with the two mass flow meters perfectly corresponds to the value measured by the humidity probe. Finally, it is valuable to note on the absorption curves (Fig. 4 and 5), that the equilibrium was not attained even after quite a long period of time. This is typical of the non-Fickian behaviour of wood. Such effects are caused by internal relaxation whose time constant may be higher than the sorption process [23].

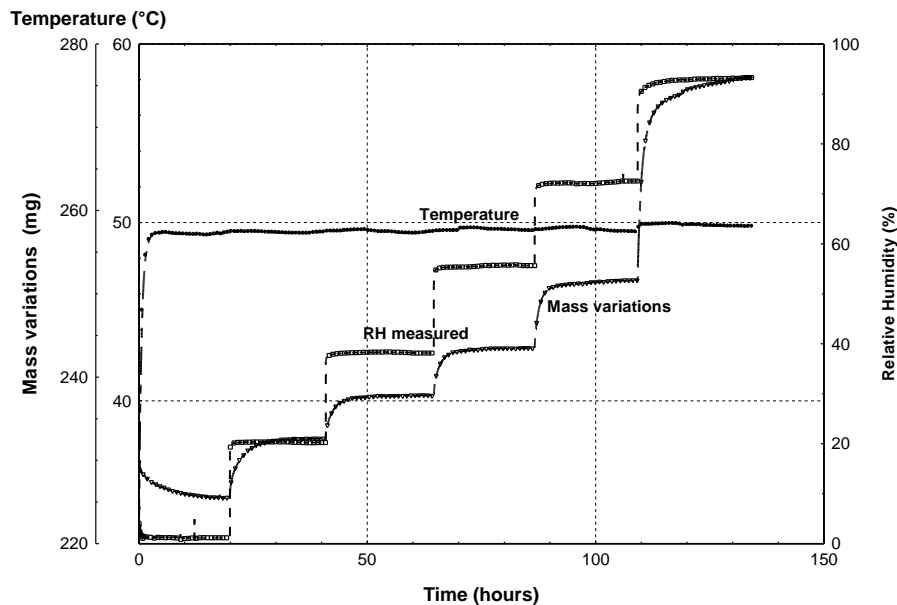


Figure 4: Water absorption at 50°C of teak in Tangential Direction for a stepwise variation of relative humidity

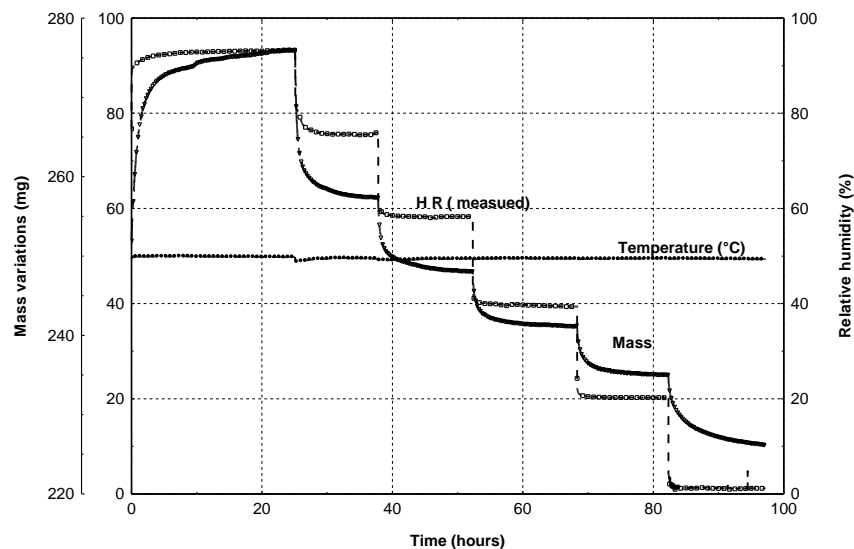


Figure 5: Water desorption at 50°C of teak in Tangential direction for a stepwise variation of relative humidity

