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Experimental determination and modelling of water desorption isotherms of tropical woods: afzelia, ebony, iroko, moabi and obeche

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Abstract Desorption isotherms of Afzelia, Ebony, Iroko, Moabi and Obeche have been experimentally found at 20, 30, 40, 50 and 60 °C by use of the salt method for a range of water activities from 0.06 to 0.97. The sorption capacity of these woods increases with the temperature for a given water activity. The experimental curves have been simulated by the GAB and BET models. The GAB model enables the representation of the whole desorption isotherms. Meanwhile, the BET model ensures a better representation of the experimental results for water activity lower than 0.35 with mean relative deviation of 2.9, 2.1, 1.3, 3.2 and 3.3% for respectively Afzelia, Ebony, Iroko, Moabi and Obeche and a better estimation of the water content corresponding to monolayer saturation.

Experimentelle Bestimmung und Modellierung von Desorptionsisothermen der tropischen Hölzer Afzelia, Ebenholz, Iroko, Moabi und Obeche

Zusammenfassung Desorptionsisothermen von Afzelia, Ebenholz, Iroko, Moabi und Obeche wurden bei Temperaturen von 20, 30, 40, 50 und 60 °C experimentell bestimmt. Mit Salzlösungen wurden relative Luftfeuchten von 6–97% erzeugt. Die Sorptionskapazität dieser Hölzer nimmt bei gegebener relativer Luftfeuchte mit steigender Temperatur zu. Die experimentell bestimmten Kurven wurden mittels der GAB- und BET-Modelle nachgebildet. Anhand des GAB- Modells können die gesamten Desorptionsisothermen dargestellt werden. Das BET-Modell ermöglicht indessen eine bessere Darstellung der Versuchsergebnisse im Bereich unterhalb 35% relativer Luftfeuchte bei einer mittleren relativen Abweichung von 2,9; 2,1; 1,3; 3,2 und 3, 3% bei Afzelia, Ebenholz, Iroko, Moabi und Obeche. Zudem kann mit diesem Modell der Wassergehalt entsprechend einer einlagigen Sättigung besser geschätzt werden.

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Notation

a_w Product water activity
b Constant of the BET model
C Constant of the GAB model linked to monolayer heat of sorption
K Constant of the GAB model linked to multilayers heat of sorption
M Molecular mass $kg \cdot mol^{-1}$
N Avogadro number
S Specific area $m^2 \cdot m^{-3}$
X Dry basis water content $kg_w \cdot kg_{dm}^{-1}$

Greek Symbols

ρ Density $kg \cdot m^{-3}$
θ Air temperature $°C$

Subscripts

w Water
eq Equilibrium
m Monolayer
dm Dry matter

1 Introduction

Water activity a_w of a product essentially depends on its water content X and on its temperature θ. The curve representing, for a temperature θ, the water content X_{eq} of a product in equilibrium as a function of its water activity a_w (or of air relative humidity HR) is called the sorption isotherm.

The sorption isotherm enables the calculation of the equilibrium water content X_{eq} depending on air conditions that will be the limit of the product water content at the end of the drying. This equilibrium water content X_{eq} is thus an important parameter used in drying models.

The sorption isotherm gives also information on the sorption mechanism and on the interaction between adsorbate and adsorbent as pointed out by Bizot et al. (1987). The equilibrium water content of a product is one of the most important parameter to predict its behaviour during storage according to Chirife and Buera (1994) and Vilades et al. (1995).

Many authors have published results about sorption isotherms studies of various products but very little information is available about sorption isotherms of tropical woods. This paper presents a study on the determination of desorption isotherms of five tropical woods: Afzelia, Ebony, Iroko, Moabi and Obeche.

2 Mathematical models

Sorption isotherms of a material have been described by various mathematical models with two or more parameters as presented by Van der Berg and Bruin (1981). Nevertheless, models with more than three parameters lead to uneasy use and physical interpretation. The model presented by Brunauer, Emmet and Teller (1938) known as “BET model”, and its modified version from Guggenhein, Anderson and Boer (GAB) as described by Bizot et al. (1987) have been successfully used by many authors such as Lahsani et al. (2003) for modelling sorption isotherms. These models include parameters which have physical meaning.

