# CHAPITRE 7. Effect of the anatomical parameters on the dimensional stability of some temperate and tropical hardwoods

## 7.1 Résumé

L'influence des éléments anatomiques sur la stabilité dimensionnelle du bois a été étudiée sur deux feuillus tempérés et cinq feuillus tropicaux. Des essais de désorption à 25°C ont été effectués à l'aide de solutions salines saturées (valeurs entre 33% et 90% d'humidité relative) et de la membrane poreuse sous pression (au-dessus de 96% d'humidité relative). Des mesures dimensionnelles ont accompagné ces essais. Des coupes transversales et tangentielles de ces sept espèces ont été préparées pour quantifier les éléments anatomiques. Une analyse statistique a permis de préciser leur rôle sur la stabilité dimensionnelle du bois. Les résultats ont montré des différences importantes du retrait entre les espèces étudiées. À masses volumiques similaires, le retrait des espèces tempérées fut largement supérieur à celui des espèces tropicales. Le retrait du bois a débuté à des valeurs d'humidité d'équilibre plus élevées que le point de saturation des fibres, ce qui indique que la perte de l'eau liée a lieu en présence d'eau liquide. Des analyses de corrélation ont montré que la teneur en humidité d'équilibre à laquelle le retrait a débuté est positivement corrélée à la proportion des rayons. Cela corrobore l'hypothèse selon laquelle l'eau liquide la plus réfractaire à quitter le bois serait logée dans les tissus de rayon. Le retrait différentiel (g) est inversement proportionnel au plus petit diamètre des lumens des fibres (FSD), ce qui indique que les espèces ayant une faible épaisseur de paroi sont plus stables. Les paramètres anatomiques qui expliquent le mieux le facteur de retrait (m) sont reliés aux éléments des vaisseaux. Les espèces à grands vaisseaux (tornillo, cachimbo and huayruro) ont de facteurs m plus faibles que l'unité, ce qui indique qu'il y a eu une augmentation des cavités cellulaires.

## 7.2 Abstract

The influence of the anatomical elements on the dimensional stability was studied on two temperate and five tropical hardwoods. Desorption essays at 25°C were made using saturated salt solutions (from 33% to 90% relative humidity) and pressure membrane procedures (above 96% relative humidity). These essays were combined with dimensional measurements. Transverse and tangential sections of the seven species were obtained in order to evaluate quantitative anatomical parameters. Statistical analyses were made to evaluate the role played by the anatomical elements on the dimensional stability of wood. The results showed a large variation in the shrinkage values among the species studied. At similar basic densities, temperate species had larger shrinkage than tropical species. At equilibrium conditions, shrinkage starts at EMC values higher than the fiber saturation point for the seven wood species, meaning that bound water starts to be removed in presence of liquid water. The EMC value at which shrinkage starts increase as ray proportion increase, indicating that this entrapped liquid water must be principally located in the ray cells. The dimensional stability parameters, differential shrinkage (q) was inversely proportional to the smaller diameter of fiber lumen (FSD), showing that species with thin fiber wall (small density) have more dimensional stability. The anatomical parameters that more influenced shrinkage factor (R) were related to vessel elements. Species presenting large vessel dimensions (tornillo, cachimbo and huayruro) presented more variation of the cell cavities (smaller shrinkage factor).

## 7.3 Introduction and background

In the use of the wood material, hygroscopic and anisotropic, the knowledge of the dimensional properties is very important. The biological nature of wood makes its study even more complex. Concerning the wood anatomical characteristics, the structure of the hardwoods is more complex and variable compared to that of softwoods. In temperate hardwood species, the vessel proportion is approximately 30% with a range from 6.5 to 55% (Panshin and de Zeeuw 1980). Fibers may account for 20% to 70% of wood volume depending on the species. 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 large variability of anatomical parameters among species gives different dimensional properties.

The influence of the anatomical elements on the dimensional properties of wood was studied by several works. Trenard and Guéneau (1977) studied shrinkage, morphological and density characteristics of five firs and three beechs. It was observed that the shrinkage phenomenon is presented in the macroscopic level on a complex form and for this reason it was difficult to establish simple relations between the anatomical structure and the shrinkage of wood. They also observed that the lumina dimensions and wall thickness better explained the wood shrinkage than the macroscopic parameters (as growth ring). Another work studied the influence of the large wood rays on the shrinkage of beech wood (*Fagus sylvatica*) (Keller and Thiercelin 1975). It was observed that the number of large rays per square centimeter was positively correlated with the radial and tangential shrinkage. Also, the radial shrinkage decreased as the large ray dimension increased. The effect of wood structure and extractives on swelling of mahogany wood was studied by Arévalo (2002). The shape of rays and vessels were the most important anatomical parameters affecting tangential and radial swellings. However, their effect on wood swelling was quite lower than that related to extractives.

Several works also reported the proportionality between shrinkage and wood density in woods with low extractives (Stamm 1964; Noack et al. 1973). For instance, it has been observed that the presence of extractives in cell walls enhances dimensional stability of wood and limit shrinkage (Hernández 1989; Mantanis et al. 1995; Arévalo 2002).

Early works, as Barkas (1941), reported that the rays are responsible for asymmetrical shrinkage across the grain, which will partially inhibit the free shrinkage of the wood in the radial direction. Boyd (1974) studying softwoods found that the ray-restraint mechanism is not an important factor of the transverse dimensional anisotropy while it is for hardwoods.

It is normally assumed that between about 20% and 7% equilibrium moisture content (EMC) the slope of relationship between shrinkage and EMC is constant and that the shrinkage starts at the fiber saturation point (FSP). The FSP is defined as the moisture content (MC) at which the cell walls are saturated with bound water with no free water in the cell cavities (Tiemann 1906). Below this point, bound water is removed from the cell wall and appreciable shrinkage will occur. However, a study focusing on high humidities (above 96% RH) demonstrated that at the EMC, changes in transverse and volumetric shrinkage, as well as changes in transverse strength, occur above the nominal FSP (Hernández and Bizoň 1994). The results of this study and those observed in items 2.5 and 3.5 were made on temperate and tropical hardwood species and it was observed that bound water is removed in the presence of liquid water within the wood structure. This remaining liquid water would be located in the regions less permeable of the wood structure. During desorption, a region exists where the loss of bound water takes place in the presence of liquid water. This range will depend on the size distribution of wood capillaries and, as a result, this will vary among wood species.

The stability of wood is one important factor in its utilization. A stable wood is one that exhibits small dimensional changes in conditions of oscillating relative humidity (RH) and a small distortional tendency (Torelli and Gorisek 1995; Choong et al. 1998). Noack et al. (1973) proposed the differential shrinkage (ratio of shrinkage) q to quantify the dimensional stability of wood. This parameter indicates the percentage change of tangential and radial dimensions when the moisture content (MC) changes by 1%. According to this researcher, q can be considered to be constant in the range of MCs between 7% and 20%, a range that is important for the practical application of wood. Another useful parameter for describing dimensional stability is the shrinkage factor R. Various expressions have been used for the shrinkage factor, including R ratio (Chafe 1987) and specific moisture expansion coefficient MX (Skaar 1988). According to Chafe (1987), this factor represents the change in the external volume of wood during shrinkage or swelling per change in the weight of an equivalent volume of water. R equals 1 if the cell cavity remains constant in size and if the swelling or shrinkage of the cell wall is equal to the volume of water added or removed (Stamm 1964; Skaar 1988).

The principal objective of the present work was to improve the knowledge about the effect of the different anatomical elements on the dimensional properties of wood. In order to account with a large variation of wood structure, two temperate and five tropical hardwoods were analyzed. The dimensional properties were evaluated at EMC under desorption conditions at 25°C. Matched samples of the sorption tests were used to determine the anatomical parameters.

## 7.4 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% relative humidity (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 physical, mechanical and anatomical analyses. Twenty specimens of each wood species were used for the quantitative anatomical analysis.

