CHAPITRE 6. Effect of the anatomical parameters on the sorption behavior of some temperate and tropical hardwoods

6.1 Résumé

L'influence des éléments anatomiques sur le comportement en sorption a été étudiée sur des feuillus, deux espèces tempérées et cinq espèces tropicales. Deux techniques expérimentales (solutions salines saturées et membrane poreuse sous pression) ont été utilisées pour la réalisation des essais de sorption à 25ºC. Des coupes transversales et tangentielles de ces sept espèces ont été préparées pour quantifier les éléments anatomiques. Une analyse statistique a permis de quantifier le rôle des éléments anatomiques sur le comportement du bois en sorption. De fortes différences de paramètres anatomiques ont été constatées selon les espèces. L'effet des éléments anatomiques sur la teneur en humidité d'équilibre pour de fortes valeurs d'humidité relative diffère fortement d'une espèce à l'autre. La masse volumique du bois et les paramètres des vaisseaux sont corrélés négativement avec la valeur d'humidité d'équilibre du bois. Les paramètres relatifs aux rayons sont aussi corrélés au drainage de liquide pour certaines espèces, notamment pour des valeurs de RH au voisinage de 96%, valeur pour laquelle l'eau liquide est plus fortement retenue par les forces capillaires. Les résultats indiquent que, à des valeurs d'humidité relative au-dessous de 90%, l'humidité d'équilibre augmente avec la masse volumique du bois. Le rapport de sorption (s) dépend de la masse volumique du bois, les espèces plus denses ayant une meilleure stabilité hygroscopique. Le PSF décroît également quand la masse volumique augmente. Cependant, une comparaison entre espèces tempérées et tropicales montre que d'autres paramètres, non étudiés dans ce travail, ont une influence sur le comportement en sorption.

6.2 Abstract

The influence of the anatomical elements on the sorption behavior was studied on two temperate and five tropical hardwoods. Two experimental techniques were used to perform moisture sorption tests at 25ºC. The first one was the saturated salt solutions (from 33% to 90% relative humidity) and the second one used the pressure membrane method (above 96% relative humidity). Transverse and tangential sections of the seven species were

analyzed in order to measure quantitative anatomical parameters. Statistical analyses were made to evaluate the role of the anatomical elements on the sorption behavior. Special attention was paid to the region of high humidities (above 96% RH), where capillary forces dominate. It was observed a large variation of anatomical parameters among species, which was reflected on the liquid water drainage. At high humidities, the equilibrium moisture content (EMC) results indicated that the effect of the anatomical elements varied among wood species. The wood density and vessel parameters had a negative correlation with EMC values. The ray parameters were also correlated to water drainage in some wood species, especially at RH values close to 96% RH where the liquid water is more strongly retained by the capillary forces. At RH values below 90%, the EMC increased as wood density decreased. The ratio of sorption (s) was affected by wood density, showing that woods presenting high densities had more hygroscopic stability. The FSP also increased as wood density decreased. Nevertheless, a comparison between results of temperate and tropical hardwoods showed that other parameters not studied in the present work have an important influence on the sorption parameters.

6.3 Introduction and background

The knowledge of the structure of a material is very important to improve its utilization. The high variability of the wood structure makes the study of the water-wood relationships more complex. Compared to softwoods, the anatomical structure of the hardwoods is more complex and variable. In temperate hardwood species, the vessel tissue can represent approximately 30% of the wood volume, with a range within 6.5 and 55% (Panshin and de Zeeuw 1980). Fibers may account for 20% to 70% of the wood volume. Axial parenchyma makes up 1% to 18% of the volume of temperate woods, but this may reach 50% in tropical woods. Ray parenchyma may include 5% to 30% of the volume of temperate woods (Siau 1995). The vessels, when not occluded, are the principal flow paths in hardwoods. Liquids then flow from vessels to vasicentric tracheids (when present), axial parenchyma, fibers and rays (Siau 1995).

Several works have studied the influence of the wood structure on the fluid paths within wood. In order to improve its use (wood treatment or drying) most of these works were focused on wood permeability and on water movements through this material (Stamm

1967; Behr et al. 1969; Tesoro et al. 1974; Thomas 1976; Gonzalez and Siau 1978; Murmanis and Chudnoff 1979; Choong and Tesoro 1989; Choong et al. 2001). The importance of the vessel tissue on the longitudinal permeability and the negative effect of tyloses and gum deposits were largely observed by the works cited above. Choong and Tesoro (1989) submitted hardwoods to centrifugal force and observed that the majority of the water removed came from the larger capillaries (lower capillary resistance). The loss of liquid water from fibers and parenchyma cells takes place by the pits, which make the drainage of these elements more difficult. Similar results were observed by Gonzalez and Siau (1978). These researchers observed three distinct zones of absorption of oil in beech. They concluded that the first zone impregnated corresponded to the earlywood and latewood vessels, since these are probably the most permeable cells. The second zone may represent relatively permeable parenchyma tissue, while the third zone may represent a portion of the fiber tissue. Finally, the untreated fraction would correspond to the wide rays.

In contrast, the effect of the wood structure on its equilibrium moisture content (EMC) was subject of a small number of studies. The most important factor controlling the EMC is the relative humidity of air (RH) but it is also affected by temperature, state of sorption (adsorption or desorption), mechanical stress, wood species, specific gravity and extractive content (Siau 1995). A single example of work studying the effect of the anatomical parameters on the EMC is given by Arévalo (2002). In this work, regression models indicated a significant influence of vessels and rays as well as wood density on the sorption behavior of mahogany wood. The EMC decreased as the vessels diameter decreased and as the number of rays per mm increased. However, the influence of the wood extractives on EMC was greater than that of the anatomical parameters. These observations were restricted to the hygroscopic range.

The principal objective of the present work was to determine the effect of the anatomical structure on the sorption behavior (capillary and hygroscopic domains). In order to enlarge the wood variability, two temperate and five tropical hardwoods presenting different wood structure were analyzed. EMC values between 33% and ≈100% RH were obtained using two experimental techniques.

6.4 Material and methods

Experiments were carried out on two temperate hardwoods: yellow birch (*Betula alleghaniensis* Britton) and beech (*Fagus grandifolia* Ehrhart), and five tropical hardwoods: tornillo (*Cedrelinga cateniformis* Ducke), congona (*Brosimum alicastrum* Swartz), cachimbo (*Cariniana domesticata* (C. Martius) Miers), pumaquiro (*Aspidosperma macrocarpon* C. Martius) and huayruro (*Robinia coccinea* Aublet). All these seven species are diffuse porous woods. Twenty defect-free flatsawn boards of each wood species were carefully selected and stored in a conditioning room at 20°C and 60% RH. After conditioning, specimens were cut with a cross-section of 20 mm (R) by 20 mm (L) and a height of 60 mm (T). Matched samples were chosen from each board to make sorption tests and quantitative anatomical analyses. The average basic wood density (oven-dry mass to green volume) was 490 kg m^{-3} for tornillo (coefficient of variation (CV) of 3%); 533 kg m^{-3} for yellow birch (CV of 4 %); 540 kg m^{-3} for congona (CV of 4%); 543 kg m^{-3} for beech (CV of 3%); 550 kg m^{-3} for cachimbo (CV of 5%); 585 kg m^{-3} for pumaquiro (CV of 3%) and 639 kg m^{-3} for huayruro (CV of 3%).

