DIMENSIONAL VARIATION OF THREE SOFTWOOD DUE TO HYGROSCOPIC BEHAVIOR

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Abstract: With the aim of monitor the hygroscopic behavior of three softwood species in situations of changes in its moisture content, an experimental program based on dimensional measurements, hygrometer readings and weightings procedure, was carried out. Maritime Pine (*Pinus pinaster*), Spruce (*Picea abies*) and Scots Pine (*Pinus sylvestris*) specimens were evaluated and compared. For each wood species, half of specimens were previously dried while the other half was previously saturated. Three main variables studied during the period of specimen's adjustment to an external environment of 20ºC and 57.5% relative humidity (RH) were: mass, dimensional and moisture content variations. Based on the obtained experimental results, the equilibrium moisture content, as well as coefficients of linear shrinkage and expansion, were determined. Experimental results confirmed that besides RH and temperature, the equilibrium moisture content of wood depends on its moisture history. Moreover, using the obtained values it was possible to identify differences between the hygroscopic behavior of the softwood species studied.

Keywords: Dimensional variations; equilibrium moisture content; shrinkage; swelling

1. Introduction

Wood is a natural and renewable resource, with significant applications in material production, building construction and civil engineering. In use, wood is jointly subjected to mechanical and moisture loads and inappropriate loading of wood can result in mechanical damage and biodegradation.

The amount of moisture, or water, in wood depends on the surrounding climate. After harvesting and in the absence of direct contact with liquid water, the moisture content of wood is controlled by temperature (T) and relative humidity (RH). Wood is constantly gaining and losing moisture from or to the surrounding air until an equilibrium point is reached, called equilibrium moisture content (EMC).

Owing to the cellular structure of wood, water can be held in two ways: (1) free water in the cell cavities, and (2) chemically bounded water in the cell walls. In the drying process of wood after harvest, the removal of free-water occurs first, with no change either in dimension or in physical and mechanical properties of wood. At the state where no free-water is present in the cell cavity and the cell wall is fully saturated with bounded water, the cell is said to be at the fiber-saturation point (FSP). For practical purposes, this level of moisture content is generally considered around 25-30%, but it may be significantly different among wood species [1]. The variation of moisture content below the FSP is accompanied by changes on both physical (dimensional variation) and mechanical properties [2]. During desorption the specimen undergoes shrinkage, whilst during absorption the specimen swells. Macroscopically, this process can be quantified by the volumetric or linear shrinkage coefficient: radial (k_r), tangential (k_t) and longitudinal (k_l). Moreover, the shrinkage process is direction dependent: $k_t >> k_r >> k_l$. This anisotropy is the origin for relevant distortions on the shape of wood pieces.

Furthermore, changes in the moisture content below the FSP also result in variations in the mechanical properties of wood. In practice, a linear relationship between elastic modulus of wood and moisture content can be assumed within a range of 8-20% [3].

Standard methods specify methodologies for measuring shrinkage and swelling [4-8]. These methods use oriented small wood specimens. For measuring volumetric changes generated by moisture content variations below the FSP the immersion method is proposed. On the other hand, radial and tangential shrinkage are determined by measuring changes on dimensions with accuracy not less than 0.02mm.

Aside recommended standards used for present research, it is important to mention that new image-based measurement methods, such as digital image correlation (DIC) have been developed [9]-[10]. This recent contact free technique was already used in some published researches for determination of shrinkage coefficients [11-12].

Important research efforts have been made on the use of high temperature in the drying process with the purpose to reduce wood hygroscopicity [13-14]. There are studies regarding prediction models for wood moisture content and density [15], and studies that explore variations of moisture content at different temperatures and relative humidity, in order to understand wood hygroscopic behavior and enable comparisons between different species and also within the same species [16-18].

To understand shrinkage and swelling anisotropic phenomena of wood it is mandatory to determine the equilibrium condition of wood species in different environments. This knowledge is important to predict the performance of wood elements during their life-time. Moreover, data from the equilibrium condition of wood and the magnitude of the shrinkage and swelling coefficients allows taking into account design measures to predict and avoid cracks and induced stresses. The development of cracks reduces the market value of the wood elements and can decrease significantly its performance from a structural point of view, in particular, if located near the joints.

This study is focused on understanding and comparing the relation between dimensional variation and moisture content of three softwoods largely applied in the European construction sector, namely Maritime Pine (*Pinus pinaster*), Spruce (*Picea abies*) and Scots Pine (*Pinus sylvestris*).

2. Experimental program

2.1 Specimens and Test Configuration

Two experimental campaigns were performed in order to monitor shrinkage and swelling behavior of the three softwoods selected. One tested 220 specimens: eighty of Maritime Pine, eighty of Spruce and sixty of Scots Pine. The other one tested a total of sixty wood specimens: twenty specimens of each species.

Specimens have dimensions of 50(R)x50(T)x10(L)mm^3, in which R, T and L stands for radial, tangential and longitudinal orthotropic directions.