In the preparation of the anatomical samples, several species were very difficult to be softened and, in order to improve the quality of the microtome sections, a method based on Kukachka (1977) was applied on wood blocks of 1 $cm^3$. After this treatment, microtome samples of transversal (20 μm) and tangential-longitudinal (30 μm) sections were prepared. The sections was double stained with safranin and fast-green, and permanently mounted on glass slides.

## EXPERIMENTS

### ***Sorption tests***

Twenty samples per species were tested on each desorption condition. Prior to the desorption tests, specimens were saturated in three steps until their full moisture content was reached. This was done in order to avoid internal defects caused by a rapid moisture adsorption (Naderi and Hernández 1997). Thus, specimens were conditioned over a KCl saturated salt solution for 30 days, then over distilled water for at least 60 days and finally they were immersed in distilled water until full saturation by cycles of vacuum and pressure. At this state, their full saturated masses were measured to the nearest 0.001 g with a digital balance and dimensions in all principal directions were taken to the nearest 0.001 mm with a digital micrometer.

The sorption tests were conduct at 25°C and required two experimental techniques. The first technique was the saturated salt solutions (from 33% to 90% RH). In the second one, specimens were conditioned following a pressure membrane procedure (above 96% RH). Table 7.1 shows some characteristics of the sorption tests. In the present work, just three conditions per species obtained by the pressure membrane procedure will be presented (lower than 99.492% RH). A complete description of these two methods and the conditioning time were reported in items 2.4 and 5.4.

The saturated salt solutions use sorption vats described in detail by Goulet (1968). These vats provide a temperature control of ± 0.01°C during extended periods, thus allowing for precise RH control in the various desiccators serving as small sorption chambers. For each point of sorption, one desiccator containing twenty samples was used. All five desorption conditions were over saturated salt solutions in a single step procedure, excepting samples of pumaquiro and huayruro conditioned at 33% RH where desorption was made in two steps. For each point of sorption, control specimens were weighed periodically, without being removed from the desiccator. It was assumed that the EMC was reached when the loss (desorption) or gain (adsorption) in MC was at least less than 0.007% MC per day. As soon as each sorption test was completed, the sample mass was measured to the nearest 0.001g. Dimensions in all principal directions were taken to the nearest 0.001 mm with a micrometer.

The differences in dimensions of specimens after full moisture saturation and at EMC were used to estimate the partial percent shrinkage in the tangential ($\beta_{TH}$) and radial ($\beta_{RH}$) direction of the wood. Volumetric shrinkage was estimated to be the summation of these two directional shrinkages ($\beta_{TH} + \beta_{RH} - \beta_{TH} \times \beta_{RH}$). The mass of the specimens at the equilibrium state and their mass measured after oven-drying were used to calculate the EMC, expressed as a percentage of oven-dry mass. The results of mass and volume were also used to calculate the basic wood density (oven-dry mass to green volume) for each wood specimen.

The equations of the dimensional parameters used in this work are shown below (equations 7.1 and 7.2):

Differential shrinkage q:

$$q_{(EMC_1-EMC_2)} = \frac{\beta_{EMC_1} - \beta_{EMC_2}}{EMC_2 - EMC_1} \tag{7.1}$$

where: $\beta_{EMC1}$ is the radial, tangential or volumetric shrinkage at $EMC_1$; $\beta_{EMC2}$ is the radial, tangential or volumetric shrinkage at $EMC_2$.

Shrinkage factor R:

$$R(EMC_1 - EMC_2) = \frac{q_v(EMC_1 - EMC_2)}{BD(EMC_1 - EMC_2)} = \frac{\Delta V}{\Delta M_{water}} \qquad (7.2)$$

where: $q_{v(EMC1-EMC2)}$ is the volumetric differential shrinkage between $EMC_1$ and $EMC_2$; BD is the basic density of two specimens equilibrated at $EMC_1$ and $EMC_2$ (g $cm^{-3}$); ΔV is the volumetric variation between the volumetric dimension at $EMC_1$ ($cm^3$) and that at $EMC_2$ ($cm^3$); $\Delta M_{water}$ is the weight of water variation between $EMC_1$ (g) and $EMC_2$ (g).

In the equation 7.2 is considered that weight of water (g) is equal to volume of water ($cm^3$) and R can be expressed in terms of change in wood volume per change in volume of water, or as a dimensionless ratio.

### ***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 dimensional 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 it was also determined the proportion of axial parenchyma (APP). 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 in the statistical analysis.

### *Statistical analysis*

The results of the seven species were combined in the analysis of the influence of anatomical parameters on the dimensional properties. Only the average values were used. 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 dimensional properties.

## 7.5 Results and discussion

### *Dimensional properties*

EMC values of the seven wood species are presented in Table 7.1. The basic density values as well as the partial tangential and radial shrinkage results are presented in Table 7.2. The shrinkage values largely varied among species. Considering the values at 33% RH, tornillo results were of 2.7%, 5.1% and 7.7% for radial, tangential and volumetric shrinkage, respectively. In contrast, beech results were of 3.9%, 9.4 and 12.9% for radial, tangential and volumetric shrinkage, respectively. Beech is known for its large tangential shrinkage and high dimensional anisotropy, which is confirmed by the results presented in Table 7.2. According to Panshin and de Zeeuw (1980), the total tangential and radial shrinkage values of beech and yellow birch are 11.9%-5.5% and 9.5%-7.5%, respectively. Even if Table 7.2 shows partial shrinkage (until 33% RH), the results cited by Panshin and de Zeeuw (1980) can be considered similar to those shown in this table.

The ratio of tangential to radial shrinkage (T/R) is also presented in Table 7.2. This ratio is

Table 7.1. Characteristics of the moisture sorption conditions at 25°C and results of the equilibrium moisture content (EMC) for the seven species studied.

| Nominal relative humidity (%) | EMC (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Tornillo | Yellow birch | Congona | Beech | Cachimbo | Pumaquiro | Huayruro |
| 99.492<br>(-700 $\text{Jkg}^{-1}$) [1] | 95.63<br>(5.2) [3] | 41.18<br>(3.6) | 43.39<br>(13.8) | - | 56.04<br>(5.4) | 44.80<br>(6.4) | 77.29<br>(5.2) |
| 98.557<br>(-2 000 $\text{Jkg}^{-1}$) | 51.50<br>(11.4) | 38.58<br>(3.0) | 39.36<br>(3.5) | 40.19<br>(2.4) | 45.71<br>(7.7) | 36.35<br>(9.0) | 48.55<br>(7.8) |
| 96.782<br>(-4 500 $\text{Jkg}^{-1}$) | - | - | - | 35.16<br>(2.3) | - | - | - |
| 96.431<br>(-5 000 $\text{Jkg}^{-1}$) | 36.49<br>(3.1) | 34.62<br>(5.9) | 30.29<br>(3.0) | - | 30.24<br>(5.7) | 33.07<br>(9.3) | 25.01<br>(8.4) |
| 90<br>($ZnSO_4$) [2] | 23.22<br>(1.6) | 23.66<br>(1.0) | 23.13<br>(2.2) | 25.23<br>(1.8) | 22.26<br>(1.7) | 21.80<br>(1.4) | 19.97<br>(3.1) |
| 86<br>(KCl) | 20.44<br>(1.8) | 21.40<br>(1.4) | 20.75<br>(1.3) | 21.87<br>(1.4) | 20.40<br>(1.4) | 19.20<br>(0.6) | 18.37<br>(2.6) |
| 76<br>(NaCl) | 16.73<br>(1.9) | 17.51<br>(0.9) | 17.06<br>(2.7) | 17.37<br>(0.8) | 16.92<br>(1.8) | 16.55<br>(0.6) | 16.02<br>(2.1) |
| 58<br>(NaBr) | 12.11<br>(1.9) | 12.36<br>(1.1) | 12.57<br>(1.2) | 12.37<br>(0.4) | 12.25<br>(1.9) | 12.37<br>(0.5) | 12.09<br>(1.4) |
| 33<br>($MgCl_2$) | 7.59<br>(1.6) | 7.46<br>(0.5) | 7.75<br>(0.9) | 7.40<br>(0.8) | 7.40<br>(2.0) | 6.51 [4]<br>(0.8) | 6.31 [4]<br>(1.3) |

[1] Pressure membrane method.