For the quantitative anatomical analysis, twenty specimens of each wood species were used. Given the refractory character of some of the tropical woods used, wood blocks of 1 cm^3 were softened according to a method suggested by Kukachka (1977). After this treatment, microtome samples of transverse (20 µm thick) and tangential (30 µm thick) sections were prepared using a sliding microtome. The sections were then double stained with safranin and fast-green, and mounted permanently.

EXPERIMENTS

Sorption tests

Twenty samples per species were tested for each sorption condition. The sorption tests required two experimental techniques. The first technique involved the use of saturated salt solutions (from 33% to 90% relative humidity). In the second one, specimens were conditioned following a pressure membrane procedure (above 96% relative humidity). Table 6.1 shows some characteristics of the sorption tests. A complete description of these two methods and the conditioning time were reported in items 2.4 and 5.4.

In the present study, the concept of water potential (ψ) was used, where the water in a medium is characterized in term of its energy state (Iwata et al. 1994). The use of the ψ as the independent variable in the sorption isotherm gives the important advantage of spreading out the region of high RH (between 96% and 100% RH), where the MC is highly affected by the wood structure.

As soon as each sorption test was completed, the sample mass was measured to the nearest 0.001g. These masses were used to calculate the equilibrium moisture content (EMC), expressed as a percentage of oven-dry mass.

Quantitative anatomical analysis

Two images of each sample were randomly taken using a Pixelink camera, generating 40 transversal images for the determination of vessel parameters, 40 transversal images for the determination of fibers and axial parenchyma parameters and 40 tangential-longitudinal images for determination of ray parameters by wood species. Image treatments were made using Micromorph 1.3 and Adobe Photoshop Elements 2.0. A Regent Instruments WinCell 2004 image analyzer was used to measure the quantitative anatomical parameters.

Nineteen quantitative anatomical parameters were defined to evaluate their relationships with the physical properties of the seven wood species. Thus, transverse section slides were used for the measurement of vessel proportion (VP), individual vessel surface (VS), number of vessels per square millimeter (VSM), tangential vessel diameter (VTD), larger vessel diameter (VLD) and smaller vessel diameter (VSD). The fiber parameters were also determined on transverse sections: fiber proportion (FP), smaller diameter of fiber lumen (FSD) and larger diameter of fiber lumen (FLD). The ray parameters as the proportion of rays (RP), individual ray surface (RS), number of rays per square millimeter (RSM), rays height (RH), rays maximum height (RHMA), rays width (RW) and rays maximum width (RWMA) were measured on the tangential section slides. Finally, the proportion of axial parenchyma (APP) was also determined. As suggested by Ifju (1983), the shape factors of vessels (VSF) and rays (RSF) were determined by the ratio between VLD and VSD, and between RH and RW, respectively. To evaluate the proportion of different elements, vessels, rays and axial parenchyma were distinguished from fibers using Micromorph 1.3 or Adobe Photoshop Elements 2.0. Their area relative to the whole section was then calculated using WinCell software. The proportion of fiber was obtained by subtracting the proportion of vessels, rays and axial parenchyma from unity (100%). For huayruro wood, the proportion of axial parenchyma was obtained by subtracting the proportion of vessels, rays and fibers from unity (100%). The axial parenchyma of tornillo was very difficult to differentiate in the majority of the samples. For this reason, the APP for this wood is a result of measurements made on five samples. The APP of tornillo was not included on the statistical analysis.

Statistical analysis

All data was analyzed using the SAS software (SAS Institute 2002-2003). Pearson correlation was used to determine the relationships between the anatomical parameters and the sorption characteristics. In the high values of EMC (above 96% RH) the results of each species were analyzed separately.

Concerning the sorption characteristics, two more dependent variables were determined: the ratio of sorption (s) and the fiber saturation point (FSP). The ratio of sorption indicates the amount of change in EMC with a change of RH of 1%, where the range between 33% and 76% RH was studied. The FSP was determined using the volumetric shrinkage intersection point method (moisture content at which the extended linear portion of shrinkage-moisture curve intersects the line of zero shrinkage). For this estimation, only volumetric shrinkage values obtained between 33% and 76% RH were used (between 58% and 76% RH for pumaquiro and huayruro). This was done because of the non-linearity of the shrinkage-moisture curve at low moisture contents (Kelsey 1956) and the effect of the hysteresis at saturation on shrinkage at high moisture contents (Hernández and Bizoň 1994).

The results of the seven species were combined in the analysis of the influence of anatomical parameters on the EMC values (obtained at RH lower than 90%), the ratio of sorption and the FSP. Only the average values were used. All data was analyzed by stepwise regression techniques with the SAS software. The independent variables were added or removed to the model when the F-value became significant or not significant at 0.10 probability level.

6.5 Results and discussion

Wood hygroscopicity

The full saturated and EMC values obtained on each sorption condition for the seven species studied are given in Table 6.1. The coefficient of variation of EMC values generally increased as relative humidity increased. Sorption at high humidities is mainly affected by capillary forces. Thus, the higher variation in EMC at high humidities could be principally due to variations in the capillary structure among the twenty samples used. The samples of some tropical species (congona, cachimbo, pumaquiro and huayruro) conditioned over distilled water did not reach the equilibrium state, which explains the higher coefficient of variation compared to the other species.

The EMC as a function of RH for the seven species studied is depicted in Figure 6.1. This figure only displays the desorption values obtained by the saturated salt solution method. Given to a problem on the desorption at 33% RH for pumaquiro and huayruro woods, this figure does not show the EMC values at 33% RH for these two species. The boundary desorption curves of the two temperate hardwoods almost join below 76% RH (Figure 6.1). It is recognized that bound water desorption is quite similar among different temperate neutral woods. Despite the important effect of the extractives substances on EMC (Wangaard and Granados 1967; Choong and Achmadi 1991), the fact that the EMC values of all seven species becomes more similar as RH decreases is expected given that desorption of liquid water at lower levels of RH is almost achieved. More precisely, item 4.5 shows the distribution of liquid and bound water on three hardwood species using nuclear magnetic resonance and it is observed that, at equilibrium conditions, the drainage of liquid water had already achieved at 76% RH for all species studied.

The EMC - ψ relationships of the seven wood species are shown in Figure 6.2. This figure only displays the desorption curve obtained by using either the pressure membrane or the saturated salt solution method. Desorption was carried out beginning from the full saturated state and the term boundary desorption curve is therefore used to describe this feature. By

Table 6.1. Characteristics of the moisture sorption conditions and results of the equilibrium moisture content (EMC) for the seven species studied.