### Sorption isotherm results

The sorption isotherms of most building materials have sigmoid shape like those displayed in Fig. 6 and the isotherm can be divided into three zones. At low relative humidity, a physicochemical sorption of moisture is produced, and then at higher relative humidity is followed by multi-layer adsorption and, finally, capillary condensation is predominant. The fit of the regression of such solid curves (Fig. 6) to the sorption data is quite good. Hysteresis is obvious in the sorption isotherm curves (figure.6). This hysteresis is explained by the fact that sorption of water vapour within porous building materials like teak happens naturally in the presence of air. At lower relative humidity levels, the attraction forces of the water molecules complete with the attraction forces of other

molecules in the air. In absorption, part of the surface of the pores is occupied by other molecules, which results in a smaller amount of water vapour molecules than by desorption [24].

Sorption hysteresis is also often expressed in terms of the ratio  $A/D$ , where  $A$  is the absorption moisture content value and  $D$  is the desorption value for a given value of the relative humidity. This is a general criterion for the extent of the sorption hysteresis on hygroscopic materials. The complete absorption and desorption isotherms which are obtained from complete dryness and near saturation, respectively, give the greatest  $A/D$  ratio. As an average ratio for wood, the  $A/D$  ratios usually range between 0.75 and 0.85 several factors may enter into the variation in

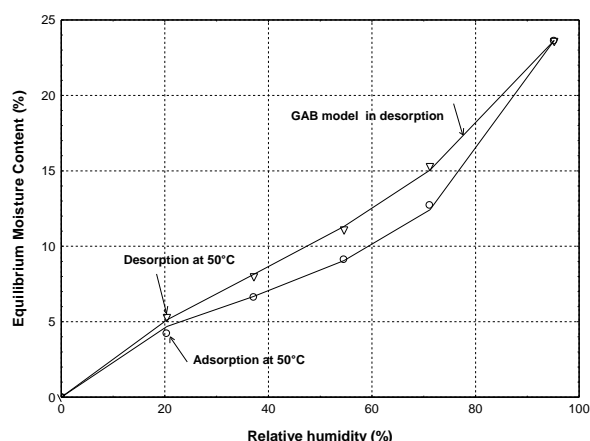


sorption hysteresis as measured by the A/D ratio. These factors include [4]:

- Incomplete attainment of equilibrium
- Immediate past history (e.g. number of absorption steps and possibly time at each step)
- Temperature
- Physicochemical differences in the cell wall
- Extractive content.

**Table 1:** Estimated parameters for GAB model and goodness of fit for the adsorption and desorption isotherms of teak at 50°C.

Model	Parameter	Teak L	Teak T	Teak L	Teak T
		Adsorption		desorption	
GAB	X <sub>12</sub>	7.0801	5.6123	10.4309	9.3651
	C	14.3271	11.6553	8.8274	5.6261
	K	0.7935	0.8074	0.6536	0.6721
	R <sup>2</sup>	0.9999	0.9996	0.9999	0.9997
	Err%	0.2	3.8	0.7	1.8



**Figure 6:** Sorption isotherms of teak in tangential direction at 50°C: simulation by GAB model and experimental results

In this study, the average of the A/D is 0.79 to 0.83 for teak sample in tangential direction and is about 0.80 to 0.88 in longitudinal direction.

The equilibrium data are satisfactorily modeled with GAB model, determining a value of 5.6% for teak in tangential direction in adsorption for the parameter X<sub>m</sub> (Table I) that corresponds to a relative humidity value of 30%. This parameter is important because it will be the value of final moisture content of the teak for its correct preservation. The standard deviation between the experimental points and the GAB simulated points is less than 4%. This result suggests that the sorption isotherms of the teak are properly described by the GAB model. It should be noted that the teak moisture content is quite significantly dependent on the relative humidity of the surrounding air.

## Conclusions

This paper presented a new experimental set-up to measure sorption isotherms from absorption and desorption cycles. In tangential and longitudinal directions, the sorption isotherms measured are in agreement with the existing literature. However, subtler mechanisms such as dual-scale mechanisms and non-Fickian behavior were revealed by the measurements. The equilibrium data are satisfactorily modelled with GAB model. It has emerged

from this experimental study that the hydrothermal properties of wood depend greatly on humidity.

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