[2] Saturated salt solution.

[3] Values between parentheses represent the coefficient of variation of EMC based on 20 specimens.

[4] An intermediate desorption step in a climate room (20°C, 40% RH) generated this result.

a parameter used to evaluate the anisotropy of shrinkage of a given wood. Beech and congona woods present the higher T/R value. Panshin and de Zeeuw (1980) reported T/R values of 2.2 and 1.3 for beech and yellow birch, respectively. Even if these values were obtained at total shrinkage, they confirm the trend observed in Table 7.2 for these two species. McIntosh (1957) observed that when the large rays are excluded from transverse sections of beech, the T/R ratio was reduced from 1.96 to 1.73. It appears, therefore, that large rays account for about 24% of the T/R ratio above unity. According to Panshin and de Zeeuw (1980), the T/R shrinkage ratio averages of some temperate and imported woods is 1.8, showing that yellow birch, cachimbo and huayruro woods can be considered as species with a good T/R ratio.

Table 7.2. Basic density and shrinkage values of the seven species studied.

| Wood species | Basic density ($kg\ m^{-3}$) | Wood shrinkage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 33% RH | | | 58% RH | | | 76% RH | | |
| | | T | R | T/R | T | R | T/R | T | R | T/R |
| Tornillo | 490 | 5.06 | 2.74 | 1.85 | 3.81 | 2.08 | 1.83 | 2.87 | 1.47 | 1.96 |
| | (3.5) [1] | (6.7) [2] | (11.3) | | (8.5) | (13.6) | | (7.5) | (9.7) | |
| Yellow birch | 533 | 6.51 | 4.64 | 1.40 | 5.11 | 3.26 | 1.57 | 3.70 | 2.25 | 1.64 |
| | (4.0) | (11.0) | (8.4) | | (11.1) | (10.8) | | (10.3) | (8.3) | |
| Congona | 540 | 5.50 | 2.65 | 2.07 | 3.94 | 1.80 | 2.19 | 2.43 | 1.02 | 2.39 |
| | (4.3) | (14.2) | (18.5) | | (18.6) | (15.6) | | (24.2) | (17.6) | |
| Beech | 543 | 9.37 | 3.93 | 2.38 | 7.45 | 2.73 | 2.73 | 5.58 | 1.95 | 2.86 |
| | (2.9) | (2.9) | (5.8) | | (3.5) | (9.0) | | (4.9) | (11.8) | |
| Cachimbo | 550 | 4.91 | 3.36 | 1.46 | 3.68 | 2.33 | 1.58 | 2.33 | 1.44 | 1.62 |
| | (5.4) | (13.5) | (16.5) | | (15.1) | (20.3) | | (21.1) | (23.8) | |
| Pumaquiro | 585 | 5.69 | 3.27 | 1.74 | 3.78 | 1.86 | 2.03 | 2.14 | 1.12 | 1.92 |
| | (2.7) | (3.8) | (8.1) | | (4.8) | (12.6) | | (6.4) | (14.4) | |
| Huayruro | 639 | 5.49 | 3.42 | 1.61 | 3.44 | 1.97 | 1.75 | 1.91 | 1.22 | 1.57 |
| | (3.5) | (8.6) | (7.6) | | (11.6) | (14.8) | | (12.2) | (22.5) | |

[1] Values between parentheses represent the coefficient of variation of basic density based on 240 specimens.

[2] Values between parentheses represent the coefficient of variation of wood shrinkage based on 20 specimens.

The volumetric shrinkage as a function of RH and EMC for the seven wood species is shown in Figure 7.1. The higher shrinkage values corresponded to the temperate hardwoods. The tropical hardwoods usually present a high amount of extractives, which may be located in the fine structure of the cell wall, normally occupied by water. Choong et al. (1998), studying tropical wood with high amounts of extractives, reported that the removal of these substances with hot water and organic solvents caused increased shrinkage.

The volumetric shrinkage as a function of EMC of the seven wood species are also presented in the Figure 7.2. This figure also displays EMC values obtained by porous membrane method. The FSP values for the seven species are shown on the ordinate axes of this figure. This property was determined by the volumetric shrinkage intersection point method. Thus, the FSP is defined as the MC at which the extended straight linear portion of the shrinkage-MC curve intersects the line of zero shrinkage. For this estimation, only volumetric shrinkage values obtained between 33% and 76% RH were used. It can be observed that for all wood species shrinkage starts before the FSP was reached. According to results observed in items 2.5 and 3.5, during desorption a region exists where the loss of bound water takes place in the presence of liquid water. This region will depend on the size distribution of wood capillaries and, as a result, this will vary among wood species.

The analyses of the total shrinkage alone may be of little value for wood in service, since wood is rarely used in the complete dry conditions. Thus, the differential shrinkage q is more useful to indicate the wood stability within a range of EMC variation. Table 7.3 presents the differential tangential, radial and volumetric shrinkages at 3 ranges of RH for all species studied. Generally, the values obtained for the three ranges of RH were similar, this fact confirms that for some species the hypothesis of linearity of the shrinkage between 76% and 33% RH can be used. As mentioned before, this parameter represents the slope of the shrinkage - EMC curve (Figure 7.1B). Table 7.3 and Figure 7.1B show that beech, pumaquiro and huayruro have similar q values, yet they exhibit different shrinkage values. Table 6.2 shows that beech wood presented a higher ratio of sorption (s) than pumaquiro and huayruro. This ratio indicates the amount of change in EMC with a change of RH of 1% (the slope of a sorption isotherm within the RH range considered). This fact represents that beech has more changes in EMC with a change of RH of 1% than pumaquiro and