Nominal relative humidity (%)	Water potential (Jkg^{-1})	EMC (%)						
		Tornillo	Yellow birch	Congona	Beech	Cachimbo	Pumaquiro	Huayruro
Full saturation under distilled water								
100	0	130.56 (5.2) [2]	118.18 (4.3)	116.64 (5.7)	115.97 (4.1)	113.58 (9.1)	101.15 (4.3)	89.00 (6.2)
Equilibrium under a pressure membrane at 25°C (longitudinal desorption)								
99.989	-15	-	-	-	82.78 (11.2)	-	-	-
99.927	-100	119.54 (4.2)	82.70 (6.2)	105.51 (4.5)	58.53 (5.5)	99.05 (12.7)	52.87 (5.1)	81.65 (4.7)
99.782	-300	114.11 (5.9)	69.20 (12.4)	84.46 (19.9)	-	60.74 (4.7)	49.72 (4.2)	79.69 (5.1)
99.637	-500	-	-	-	51.44 (2.71)	-	-	-
99.492	-700	95.63 (5.2)	41.18 (3.6)	43.39 (13.8)	-	56.04 (5.4)	44.80 (6.4)	77.29 (5.2)
98.557	-2 000	51.50 (11.4)	38.58 (3.0)	39.36 (3.5)	40.19 (2.4)	45.71 (7.7)	36.35 (9.0)	48.55 (7.8)
96.782	-4 500	-	-	-	35.16 (2.3)	-	-	-
96.431	-5 000	36.48 (5.9)	34.62 (1.7)	30.29 (3.0)	-	30.24 (5.7)	33.07 (9.3)	25.01 (8.4)
Equilibration over distilled water at 25°C (adsorption)								
≈ 100	-	30.91 (2.1)	34.56 (3.6)	36.37 (23.5)	30.78 (4.2)	32.49 (6.3)	27.52 (7.4)	27.19 (15.0)
Equilibration over saturated salt solutions at 25°C (desorption)								
90 ($ZnSO_4$) [1]	-14 495	23.22 (1.6)	23.66 (1.0)	23.13 (2.2)	25.23 (1.8)	22.26 (1.7)	21.80 (1.4)	19.97 (3.1)
86 (KCl)	-20 750	20.44 (1.8)	21.40 (1.4)	20.75 (1.3)	21.87 (1.4)	20.40 (1.4)	19.20 (0.6)	18.37 (2.6)
76 (NaCl)	-37 756	16.73 (1.9)	17.51 (0.9)	17.06 (2.7)	17.37 (0.8)	16.92 (1.8)	16.55 (0.6)	16.02 (2.1)
58 (NaBr)	-74 941	12.11 (1.9)	12.36 (1.1)	12.57 (1.2)	12.37 (0.4)	12.25 (1.9)	12.37 (0.5)	12.09 (1.4)
33 ($MgCl_2$)	-152 526	7.59 (1.6)	7.46 (0.5)	7.75 (0.9)	7.40 (0.8)	7.40 (2.0)	6.51 [3] (0.8)	6.31 [3] (1.3)

[1] Saturated salt solution.
[2] Values between parentheses represent the coefficient of variation of EMC based on 20 specimens.
[3] An intermediate desorption step in a climate room (20°C, 40% RH) generated this result.

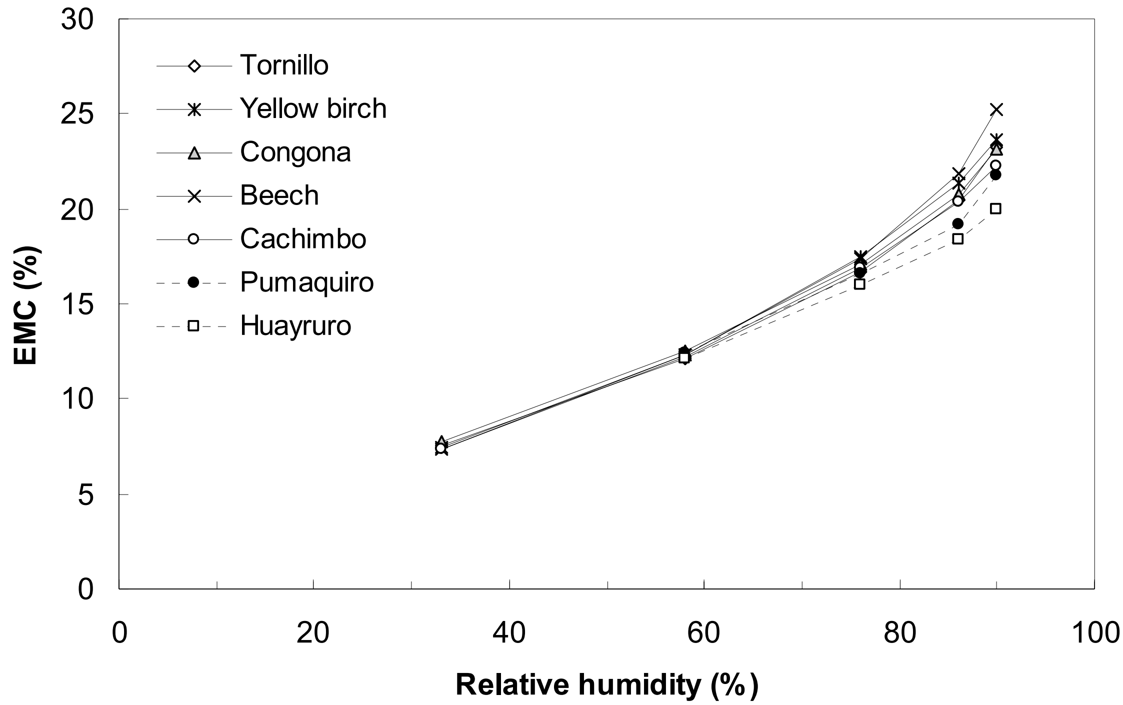

Figure 6.1. Equilibrium moisture content (EMC) as a function of relative humidity at 25°C for the seven species studied (EMC values obtained on boundary desorption by the saturated salt solution method). (Due to problems on desorption method, the values obtained at 33% RH for pumaquiro and huayruro woods were not added on this figure).

comparing the Figures 6.1 and 6.2, it can be observed that the region between 96% and 100% RH is spread-out when using the water potential concept to represent sorption isotherms (Figure 6.2). This region is very important in the study of the wood-water interactions, given that it is mainly controlled by the capillary forces and consequently by the structure of wood species. Indeed, the seven species clearly presented different trends at high water potential values (Figure 6.2). Figure 6.2 also shows the linearity of the EMC - ψ relationship at RH values below 86%. This fact corroborates the Anderson-McCarthy theory, which predicts a linear relationship between ln ln (1/h) and EMC within the hygroscopic range (Siau 1995).