2.1 BET model

This model allows the study of the phenomena of water molecules adsorption and desorption. Its mathematical expression is the following if the monolayer is not saturated:

$$X_{eq} = \left(\frac{X_m b a_w}{1-a_w}\right)\left[\frac{1-2a_w+a_w^2}{1+(b-1)a_w-ba_w^2}\right] \quad (1)$$

where

X_{eq}: equilibrium water content ($kg_w \cdot kg_{dm}^{-1}$)
X_m : water content corresponding to monolayer ($kg_w \cdot kg_{dm}^{-1}$)
b : constant

2.2 GAB model

The GAB model enables a representation of sorption isotherms for the whole values of water activity a_w. Its mathematical expression is the following:

$$X_{eq} = \frac{X_m C K a_w}{(1-Ka_w)\,[1+(C-1)Ka_w]} \quad (2)$$

where

C: constant linked to monolayer sorption heat
K: constant linked to monolayer sorption heat

With the hypothesis of an initial homogeneous monolayer filling of the product surface , one can calculate its area by the following formula:

$$S_m = \frac{\sqrt{3}\sqrt[3]{2}}{2}\left(\frac{N}{M\rho_w^2}\right)^{1/3}\rho_{dm} X_m \quad (3)$$

where

S_m : monolayer area or specific area ($m^2 \cdot m^{-3}$)
N : Avogadro number = $6{,}023.10^{23}$
M : absorbing material molecular mass ($kg \cdot mol^{-1}$)
ρ_w : water density ($kg \cdot m^{-3}$)
ρ_{dm}: solid matrix density ($kg_{dm} \cdot m^{-3}$)

The value of the specific area of a product may give information about its rehydration and its internal organisation.

3 Material and method

The static method of the saturated salts solutions has been used for sorption isotherms determination. The relative air humidity is fixed by contact with saturated salts solution whose water vapour pressure at a given temperature is perfectly known.

In our experiments, ten salts have been used that covered the range 0.06 to 0.97 for water activities, these salts are: LiBr, LiCl, KCH_3CO_2, $MgCl_2$, K_2CO_3, NaBr, $CuCl_2$, NaCl, KCl and K_2SO_4. The corresponding values of water activities are given by Bizot and Multon (1978).

A sample of each wood was set in each of the ten recipients containing the ten saturated salts solutions. The dimensions of the 50 samples were 25 × 10 × 5 mm. The recipients were set in a temperature regulated chamber. Samples were weighted each 48 h until their mass variation became less than 1 mg. The oven-dry mass was then measured after dehydration for 48 h at 102 °C to calculate the equilibrium water content X_{eq}.

The sorption isotherm is given by the experimental couples (a_w, X_{eq}). The experimental procedure consists in introducing the recipients in the chamber regulated to the lowest temperature value of the series (20 °C) then, when the equilibrium is reached, all the samples are weighted and the temperature is raised to the next value (30 °C). This procedure is repeated for 40 °C, 50 °C and 60 °C.

4 Results and discussions

Figure 1 represents the experimental desorption isotherms of Afzelia, Ebony, Iroko, Moabi and Obeche obtained at 20 °C. Figure 2 represents as an example experimental and GAB model simulations of sorption isotherms of Afzelia at 20, 30, 40, 50, and 60 °C. For a given value of the water activity, the equilibrium water content decreases with the temperature.

The constants X_m, C, K of the GAB model depend on product characteristics and on temperature, it is the same for the constants X_m and b of the BET model, all these constants are estimated from experimental results. For each temperature, these parameters are estimated by minimizing the sum of the quadratic errors between the experimental equilibrium water contents X_{eq} and the values calculated with Eqs. 1 or 2.

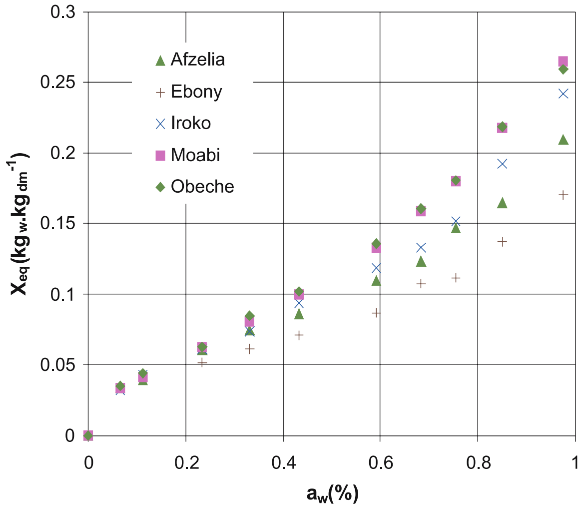

Fig. 1 Experimental desorption isotherms of Afzelia, Ebony, Iroko, Moabi and Obeche at 20 °C
Abb. 1 Experimentell bestimmte Desorptionsisothermen von Afzelia, Ebenholz, Iroko, Moabi und Obeche bei 20 °C

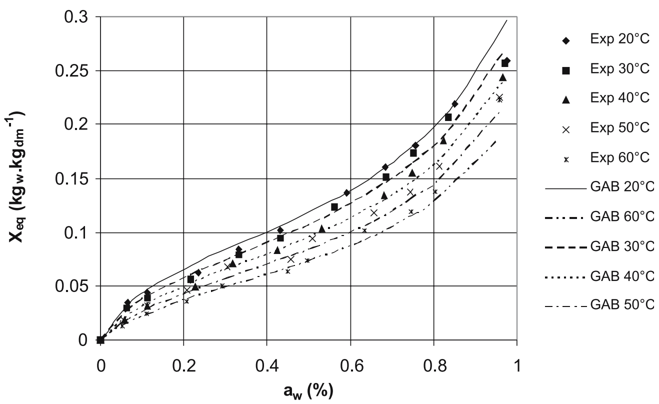

Fig. 2 Desorption isotherms of Afzelia at several temperatures: simulation by the GAB model and experimental results
Abb. 2 Desorptionsisothermen von Afzelia bei verschiedenen Temperaturen: Nachbildung anhand des GAB-Modells und Versuchsergebnisse