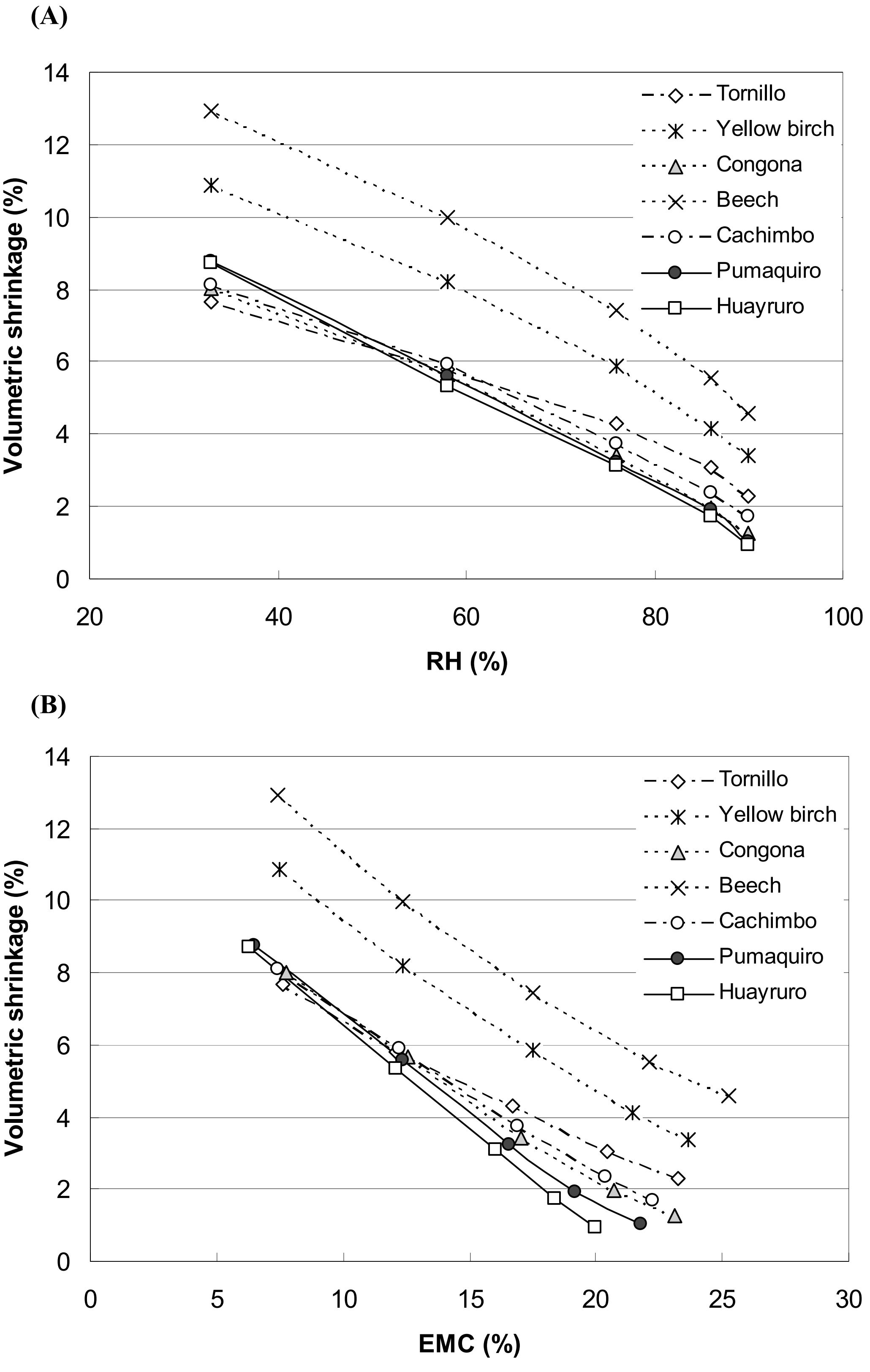

Figure 7.1. Volumetric shrinkage as a function of relative humidity (A) and equilibrium moisture content (B) for the seven species studied.

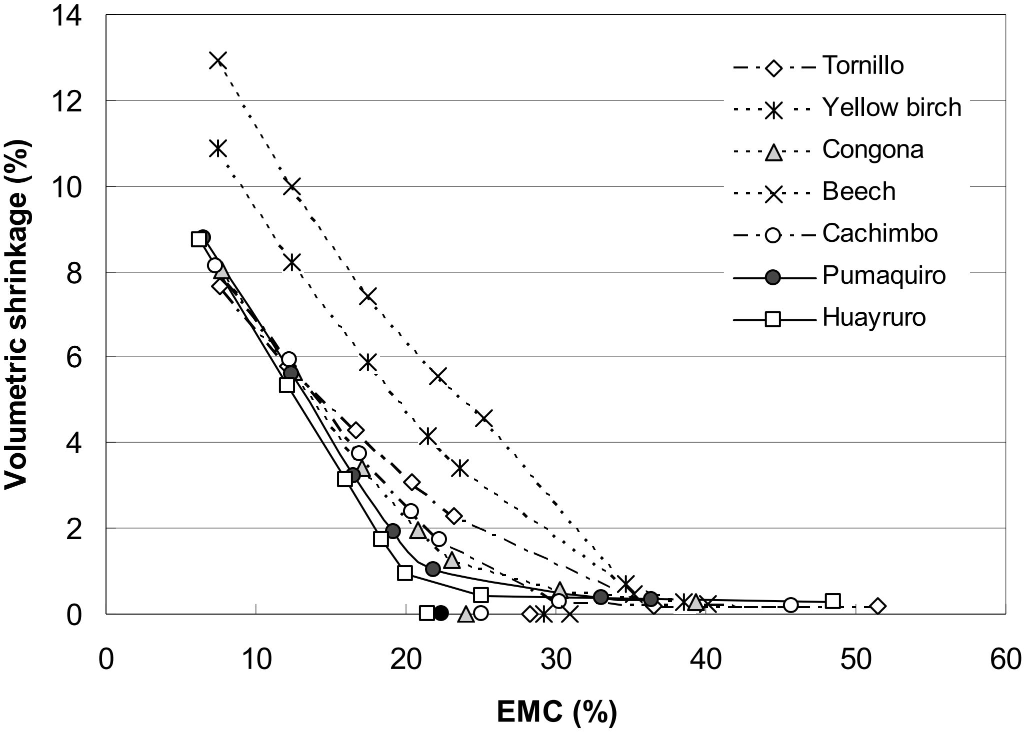

Figure 7.2. Volumetric shrinkage as a function of equilibrium moisture content for the seven species studied. Symbols at ordinate axes represent the FSP estimated by the volumetric shrinkage intersection method for each wood species.

huayruro. Thus, even if beech, pumaquiro and huayruro have similar q values, the fact that beech is more sensitive to changes on RH explains the higher shrinkage value of this species. Choong et al. (1998) also observed species presenting the same q values and different total shrinkage. These researches related that this was due to differences in FSP, which can be very low in tropical woods. Noack (1973) classified the differential shrinkage in the tangential direction, within a range of relative humidities between ≈ 35 and ≈ 85%, as favorable ($q_T < 0.3$), normal ($q_T$ between 0.3 and 0.4) and unfavorable ($q_T > 0.4$). Table 7.3 shows that tornillo, yellow birch and cachimbo may be considered as favorable q values, congona a normal q value and beech, pumaquiro and huayruro as wood species close of the unfavorable shrinkage behavior.

The shrinkage factor (R) is presented in Table 7.4. According to Chafe (1986), a R value > 1 suggests decrease in lumen volume during shrinkage and a R value < 1 suggests an increase in lumen volume. The R value varied among species, but in general its value was smaller than 1, showing an increase of lumen volume during desorption. Based on Table

Table 7.3. Differential shrinkage values at three ranges of relative humidity (RH) for the seven species studied.

| Wood species | Differential shrinkage (q) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 58-33 % RH | | | 76-33 % RH | | | 76-58 % RH | | |
| | R [1] | T | V | R | T | V | R | T | V |
| Tornillo | 0.15 | 0.28 | 0.46 | 0.14 | 0.24 | 0.40 | 0.14 | 0.20 | 0.35 |
| | (35.9) [2] | (18.1) [3] | (18.6) | (17.8) | (8.5) | (10.4) | (31.05) [2] | (16.8) | (21.4) |
| Yellow birch | 0.28 | 0.29 | 0.54 | 0.24 | 0.28 | 0.50 | 0.20 | 0.27 | 0.45 |
| | (15.2) | (14.6) | (12.1) | (13.5) | (12.4) | (10.9) | (25.1) | (13.6) | (15.5) |
| Congona | 0.20 | 0.32 | 0.49 | 0.19 | 0.33 | 0.49 | 0.18 | 0.34 | 0.51 |
| | (14.0) [2] | (8.0) | (19.3) | (15.0) [2] | (9.7) | (13.4) | (23.2) | (16.9) | (18.1) |
| Beech | 0.24 | 0.39 | 0.59 | 0.20 | 0.38 | 0.55 | 0.16 | 0.37 | 0.51 |
| | (20.9) | (9.6) | (10.5) | (10.8) | (6.4) | (6.2) | (35.6) | (8.8) | (11.5) |
| Cachimbo | 0.21 | 0.26 | 0.45 | 0.20 | 0.27 | 0.46 | 0.19 | 0.29 | 0.47 |
| | (18.8) | (12.8) | (10.7) | (12.3) | (7.6) | (7.7) | (17.0) | (7.0) | (8.4) |
| Pumaquiro | 0.24 | 0.32 | 0.56 | 0.21 | 0.35 | 0.56 | 0.18 | 0.39 | 0.57 |
| | (19.6) | (6.6) | (10.9) | (10.9) | (3.8) | (4.9) | (28.0) | (4.6) | (11.5) |
| Huayruro | 0.25 | 0.35 | 0.59 | 0.23 | 0.37 | 0.58 | 0.19 | 0.39 | 0.56 |
| | (12.8) | (4.8) | (7.5) | (12.7) | (6.6) | (8.3) | (29.7) | (10.6) | (16.8) |

[1] R: radial differential shrinkage; T: tangential differential shrinkage; V: volumetric differential shrinkage.