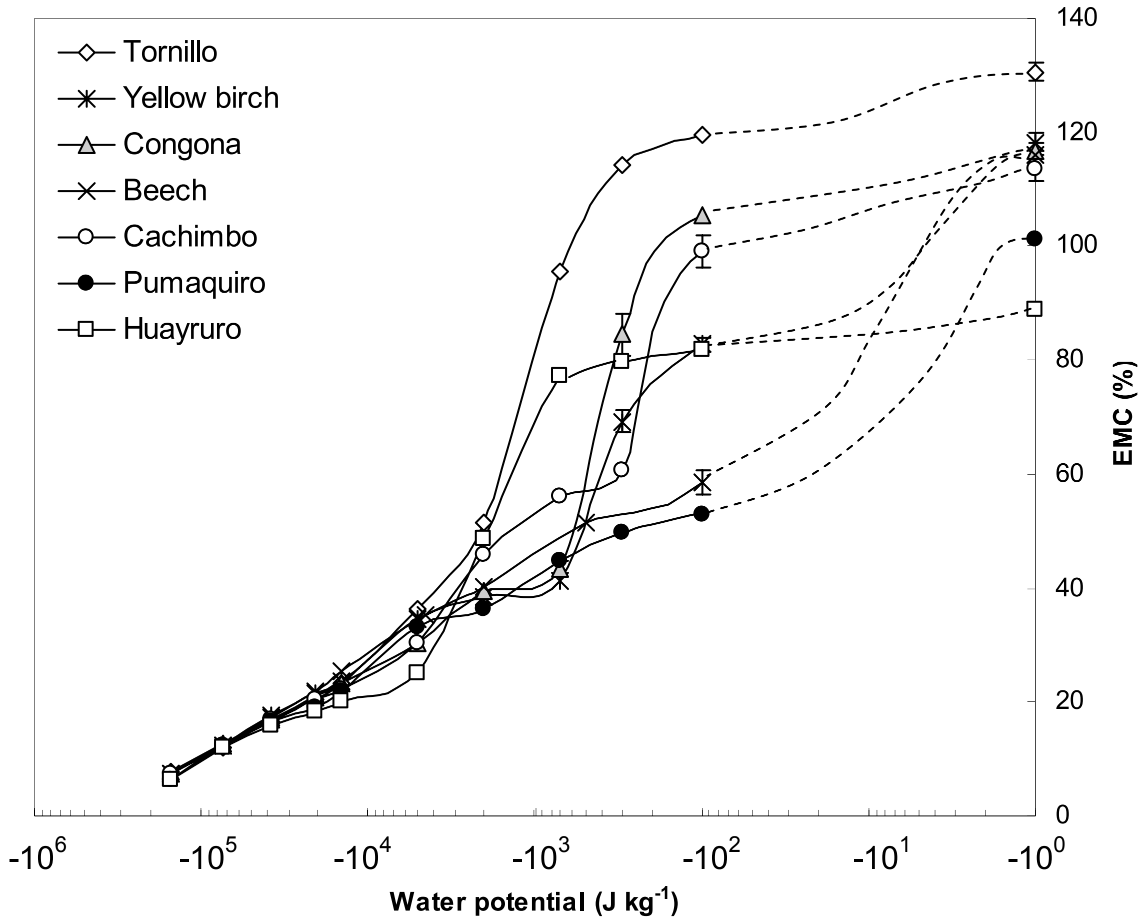

Figure 6.2. EMC-water potential relationship obtained by boundary desorption tests at 25°C for the seven hardwoods (standard errors are shown only when they exceed the symbol size).

The sorption ratio (s) was also calculated for all species studied. This ratio indicates the amount of change in EMC with a change of RH of 1%. S ratio represents the slope of a sorption isotherm within a RH range considered. The sorption ratio depends on the chemical composition of the wood, on their internal surface, on the amount and nature of wood extractives (Noack et al. 1973). In the present work, different s ratios within the range between 33% and 76% RH were calculated (Table 6.2). For all species, lower values of s were obtained for low humidities (58% to 33% RH) than for high humidities (76% to 58% RH). This fact was also observed on mahogany wood by Arévalo (2002). The s values also

Table 6.2. Sorption ratio (s) of the seven species as a function of different ranges of RH changes at 25°C.

Wood species	Sorption ratio s		
	58% - 33%	76% - 33%	76% - 58%
Tornillo	0.181 (3.8)[1]	0.213 (2.7)	0.257 (3.0)
Yellow birch	0.196 (2.5)	0.234 (1.4)	0.286 (2.3)
Congona	0.193 (3.2)	0.217 (4.7)	0.250 (9.5)
Beech	0.199 (1.5)	0.232 (1.3)	0.278 (2.9)
Cachimbo	0.194 (2.4)	0.222 (2.1)	0.260 (2.7)
Pumaquiro	n.a. [2]	n.a.	0.232 (2.1)
Huayruro	n.a.	n.a.	0.218 (5.4)

[1] Values between parentheses represent the coefficient of variation based on 20 specimens.
[2] n.a - not available.

varied among species. Noack et al. (1973) calculated s values for 28 species, on a range of relative humidities between ≈ 35 and ≈ 85%, and classified values of s smaller than 0.16 as very favorable sorption behavior, between 0.16 and 0.18 as favorable, between 0.18 and 0.22 as normal and larger than 0.22 as unfavorable. According to this classification, the s values (Table 6.2) indicate that the species have normal and unfavorable sorption behavior. Temperate hardwoods presented higher values of s, indicating that these species are more sensitive to changes in RH. Hernández (1989) studying tropical and temperate hardwoods observed that sugar maple had the higher s value and that species presenting high amount of extractives had higher hygroscopic stability. Even if in the present work desorption started from the full saturated state, the s value for *Robinia spp.* (0.22) obtained by Noack et al. (1973) agrees with the values of Table 6.2 for huayruro (*Robinia coccinea*).

Quantitative anatomical results

Table 6.3 shows the results of some quantitative anatomical properties for the seven species studied. A large variation of these properties among the twenty boards of each species was observed. The anatomical parameters with higher variability were the proportion of vessels (VP) for cachimbo (CV of 43%), the surface of individual rays (RS) for beech (CV of 44%)

and the proportion of axial parenchyma (APP) for yellow birch (CV of 68%) and for pumaquiro (CV of 47%). Thus, VP for cachimbo ranged from 4% to 16% with a mean of 8%, the RS for beech ranged from 2 474 μm^2 to 13 841 μm^2, the APP for yellow birch ranged from 0.12% to 1.09% and this same proportion for pumaquiro ranged from 1.27% to 6.43%. Beech wood is composed by rays of two distinct sizes and this fact contributed to the high variation of this parameter. This species presented 7% of rays with height larger than 500 μm.