Contrarily to the GAB model which represents the sorption isotherm on a wide range of a_w values, the BET model enables the representation of the sorption isotherms only in the range of activities from 0 to 0.35 according to Brunauer et al. (1938). Table 1 resumes the whole results of the estimation for each wood species and for each temperature.

The mean relative deviation of the GAB model using the values of Table 1 compared to the fifty experimental points is 3.0, 3.4, 3.1, 4.3 and 3.8% for respectively Afzelia, Ebony, Iroko, Moabi and Obeche, that is quite satisfactorily. Nevertheless, the deviation is quite low for water activities lower than 0.35 and is thus interesting for drying modelling since final water content around 0.15 is generally recommended. For water activities lower than 0.35, the BET model is better fitting the experimental results: in this range of water activities, the mean relative deviation of the BET model compared to the twenty experimental points is 2.9, 2.1, 1.3, 3.2 and 3.3% for respectively Afzelia, Ebony, Iroko, Moabi and Obeche. The relatively low deviations lead to the conclusion that these two models represent the desorption isotherms quite satisfactorily.

Table 1 Estimated values of the parameters of the GAB and BET models
Tabelle 1 Schätzwerte der Parameter

Product	θ	GAB model			BET model		
	°C	X_m $kg_w \cdot kg_{dm}^{-1}$	C	K	X_m $kg_w \cdot kg_{dm}^{-1}$	b	S_m $m^2 \cdot g^{-1}$
	20	0.068	16.00	0.710	0.0539	18.24	190
	30	0.063	14.00	0.734	0.0494	16.92	174
Afzelia	40	0.057	11.45	0.742	0.0478	11.08	168
	50	0.049	12.33	0.757	0.0448	10.43	158
	60	0.040	11.41	0.806	0.0359	10.68	126
	20	0.051	36.35	0.731	0.0434	43.02	153
	30	0.047	25.13	0.754	0.0398	28.90	140
Ebony	40	0.043	17.04	0.770	0.0369	17.70	130
	50	0.037	12.70	0.790	0.0332	11.78	117
	60	0.030	9.78	0.847	0.0273	9.50	96
	20	0.070	14.29	0.742	0.056	16.676	197
	30	0.064	13.25	0.774	0.0508	16.509	179
Iroko	40	0.062	9.75	0.762	0.0522	9.521	184
	50	0.055	10.85	0.761	0.0489	9.594	172
	60	0.047	8.98	0.796	0.0426	7.943	150
	20	0.082	10.69	0.738	0.0595	14.68	209
	30	0.077	9.55	0.753	0.0564	12.82	198
Moabi	40	0.069	8.48	0.772	0.0523	10.36	184
	50	0.062	8.16	0.780	0.0507	8.60	178
	60	0.053	7.40	0.811	0.045	7.47	158
	20	0.083	11.51	0.728	0.0604	15.94	212
	30	0.079	10.05	0.744	0.0581	13.15	204
Obeche	40	0.078	6.67	0.732	0.061	6.71	214
	50	0.065	8.79	0.756	0.0584	7.49	205
	60	0.053	7.30	0.805	0.0473	6.67	166

According to experimental results, the estimated parameters X_m and C decrease when the temperature rises since the parameter K increases with temperature (Table 1). This is in agreement with the behaviour of other products as reported by Labuza et al. (1985), Maroulis et al. (1988), Okos et al. (1992), Sopade and Ajisegiri (1994). The decreasing of the specific area S_m with temperature increasing can be explained by the decrease of porosity as an effect of the thermal expansion of the solid matrix leading to pores shrinkage. Table 1 shows that the values of X_m estimated from the BET model are always greater than the values obtained from the GAB model. This difference is linked to the fitting of the model with the experimental curve especially in the area corresponding to the monolayer saturation (water activity lower than 0.2). The values obtained from the BET model which better fits the experimental values in this area must be more reliable than those obtained with the GAB model.

5 Conclusion

In this study, the desorption isotherms of Afzelia, Ebony, Iroko, Moabi and Obeche have been experimentally established and then modelled by BET and GAB models. The BET model enables the calculation of the monolayer water content leading to the value of the specific area for different temperatures. A comparison between BET and GAB models shows that the first one gives a better fitting with experimental results for water activities lower than 0.35. Nevertheless, the mean relative deviation between experimental results and calculated values the values of the equilibrium water content X_{eq} calculated by the GAB model is less than 5% and remains acceptable.

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