[2] Coefficient of variation based on 19 specimens.

[3] Values between parentheses represent the coefficient of variation based on 20 specimens.

Table 7.4. Shrinkage factors at three ranges of relative humidity (RH) for the seven species studied.

| Wood species | Shrinkage factor (R) | | |
|---|---|---|---|
| | 58 – 33% RH | 76 – 33 % RH | 76 – 58 % RH |
| Tornillo | 0.95<br>(17.5) [1] | 0.83<br>(10.0) | 0.71<br>(22.1) |
| Yellow birch | 1.02<br>(11.4) | 0.93<br>(8.7) | 0.85<br>(13.0) |
| Congona | 0.90<br>(19.1) | 0.91<br>(11.6) | 0.93<br>(15.4) |
| Beech | 1.10<br>(10.8) | 1.02<br>(5.7) | 0.94<br>(10.5) |
| Cachimbo | 0.82<br>(9.2) | 0.83<br>(6.9) | 0.85<br>(8.8) |
| Pumaquiro | 0.96<br>(10.8) | 0.97<br>(4.9) | 0.97<br>(11.5) |
| Huayruro | 0.92<br>(7.7) | 0.90<br>(8.0) | 0.88<br>(16.3) |

[1] Values between parentheses represent the coefficient of variation based on 20 specimens.

7.4, the lumen volume of pumaquiro wood almost did not change during desorption, which is in agreement with the assumption of Stamm (1964) and other works. Chafe (1986) also observed that R values varied from 1, with a higher proportion of values between 0.8 and 1.2. R values of tornillo, yellow birch and beech were not constant on the hygroscopic ranges studied. In order to assure the linearity of the shrinkage - EMC relationship, Hernández (1989) only determined R values in desorption on the range between 58 and 33 % RH. This author obtained R value for pumaquiro wood of 0.92, the high variation of this parameter (coefficient of variation of 10.8%) shows its large variability within the same species.

### *Correlations between dimensional properties and anatomical parameters*

The anatomical parameters whose most influenced the dimensional properties are shown in Table 7.5. As discussed earlier, beech wood was the species presenting higher tangential and volumetric shrinkage. The presence of large rays in this species (can attaint a height of more than 1 000 μm) affect its dimensional properties. McIntosh (1957) studying the effect of large rays on dimensional properties of beech and red oak reported that large rays possess a relatively large tangential shrinkage.

Table 7.5. Quantitative anatomical parameters for the seven wood species.

| Anatomical parameters [1] | Wood species | | | | | | |
|---|---|---|---|---|---|---|---|
| | Tornillo | Yellow birch | Congona | Beech | Cachimbo | Pumaquiro | Huayruro |
| | Vessel parameters | | | | | | |
| VP (%) | 8.4<br>(32.5) [2] | 15.3<br>(15.8) | 6.5<br>(15.1) | 24.9<br>(21.9) | 8.2<br>(42.6) | 28.3<br>(13.6) | 5.25<br>(32.0) |
| VS ($\mu m^2$) | 42 228<br>(20.8) | 7 281<br>(11.8) | 7 361<br>(13.6) | 1 710<br>(21.1) | 15 773<br>(20.4) | 8 419<br>(17.4) | 24 653<br>(18.6) |
| VSD ($\mu m$) | 207.05<br>(14.7) | 82.8<br>(6.6) | 85.1<br>(6.6) | 37.9<br>(8.7) | 122.9<br>(7.4) | 84.6<br>(8.4) | 152.7<br>(9.6) |
| | Fiber parameters | | | | | | |
| FP (%) | 65.3<br>(6.4) | 74.0<br>(3.6) | 71.0<br>(4.9) | 59.9<br>(9.8) | 61.2<br>(10.5) | 59.3<br>(7.7) | 41.2<br>(12.7) |
| FLD ($\mu m$) | 15.9<br>(18.0) | 13.5<br>(12.7) | 8.45<br>(8.9) | 6.0<br>(18.3) | 12.4<br>(14.8) | 9.7<br>(17.3) | 4.2<br>(15.7) |
| FSD ($\mu m$) | 10.3<br>(18.4) | 8.4<br>(17.2) | 5.6<br>(11.6) | 3.5<br>(21.3) | 7.9<br>(17.0) | 5.25<br>(17.1) | 2.6<br>(16.4) |
| | Ray parameters | | | | | | |
| RP (%) | 14.0<br>(17.0) | 10.3<br>(10.3) | 17.2<br>(16.1) | 11.9<br>(21.9) | 21.1<br>(18.2) | 9.2<br>(18.5) | 20.1<br>(13.9) |
| RHMA ($\mu m$) | 5.92<br>(22.3) | 10.61<br>(22.7) | 11.36<br>(22.8) | 8.53<br>(22.6) | 9.74<br>(22.7) | 9.69<br>(22.7) | 7.05<br>(22.5) |
| RWMA ($\mu m$) | 5.92<br>(22.3) | 10.61<br>(22.7) | 11.36<br>(22.8) | 8.53<br>(22.6) | 9.74<br>(22.7) | 9.69<br>(22.7) | 7.05<br>(22.5) |
| | Axial parenchyma parameter | | | | | | |
| APP (%) | 12.3 [3]<br>(21.4) | 0.4<br>(67.8) | 5.3<br>(29.2) | 3.3<br>(32.2) | 9.5<br>(18.5) | 3.2<br>(47.2) | 33.5<br>(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.

Differences in volumetric shrinkage between temperate and tropical hardwoods can be better observed on Figure 7.3. This figure shows the influence of wood density on volumetric shrinkage and the higher shrinkage behavior of temperate species compared to that of tropical species at equal density values becomes evident. As observed on earlier works (Noack 1973; Hernández 1983; Mantanis et al. 1995; Arévalo 2002), other facts than wood density affects the shrinkage behavior of wood and this affirmation becomes evident when results of tropical and temperate hardwoods are mixed.

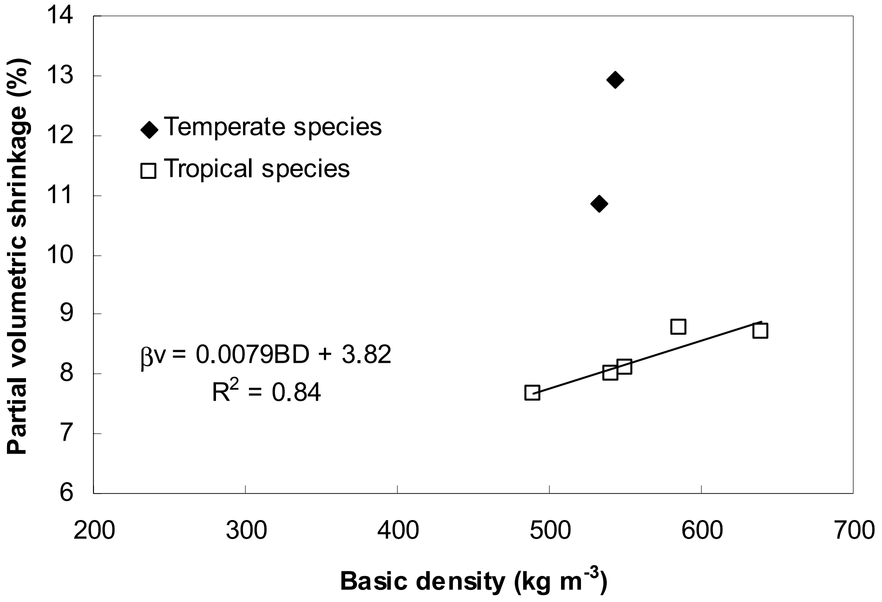

Figure 7.3. Volumetric shrinkage at 33% RH as a function of basic density.