An even higher variation was observed among wood species, which was expected since the species were chosen in function of their anatomical differences. For example, the proportion of vessels ranged from 5% to 28%, for huayruro and pumaquiro, respectively. According to the classification given by Richter and Dallwitz (2000), the number of vessels per mm^2 was very low (less than 5 vessels per mm^2), low (between 5 and 20 vessels per mm^2), moderately high (between 20 and 40 vessels per mm^2) and very high (more than 100 vessels per mm^2). Concerning the tangential diameter of vessels, the classification of the different species is small (beech), medium (yellow birch, pumaquiro and congona) and large (cachimbo, huayruro and tornillo). The large variability of the vessel dimension among the species can also be observed in Figure 6.3, where the frequency curves for the tangential vessel diameter of the seven species are presented. This figure also shows the Gaussian fit and it can be observed that the tangential vessel diameter follows a normal distribution for yellow birch, congona, beech, cachimbo, pumaquiro and huayruro, with a coefficient of determination (R^2) higher than 0.9. The normal distribution of the tangential vessel diameter was also observed by Kollmann (1987) for beech and boxwood. Figure 6.3 shows that tornillo was one exception from the normal distributions of the tangential vessel diameter; some samples of this species had multiple vessels with a distinct smaller diameter than the single vessels.

In general, the results of the anatomical parameters were in agreement with those of Acevedo and Kikata (1994) for the tropical hardwoods and with those of Panshin and de Zeeuw (1980) for the temperate hardwoods. Nevertheless, the basic density given by Acevedo and Kikata (1994) for pumaquiro (670 kg m^{-3}) and congona (680 kg m^{-3}) presented important differences in relation to the values obtained in the present study.

Table 6.3. Quantitative anatomical results.

Anatomical parameters [1]	Wood species						
	Tornillo	Yellow birch	Congona	Beech	Cachimbo	Pumaquiro	Huayruro
Vessel parameters							
VP (%)	8.4 (32.5) [2]	15.3 (15.8)	6.5 (15.1)	24.9 (21.9)	8.2 (42.6)	28.3 (13.6)	5.2 (32.0)
VS (μm^2)	42 228 (20.8)	7 281 (11.8)	7 361 (13.6)	1 710 (21.1)	15 773 (20.4)	8 419 (17.4)	24 653 (18.6)
VSM (number/mm^2)	2 (37.2)	21 (11.8)	9 (11.3)	147 (13.7)	5 (30.1)	34 (11.7)	2 (24.0)
VTD (µm)	255.3 (14.8)	86.2 (6.9)	94.9 (6.4)	40.3 (9.6)	137.7 (8.8)	90.3 (8.0)	171.9 (8.5)
VLD (µm)	288.75 (13.0)	127.5 (5.9)	121.7 (7.0)	58.9 (11.0)	182.1 (7.3)	134.5 (10.0)	213.8 (9.6)
VSD (µm)	207.1 (14.7)	82.8 (6.6)	85.1 (6.6)	37.9 (8.7)	122.9 (7.4)	84.6 (8.4)	152.7 (9.6)
VSF	1.39 (11.2)	1.54 (13.3)	1.43 (11.7)	1.55 (13.5)	1.48 (12.5)	1.59 (13.9)	1.40 (11.2)
Fiber parameters							
FP (%)	65.3 (6.4)	74.0 (3.6)	71.0 (4.9)	59.9 (9.8)	61.2 (10.5)	59.3 (7.7)	41.2 (12.7)
FLD (µm)	15.9 (18.0)	13.5 (12.7)	8.45 (8.9)	6.0 (18.3)	12.4 (14.8)	9.7 (17.3)	4.2 (15.7)
FSD (µm)	10.3 (18.4)	8.4 (17.2)	5.6 (11.6)	3.5 (21.3)	7.9 (17.0)	5.25 (17.1)	2.6 (16.4)
Ray parameters							
RP (%)	14.0 (17.0)	10.3 (10.3)	17.2 (16.1)	11.9 (21.9)	21.1 (18.2)	9.2 (18.5)	20.1 (13.9)
RS (μm^2)	2 854 (22.6)	2 551 (20.4)	10 482 (11.5)	6 812 (43.5)	6 826 (21.7)	2 293 (20.9)	11 702 (19.6)
RH (µm)	149.8 (8.4)	167.9 (13.8)	412.6 (12.9)	225.55 (22.8)	286.5 (12.4)	166.5 (12.0)	328.9 (10.0)
RW (µm)	25.3 (14.1)	15.8 (11.4)	36.3 (9.4)	26.4 (23.7)	29.4 (18.9)	17.2 (12.2)	46.7 (12.8)
RSF	5.92 (22.3)	10.61 (22.7)	11.36 (22.8)	8.53 (22.6)	9.74 (22.7)	9.69 (22.7)	7.05 (22.5)
Axial parenchyma parameter							
APP (%)	12.3 [3] (21.4)	0.4 (67.8)	5.3 (29.2)	3.3 (32.2)	9.5 (18.5)	3.2 (47.2)	33.5 (14.1)

[1] VP: vessel proportion; VS: individual vessel surface; VSM: number of vessel per mm^2; VTD: tangential vessel diameter; VLD: larger vessel diameter; VSD: smaller vessel diameter; VSF: vessel shape factor; FP: fiber proportion; FLD: larger diameter of fiber lumen; FSD: smaller diameter of fiber lumen; RP: ray proportion; RS: individual ray surface; RH: ray height; RW: ray width; RSF: ray shape factor; APP: axial parenchyma proportion.

[2] Values between parentheses represent the coefficient of variation based on 20 averages.

[3] APP of tornillo wood is based on 5 averages.