Both experimental campaigns aimed to understand the shrinkage and swelling behavior, under controlled conditions, of maritime pine, spruce and scots pine. To analyze the shrinkage behavior specimens were saturated, while to analyze the swelling behavior specimens were oven dried. For both experimental campaigns, before start test program, half of specimens of each species were dried (D) while the other half was saturated (S). Drying process was made using an oven at 103ºC +/- 2ºC until obtaining constant mass. Saturation was obtained after submersion of specimens in a water tank, during a period of 2 weeks, ensuring that the specimens had constant mass [5]. Mass was considered constant when the difference between two successive weight measurements, spaced by 2 hours, was less than 0.5% [19].

After imposing these two different starting conditions, all specimens were placed in a climatic chamber (FITOCLIMA 28000 EDTU from ARALAB) with constant environmental conditions of 20ºC and 57.5% (RH) until reach stabilization of specimens.

The stabilization process was considered complete when dimensional variation of specimens was less than 0.5% in a period of 12 hours. Although the three softwoods studied had different speeds of stabilization, all specimens remained inside the climatic chamber until the three softwoods were considered stable. Dimensional and weight variations were collected during the stabilization processes, respecting pre-defined periods of time, until the equilibrium moisture content was attained.

The measurement system for dimensions was constituted by a metal base that supported a standard-dial gauge (with a precision of 1µm), in order to ensure the accuracy of measurements. Four metal bases were made; three of them were used to measure continuously one single specimen, one of each wood species, while the other one was used for measuring all remaining specimens. The readings obtained by the three fixed metal bases served to confirm the accuracy of the measurement collected by the fourth, non-fixed, steel base. Figure 1 shows the setup adopted for the dimensional measurements during the swelling/shrinkage process of the specimens inside the climate chamber. The weights were obtained by a lab balance with an error lower than 5mg.

In the case of experimental campaign with larger sample, in addiction to weight collection, moisture content readings were also made using a hygrometer (CSA ELECTRONIC - DELTA -8N). The goal was to evaluate the accuracy of the hygrometer readings in comparison with the oven dry method suggested by [19]. However it is important to consider the fact that hygrometer readings are only reliable for moisture contents between 8-24% [20], providing large errors in the case of higher moisture content values. In this way, the comparison between these two measuring techniques was limited to moisture content values bellow the FSP.

2.2 Test development

Besides the difference of sampling, two experimental campaigns have two important differences related with test development: the period of stabilization (1) and spacing between readings (2). Campaign with larger sample has a larger stabilization period (96 hours) with spacing of 12 hours between dimension readings and 24 hours for weight and moisture content readings. Smaller campaign submitted dried and saturated specimens to stabilization periods of 29 and 78 hours, respectively. Spacing of readings were not equidistant: the first three readings were taken in periods of 2 hours, the following three readings in periods of 3 hours, then one period of 4 hours, two periods of 10 hours and to finish a period of 42 hours.

The option to perform a campaign with smaller reading intervals during a smaller stabilization period is based on the fact that dimensional and moisture content variations are substantially larger during the first 36 hours of test in case of saturated specimens and during the first 12 hours in case of dried specimens. Further, smaller periods allowed a better observation of dimensional variation in first hours of stabilization period and allowed determining more accurately the relation between moisture content and linear shrinkage/swelling, in radial and tangential directions.

In addition to these differences, experimental campaign with smaller sample evaluated the consequences of a full humidity cycle on the swelling capacity of wood through the comparison between only dried [OD] specimens and specimens dried after a saturation process [SD]. For that, after the stabilization process of the saturated specimens, the same specimens were dried and submitted to another stabilization process, as suggested in [4]-[5].

3. Results and discussion

3.1. Larger experimental campaign

Figure 2 presents graphically the evolution of average values of linear shrinkage (β) and swelling (α) of saturated and dried specimens in radial and tangential directions (β_r, α_r, β_t and α_t, respectively). Linear shrinkage and swelling values were calculated based on formulas (1) and (2) suggested in [4][5].

$$\beta = \frac{l_{\max} - l_{\min}}{l_{\max}} \text{x } 100 \qquad (1)$$

where l_{max} is the dimension of saturated specimens, in radial or tangential direction, in mm, and l_{min} is the dimension of specimens at time of measurement, in radial or tangential direction, in mm.

$$\alpha = \frac{l_{\max} - l_{\min}}{l_{\min}} \text{x } 100 \qquad (2)$$

where l_{max} is the dimension of specimens at time of measurement, in radial or tangential direction, in mm, and l_{min} is the dimension of oven dried specimens, in radial or tangential direction, in mm.

At the end of shrinkage period of saturated specimens, obtained β_r values were: 0.80% (CoV=16.9%), 1.61% (CoV=17.7%) and 1.41% (CoV=22.1%), for Maritime Pine, Spruce and Scots Pine, respectively. Considering the same order obtained β_t values were: 1.87% (CoV=6.1%), 3.68% (CoV=6.6%) and 2.77% (CoV=18.1%).