As mentioned earlier, desorption shrinkage starts at EMC values higher than FSP for all species studied. This fact was due to a lost of bound water in the presence of liquid water. This liquid water must be entrapped on the less permeable anatomical element. Several works have reported the impermeability of the ray elements (Behr et al.1969; Gonzalez and Siau 1978). Hart et al. (1974) observed the entrapment of liquid water in parenchyma cells for hickory wood, but their presence in either the radial or axial parenchyma could not be differentiated. Figure 7.4 shows the relationships between the EMC at which shrinkage starts and radial and axial parenchyma proportions for all species studied. Figure 7.4A shows a positive relationship between radial parenchyma proportion (RP) and the beginning of the shrinkage. This supports the hypothesis of Hernández and Bizoň (1994) that species with a higher proportion of ray parenchyma presented a higher quantity of entrapped water. Among the seven species studied, six of them presented a volume of entrapped water closer to that of the radial parenchyma. Huayruro wood was an exception, since the shrinkage starts at very higher EMC values (77% EMC). Huayruro is a particular species given its high proportion of axial parenchyma (APP) within wood volume (33%). These elements present a very thin wall and one can not reject the important role of the axial parenchyma cells of huayruro on the beginning of the shrinkage and the possibility of localized collapse on the earlier states of desorption. Figure 7.4B shows the relationship

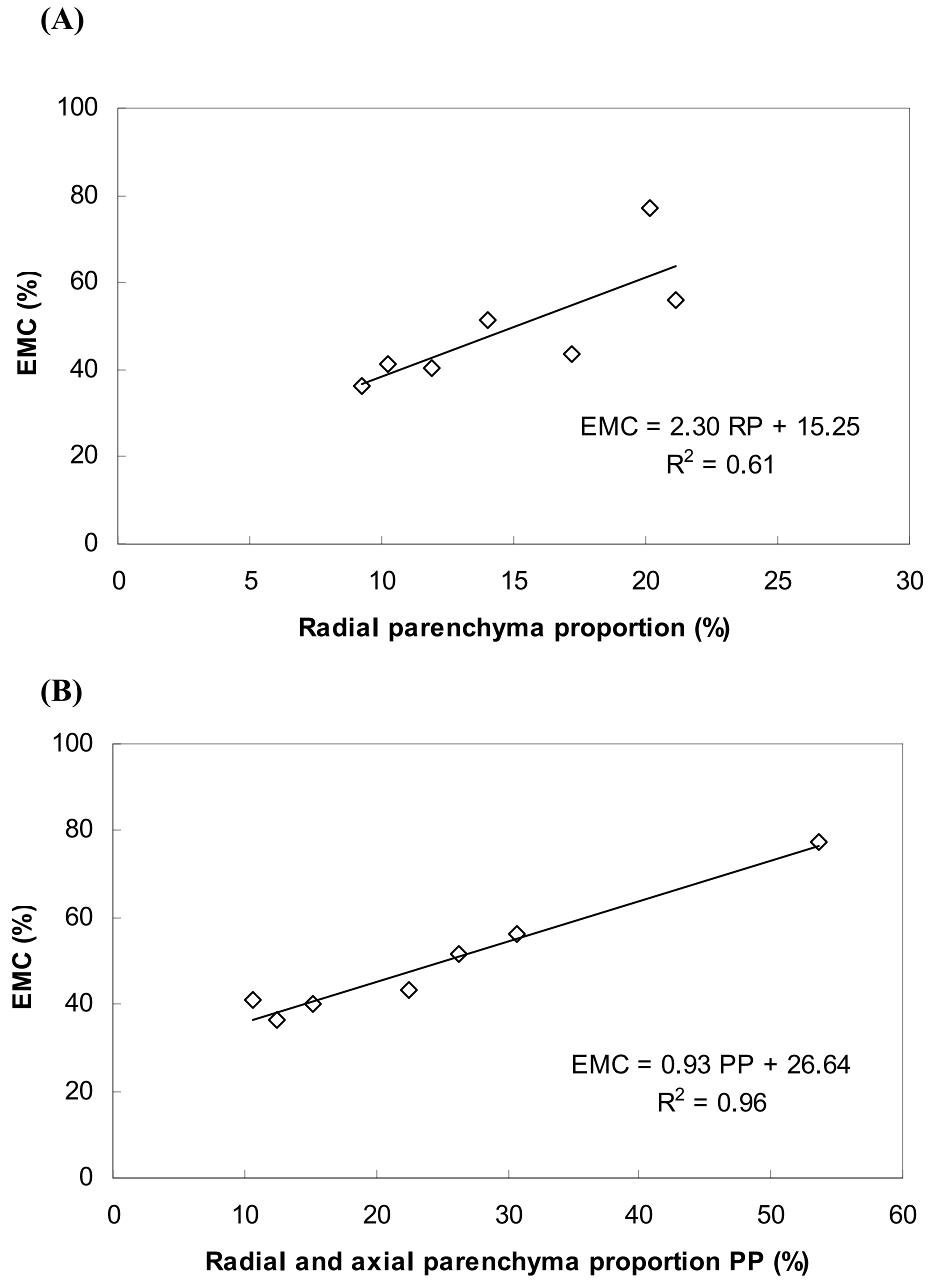

Figure 7.4. Relationships between equilibrium moisture content at which shrinkage starts to be higher than zero and anatomical parameters. A: Radial parenchyma proportion B: Radial and axial parenchyma proportion.

between radial and axial parenchyma proportion and the beginning of the shrinkage. The high coefficient of correlation obtained ($R^2 = 0.96$) was due to the effect of the axial parenchyma proportion on huayruro results.

These results show that in the study of the beginning of the shrinkage, the anatomical characteristics have to be considered, mostly when wood species presenting different structures are studied. Figure 7.5 (A to G) shows the ray elements of the seven species studied. The high variation of ray elements properties can hence be observed, which will certainly affect the drainage of liquid water present within these elements. Figure 7.5H shows the high proportion of axial parenchyma in a cross-section of huayruro.

The Pearson correlation coefficients between anatomical parameters and dimensional properties (q and R) are presented in Table 7.6. This table only shows the anatomical parameters presenting a significant level ≥ 0.05. In case of anatomical variables were statistically correlated between them (0.05 probability level), only the most important variable was included in Table 7.6. The differential shrinkage q was inversely proportional to the smaller diameter of fiber lumen (FSD), showing that species with thin fiber wall (small density) have more dimensional stability. Hernández (1989) and Arévalo (2002) also observed the positive relationship between wood anhydrous density on q, which was higher than the influence of wood extractives. Figure 7.6 shows the relationships between FSD and BD on q. In order to have better correlations between wood density and dimensional properties, Hernández (1989) and Arévalo (2002) made a correction of wood density based on the proportion of wood extractives. Even if in the present work this correction was not made, one can observe the influence of wood density on the volumetric q value. Figure 7.6 also shows that the FSD is a better anatomical parameter to explain wood dimensional stability (q) than basic density.

Table 7.6 also indicates that the vessel elements had a high influence on the shrinkage factor (R). The increase in the difference of R value from the unity indicates that cell cavities varied of dimension during desorption. The results show that species presenting large vessel dimensions (tornillo, cachimbo and huayruro) had more variation in the size of cell cavities. Arévalo (2002) observed that variation in R of mahogany wood can be attributed to the variation on wood anhydrous density (corrected by extractives amount), the polar and non-polar extracts and the ray and vessel anatomical parameters. Hernández (1989) did not observe the effect of wood density on R values and concluded that extractives soluble in acetone contribute to increase the dimensional stability of wood. Figure 7.7 shows the relationships between anatomical elements and shrinkage factor (R), where the influence of the ray and vessel parameters on this dimensional property can be observed.