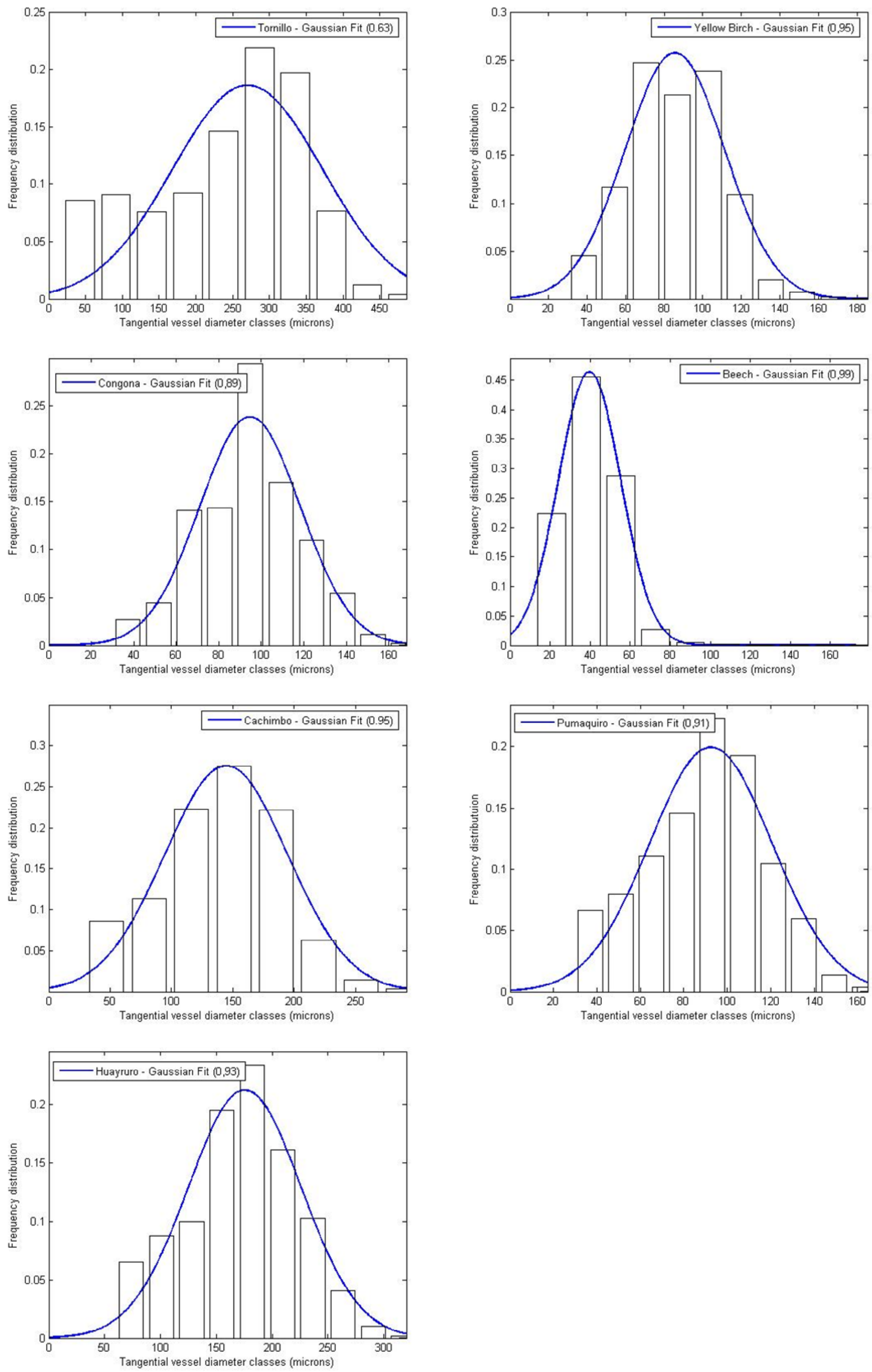

Figure 6.3. Frequency distribution of the tangential vessel diameter for the seven species studied.

Statistical analyses

Correlations between basic density and anatomical parameters

The correlations undertaken among the anatomical parameters showed that the seven species had different trends. For example, the ray parameters (surface of individual rays, ray height and width) were the most important elements affecting the basic density (BD) of beech. Specimens presenting higher quantity of small rays had higher density. It must be noticed that beech wood present two distinct types of ray elements, where the larger ones can attain a height of more than 1 mm. Keller and Thiercelin (1975) observed the positive correlation between the proportion of larger rays and wood density on beech. The vessel parameters (vessel surface, vessel proportion and vessel tangential diameter) were the most important elements affecting the BD of yellow birch, huayruro and pumaquiro, these elements having a negative correlation with the BD. A positive correlation between fiber proportion and BD was observed for congona, pumaquiro and huayruro. Smaller diameter of fiber lumen and BD had a negative correlation for congona and cachimbo woods. In the case of tornillo, no significant correlation was observed between BD and anatomical parameters.

When the values of all species are analyzed together, BD decreased as vessel parameters increased and as ray proportion decreased. The positive correlation between ray proportion and specific gravity in hardwoods was also reported by other researchers (Boyce et al. 1970; Taylor 1975; Rahman et al. 2005). Special attention must be taken in the interpretation of the results of the seven species together, for example, huayruro wood presents the highest density, smallest fiber proportion and highest axial parenchyma proportion among the seven species. However, the higher density of this species is due to the high thickness of its fiber walls.

Table 6.3 also shows that species presenting very similar basic density values (yellow birch, congona, beech and cachimbo) had variable proportions of anatomical elements. These differences will affect the EMC x anatomical relationships in different ways, depending on the wood species.

Relationships between sorption and anatomical parameters

The Pearson correlation results between EMC and anatomical parameters for the seven species are shown in Table 6.4. This table presents the full saturation and the EMC values obtained at RH higher than 96%, which were obtained by the pressure membrane method. In this procedure, the water potential values were in some way arbitrary fixed and, thus, the same ψ levels were used for the seven species. Ideally, these ψ levels should be selected based on the porous structure of each wood species in order to better determine the critical ψ values, where EMC changes abruptly. This would make easier the analysis of the influence of the different anatomical parameters on the sorption behavior of wood.

The influence of basic density and anatomical parameters on the full saturation and EMC values varied among species (Table 6.4). As expected, the full saturation moisture content was highly correlated with the BD, meaning that this MC state was achieved for all seven species. Wood density remains the principal variable explaining EMC obtained at -100 Jkg^{-1} ψ. For tornillo and huayruro, the BD had even negative correlation until -700 Jkg^{-1}. The vessels are the most permeable wood elements and the influence of this anatomical parameter is observed since the first step of drainage (-100 Jkg^{-1}), where porous presenting lower capillary resistance are already empty. Table 6.4 shows that EMC decreases as the vessel amount increases. Ray parameters were also correlated with the EMC values, this effect was combined with that of the vessel and wood density. For some wood species (beech, pumaquiro and huayruro) the effect of ray parameters is more marked at lower ψ values.

For RH values below 90%, it was observed that BD was the most important variable explaining the EMC variation. Figure 6.4 shows that BD negatively affects the EMC at 90%, 86% and 76% RH. The EMCs at 58% and 33% RH were not correlated with BD. The variable effect of BD on EMC can be explained by separating the bound water on two different components: the monomolecular water which is more strongly bonded by hydroxyl groups (taken as constant) and the weakly bound water (polymolecular water). This latter bound water component is a function of the amount of cell wall area exposed to the cell cavity (Čudinov 1981). As a result, the polymolecular water would

Table 6.4. Pearson correlation coefficients between the equilibrium moisture content (for each sorption condition) and anatomical parameters for the seven species studied.