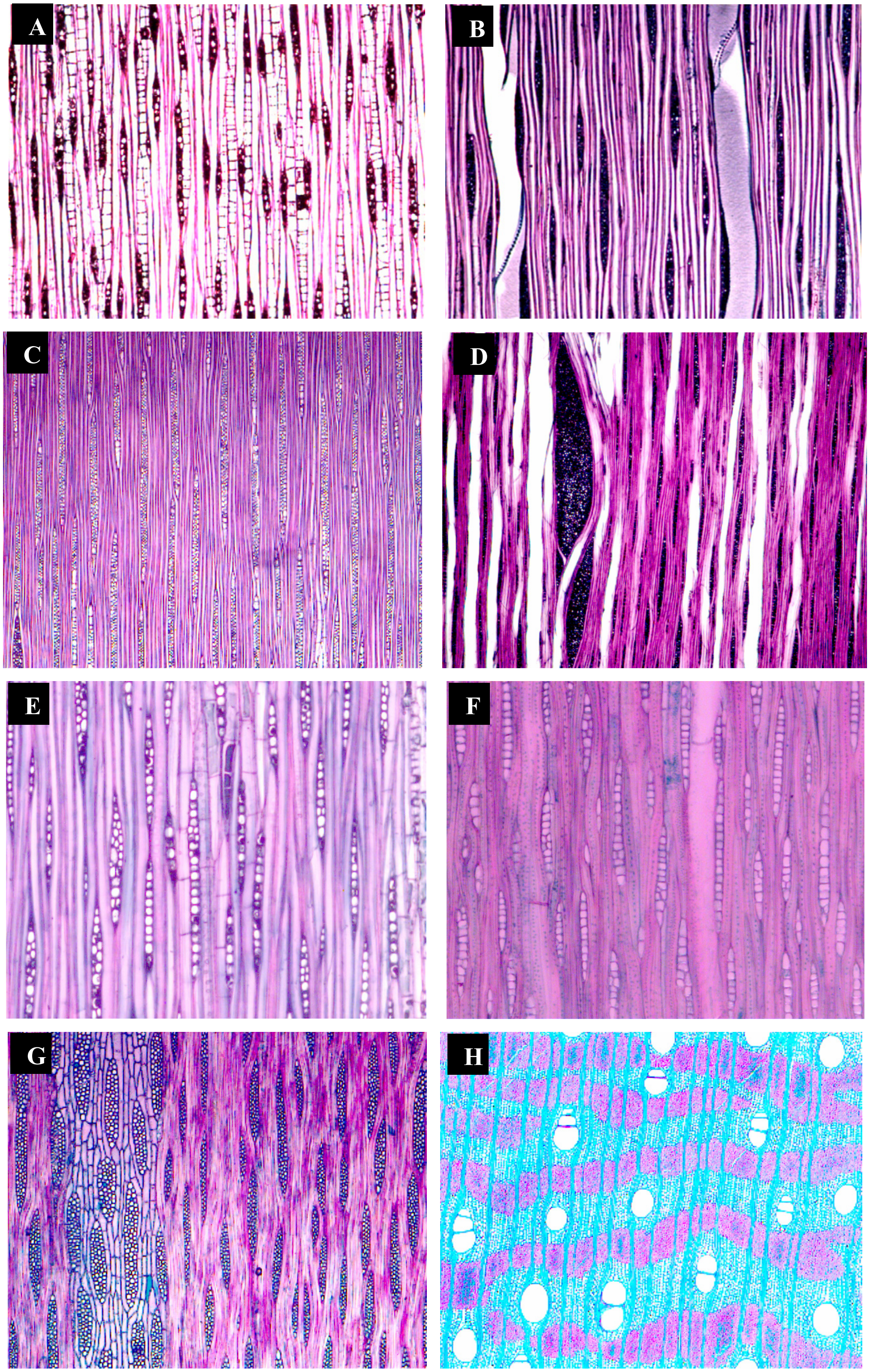

Figure 7.5. Tangential section micrographs of tornillo (A 40x), yellow birch (B 40x), congona (C 40x), beech (D 20x), cachimbo (E 40x), pumaquiro (F 40x) and huayruro (G 40x). Transversal section micrograph of huayruro (H 20x), where the green zones show the axial and radial parenchyma.

Table 7.6. Pearson correlation coefficients between dimensional properties and anatomical parameters.

| Dimensional property | Pearson correlation coefficients |
|---|---|
| $q_{R\ (58\text{-}33\%\ RH)}$ | n.s. |
| $q_{T\ (58\text{-}33\%\ RH)}$ | FSD [1]<br>-0.852<br>(0.01) [2] |
| $q_{V\ (58\text{-}33\%\ RH)}$ | FSD<br>-0.796<br>(0.03) |
| $q_{R\ (76\text{-}33\%\ RH)}$ | n.s. |
| $q_{T\ (76\text{-}33\%\ RH)}$ | FSD<br>-0.930<br>(<0.01) |
| $q_{V\ (76\text{-}33\%\ RH)}$ | FSD<br>-0.881<br>(0.03) |
| $q_{R\ (76\text{-}58\%\ RH)}$ | n.s. |
| $q_{T\ (76\text{-}58\%\ RH)}$ | FSD<br>-0.945<br>(<0.01) |
| $q_{V\ (76\text{-}58\%\ RH)}$ | FSD<br>-0.876<br>(<0.01) |
| $R_{(58\text{-}33\%\ RH)}$ | RP<br>-0.752<br>(0.05) |
| $R_{(76\text{-}33\%\ RH)}$ | VLD -0.847 (0.02)<br>VP 0.772 (0.04) |
| $R_{(76\text{-}58\%\ RH)}$ | VS -0.854 (0.01)<br>FSD -0.755 (0.05) |

[1] Wood anatomy parameters: VP: vessel proportion; VS: individual vessel surface; VLD: larger vessel diameter; RP: ray proportion; FSD: smaller diameter of fiber lumen.

[2] Values between parentheses represent the probability level, n = 7.