Wood species	Sorption condition							
	Full saturation	-100 Jkg^{-1}	-300 Jkg^{-1}	-500 Jkg^{-1}	-700 Jkg^{-1}	-2 000 Jkg^{-1}	-4 500 Jkg^{-1}	-5 000 Jkg^{-1}
Tornillo	BD [1] -0.985 ** [2]	BD -0.824 **	BD -0.915 **	-	BD -0.645 **	ns	-	ns
Yellow birch	BD -0.984 **	BD -0.897 **; VSM -0.581 **	BD -0.834 **	-	VSM -0.505 *	VSM -0.541 *	-	VP -0.502 *
Congona	BD -0.793 **	BD -0.938 **; VSD 0.459 *	RSF 0.696 **; VTD -0.546 *	-	RW -0.743 **; VTD -0.482 *	VSM -0.446 *	-	RW -0.743 **
Beech	BD -0.997 **	RSF 0.515 *; VP -0.445 *	-	VTD -0.623 **	-	VS -0.466 *	RH 0.551 *; VSF -0.470 *	-
Cachimbo	BD -0.989 **	BD -0.874 **; VP -0.776 **	ns	-	Ns	ns	-	ns
Pumaquiro	BD -0.996 **	BD -0.670 **; RH 0.586 **	RH 0.509 *; BD -0.483 *	-	APP 0.476 *	RW -0.586 **	-	RS -0.546 *
Huayruro	BD -0.971 **	BD -0.977 **	BD -0.935 **	-	BD -0.928 **	RW 0.516 *	-	ns

[1] BD: basic density. Wood anatomy parameter: VP: vessel proportion; VS: individual vessel surface; VSM: number of vessel per mm^2; VTD: tangential vessel diameter; VSD: smaller vessel diameter; VSF: vessel shape factor; RS: individual ray surface; RH: ray height; RW: ray width; RSF: ray shape factor; APP: axial parenchyma proportion.

[2] n = 20; ** = significant at the 1% probability level; * = significant at 5% probability level; ns = non significant.

be associated to wood density. Consequently, one species with less density value would present a large quantity of available spaces and a higher EMC. The fact that at RH values higher than 76% liquid water is still present in wood can also explain the inverse relationship between EMC and wood density. Hernández (1989) observed that with the decrease of the EMC the effect of wood density decreases, which may explain the fact that in present work lower EMC values were not correlated with wood density. Arévalo (2002) noticed the negative effect of the wood density on the EMC values in the hygroscopic range for mahogany wood. Nevertheless, this author also observed that in the hygroscopic range the influence of the wood density and anatomical parameters was slight compared to that associated to the extractives substances. Figure 6.4 also shows that tornillo wood presents a different behavior compared to the other six species, which suggest that other facts than wood density should be considered in the study of EMC.

The influence of the anatomical parameters on the ratio of sorption (s) and FSP is showed in Figure 6.5. As discussed before, pumaquiro and huayruro results at 33% RH were not included in this work due to experimental problems. As earlier explained, the ratio of sorption represents how the wood is affected by the changes in RH and this ratio changed according to the RH range studied (Table 6.2). Figure 6.5 shows that vessel parameters and basic density influenced this ratio. The tangential diameter of vessels was negatively correlated with vessel shape factor, which explains the trends observed on Figures 6.5A and 6.5B. The negative influence of wood density on ratio of sorption is presented on Figures 6.5C and 6.5D, where species with higher density presents more hygroscopic stability. This effect was also observed by other researchers for tropical and temperate wood species (Hernández 1989; Arévalo 2002). Nevertheless, Hernández (1989) and Arévalo (2002) also observed that the wood extractives located in the cell walls presented a high influence on the hygroscopic stability. This effect may explain the differences observed between Figures 6.5C (tropical and temperate species) and 6.5D (only tropical species). Figure 6.5C shows that temperate species present a smaller hygroscopic stability (higher s ratio) compared to its basic density values.

The effect of anatomical parameters on FSP can be observed in Figure 6.6. This figure shows that the FSP decreases as basic density increases. This could be explained by the

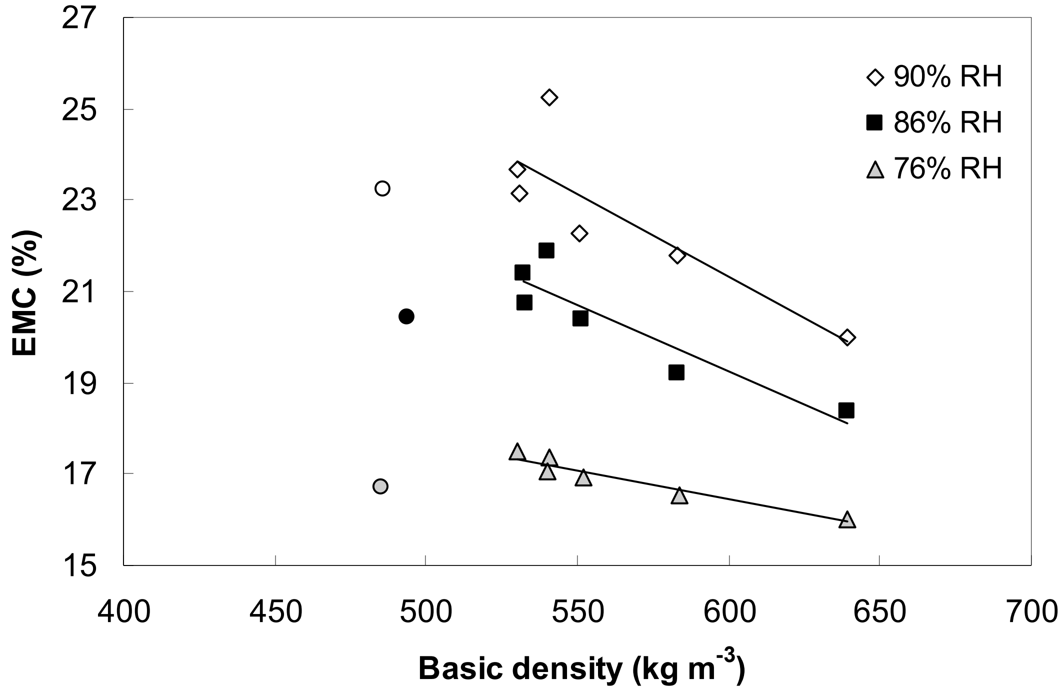

Figure 6.4. Relationship between basic density and EMC for the seven species studied. Linear regressions: EMC $_{90\%RH}$ = -0.036BD + 42.8 (R^2 = 0.73); EMC $_{86\%RH}$ = -0.029BD + 36.7 (R^2 = 0.84) and EMC $_{76\%RH}$ = -0.013BD + 24.2 (R^2 = 0.92) (tornillo wood is not included in these regressions). Symbols ○, ● and ◉ indicate tornillo EMC values determined on boundary desorption at 90% RH, 86% RH and 76% RH, respectively.

separation of the bound water in two components (monomolecular and polymolecular water). This latter bound water component increases, in relative value, as wood density decreases (Čudinov 1981). According to Feist and Tarkow (1967), lack of restraint can also explain the high FSP for low-density wood. Hernández (1989) and Arévalo (2002) also observed that wood density had a negative effect on FSP. Nevertheless, these researchers observed that wood extractives, especially the extractives soluble in acetone, have a large influence on the FSP. The differences observed between Figures 6.6A (tropical and temperate species) and 6.6B (only tropical species) show that wood density is not the only fact affecting the FSP. Figure 6.6A shows that temperate species present a higher FSP than that of tropical hardwoods at a similar basic density value.

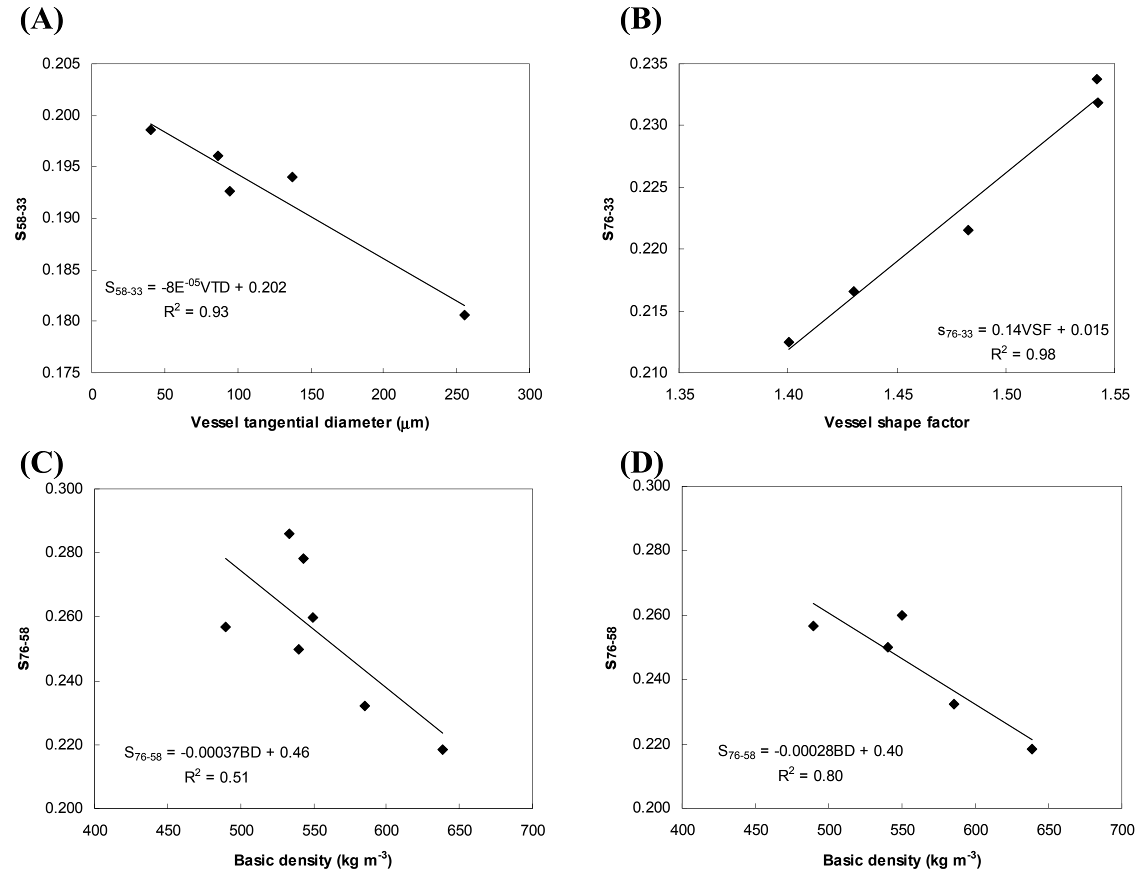

Figure 6.5. Relationship between anatomical parameters, basic density and the sorption ratio (s) using average values of the species studied. A: $s_{58\text{-}33}$ x vessel tangential diameter (VTD). B: $s_{76\text{-}33}$ x vessel shape factor (VSF). C: $s_{76\text{-}58}$ x basic density (BD) for temperate and tropical hardwoods. D: $s_{76\text{-}58}$ x basic density (BD) for tropical hardwoods. (Pumaquiro and huayruro results at 33% RH were not included in figures A and B due to experimental problems).

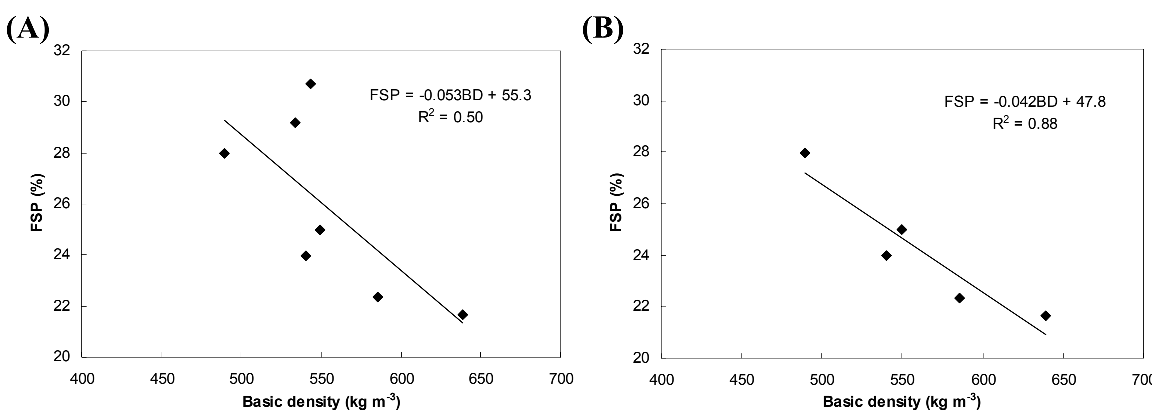

Figure 6.6. Relationship between basic density (BD) and the fiber saturation point (FSP). A: average values of tropical and temperate hardwoods. B: average values of tropical hardwoods.

6.6 Conclusions

The influence of the anatomical elements on the sorption behavior was studied on two temperate and five tropical hardwoods. Two experimental techniques were used to perform moisture sorption tests at 25ºC (between 33% and ≅100% RH). The results were associated with wood density and quantitative anatomical parameters. The analysis of these results led to the following conclusions:

1. In the region of high RH (above 96% RH), the anatomical structure affected differently the drainage curve of each species. Wood density negatively affected the EMC of all species studied. The vessel parameters also played an important role in the water drainage in the majority of the wood species, specimens with larger quantity of vessels had a lower EMC.

2. At RH values lower than 90%, wood density was negatively correlated with the EMC. The effect of wood density was not observed at low RH values (33% and 58% RH).

3. The vessel parameters and wood density also affected the ratio of sorption (s). Denser woods had more hygroscopic stability.

4. Wood species of higher densities had lower FSP values.

5. The comparison between temperate and tropical hardwoods results demonstrates that other factors than wood density and anatomical parameters play an important role on its sorption characteristics.