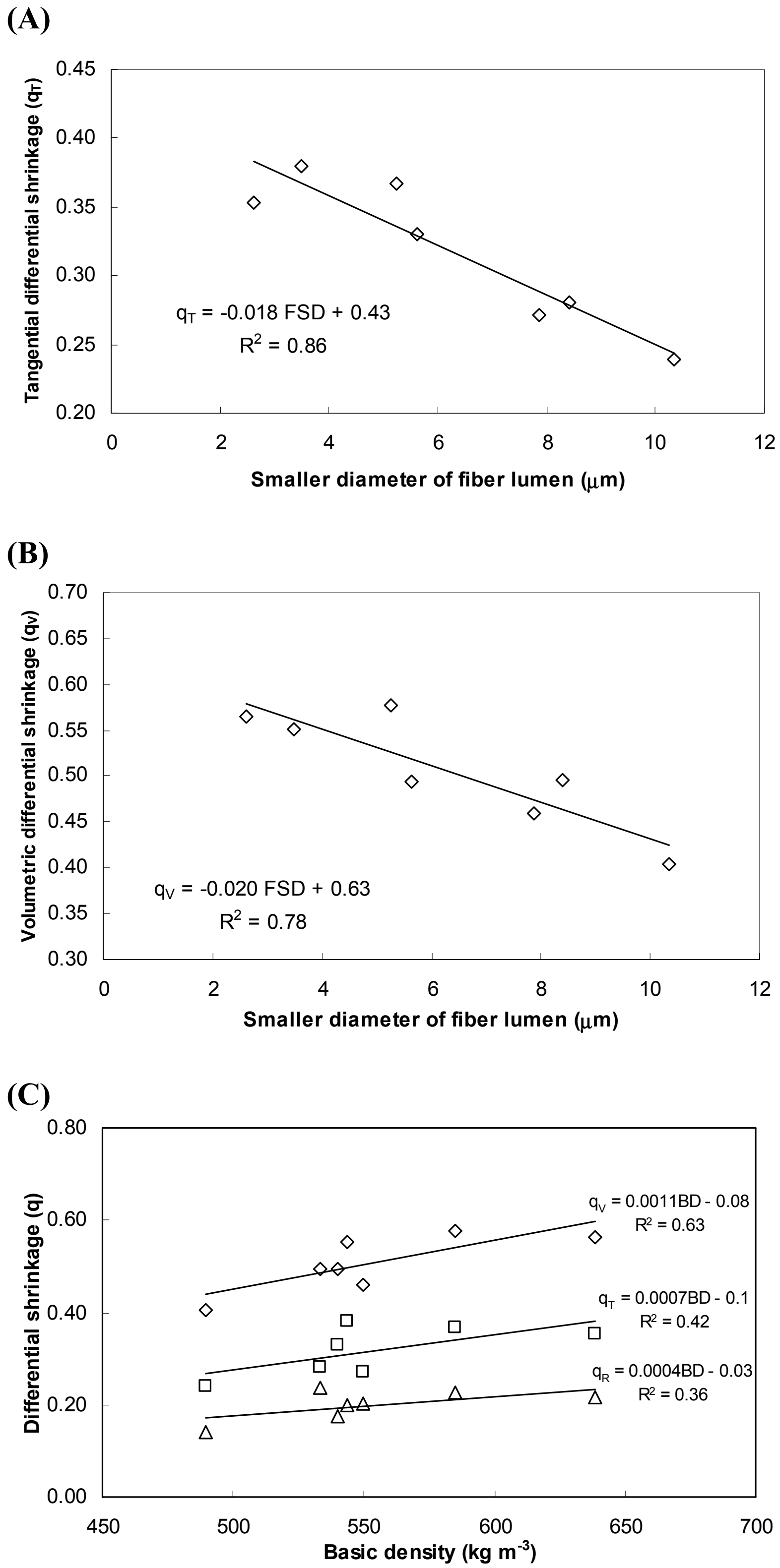

Figure 7.6. Relationships between differential shrinkage (76-33 % RH) and fiber small lumen diameter (A, B) and basic density (C). C: ◊ volumetric differential shrinkage, □ tangential differential shrinkage and Δ radial differential shrinkage.

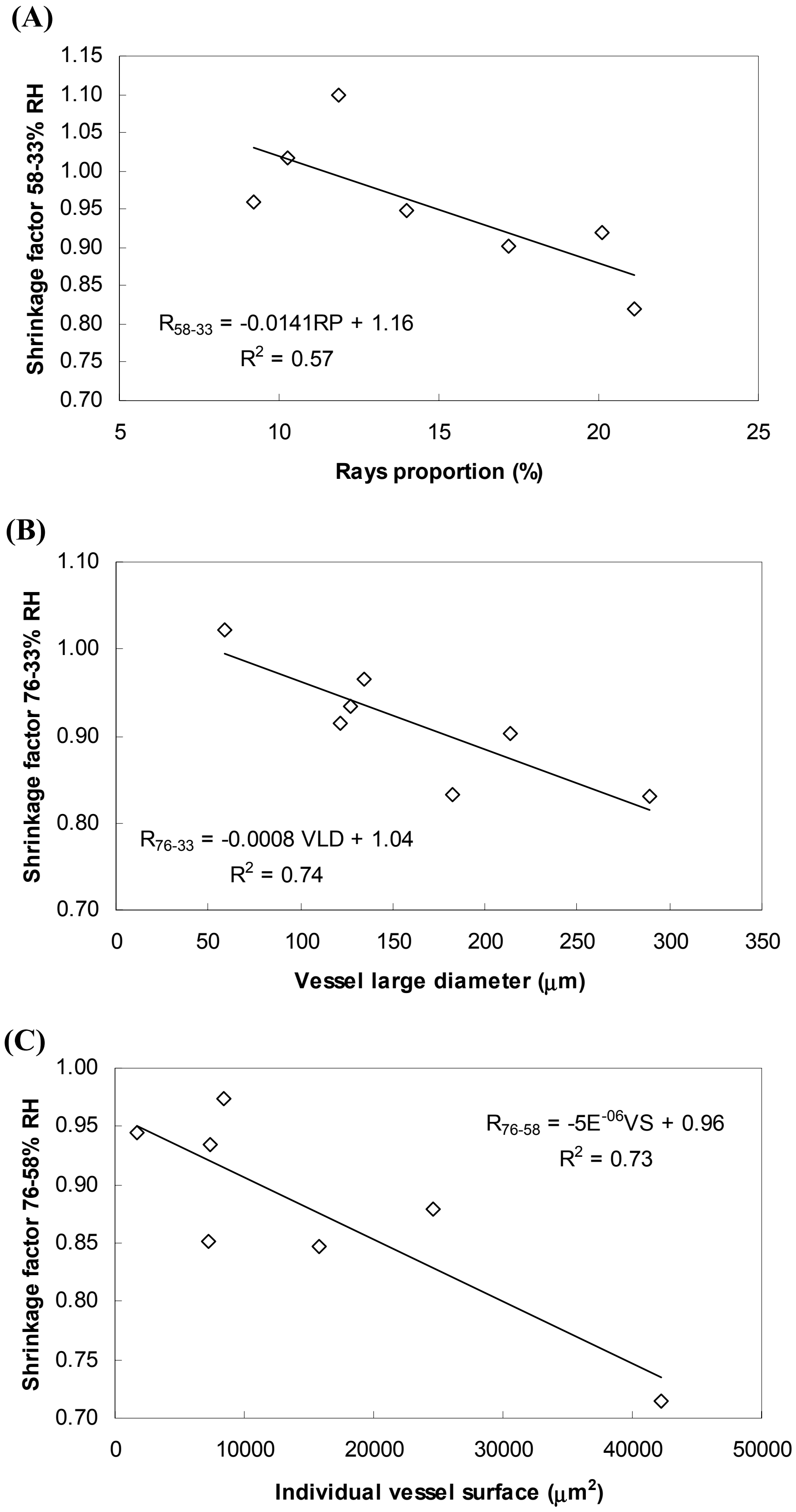

Figure 7.7. Relationships between shrinkage factor (R) and anatomical elements. (A) $R_{58\text{-}33\%\ RH}$ and ray proportion. (B) $R_{76\text{-}33\%\ RH}$ and vessel large diameter. (C) $R_{76\text{-}58\%\ RH}$ and individual vessel surface.

## 7.6 Conclusions

The influence of the anatomical elements on the dimensional properties of two temperate and five tropical hardwoods was studied. 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. Temperate and tropical hardwoods presented important differences on radial, tangential and volumetric shrinkages. Temperate species had larger shrinkage values and the basic density was not correlated with shrinkage when temperate and tropical values were analyzed together.

2. At equilibrium, shrinkage starts at EMC values higher than the fiber saturation point for the seven wood species. This fact was due to a lost of bound water in the presence of liquid water. Results show that the EMC at which shrinkage starts increases as ray proportion increases, showing that this entrapped liquid water must be principally located on the ray elements. Nevertheless, on huayruro wood the important role of the axial parenchyma in the beginning of shrinkage must be mentioned.

3. The T/R ratio of beech and congona woods showed that these species present a higher anisotropic behavior.

4. The differential shrinkage q was inversely proportional to the smaller diameter of fiber lumen (FSD), showing that species with thin fiber wall (small density) have more dimensional stability.

5. The anatomical parameters that mostly influenced the shrinkage factor (R) were related to vessel elements. Species presenting large vessel dimensions (tornillo, cachimbo and huayruro) presented more variation of cell cavities.