Relatively to dried specimens obtained swelling values α_r were: 1.07% (CoV=9.5%), 2.04% (CoV=6.0%) and 1.75% (CoV=11.1%) for Maritime Pine, Spruce and Scots Pine, respectively. Considering the same order obtained α_t values were: 1.56% (CoV=6.9%), 3.22% (CoV=6.6%) and 2.26% (CoV=11.8%).

From 0 to 24 hours the decrease of moisture content of saturated specimens was significant for all three wood species: from 127.4% to 21.0%, from 154.3% to 16.7% and from 113.2 to 19.1% for Scots Pine, Spruce and Maritime Pine, respectively. During this first 24 hours, saturated specimens had presented results for $\beta_{r/t}$ and $\alpha_{r/t}$ with a very high Coefficient of Variation (CoV) (30% and higher). It is possible to speculate that high CoV values are related with different levels of saturation between specimens. Due to the heterogeneity of wood maybe different specimens have different shrinkage velocities. Following this idea, when specimens are forced to shrink rapidly the difference between their behavior can be emphasized. Furthermore, during saturation process, different levels of absorption may result in different levels of saturation of specimens, exacerbating the difference of behavior between specimens during first 24 hours of stabilization. But more research is needed for a definitive conclusion.

Relatively to dried specimens, they present lower CoV values once dimensional variations are smaller and the oven-dry process guaranteed that all specimens began the stabilization process in an anhydrous state.

Despite the high CoV values, results prove their reliability through values representative of wood anisotropy, which match with values suggested by bibliography (a ratio between tangential and radial shrinkage $\left(A = \frac{\beta_t}{\beta_r} \text{ around } 2\right)$ [1]. Spruce and Maritime Pine specimens presented the higher *A* values, 2.29 and 2.34, respectively, while, Scots Pine achieved a *A* value of 1.96.

Figure 2a and b shows that the swelling became stable at the end of 24 hours of measurements for all wood species in both measured directions. Relatively to shrinkage (Figure 2c and d), results obtained for both measured directions and three wood species show the same trend towards stabilize after the first 48 hours.

Figure 3 exhibits the comparison between the wood moisture content values obtained through the oven dry method [19] and by hygrometer readings. As expected, for the relevant range (8-24%), hygrometer shows to be effective in the prediction of the moisture content for the three softwoods studied, presenting always slightly lower values in comparison to the oven dry method.

3.2. Smaller experimental campaign

In a general ways results obtained for linear shrinkage and swelling in both directions were a bit higher than values obtained for larger experimental campaign. Despite the differences between two experimental campaigns, similar conclusions were taken from results: Maritime Pine and Spruce have the higher ratio between tangential and radial anisotropy (2.34); Spruce has the larger values for linear shrinkage (β_r=2.72% (CoV=9.2%) and β_t=4.92% (CoV=10.4%)) and for linear swelling (α_r=2.24% (CoV=9.0%) and α_t=3.60% (CoV=5.8%)); in opposition to Maritime Pine which presents the lower values: β_r=1.31% (CoV=26.4%), β_t=2.58% (CoV=23.7%), α_r=1.09% (CoV=7.3%) and α_t=1.89% (CoV=4.9%).

Figure 4 depicts β_r, β_t, α_r and α_t along time obtained from the smaller experimental campaign, demonstrating that smaller reading intervals improve the assessment of dimensional variation. Dried specimens had the greater variations during first 2 hours and saturated specimens had the greater variations between 19 and 29 hours (period in which the moisture content becomes smaller than FSP). As noted in the previous phase, saturated specimens had presented high CoV values (30% and higher) until reach lower levels of moisture content. As shown in Figure 5, with these smaller reading periods it was possible to relate higher CoV values with moisture levels higher than FSP.

Afterwards, the methodology proposed in [4] was followed, submitting specimens to a complete humidity cycle. This procedure allowed calculating maximum linear shrinkage, in radial and tangential directions, and maximum volumetric shrinkage ($\beta_{r,max}$, $\beta_{t,max}$ and $\beta_{v,max}$, respectively). Linear and volumetric shrinkage were calculated through equations (1) and (3) as recommended in [4],[6]. To obtain maximum linear shrinkage, $l_{r/t,min}$ presented in formula (1) represents the dimension of oven dried specimens.

$$\beta_{v,max} = \frac{(l_{t,max}\ x\ l_{r,max}) - (l_{t,min}\ x\ l_{r,min})}{l_{t,max}\ x\ l_{r,max}} \quad (3)$$

where $l_{t,max}$ is the dimension of saturated specimens in tangential direction, in mm, $l_{r,max}$ is the dimension of saturated specimens in radial direction, in mm and $l_{t,min}$ is the dimension of oven dried in tangential direction, in mm, and $l_{r,min}$ is the dimension of oven dried in radial direction.

It is important to refer that as dimension of specimens on longitudinal direction are so small, their variations were not considered for calculation of volumetric rates. In addition, total linear shrinkage in longitudinal direction is in the amount of 0.1 – 0.4%, while in radial and tangential directions variability is more significant, 3.0 – 6.0% and 6.0 – 12.0%, respectively [21].

Table 1 presents the main results of the second experimental phase namely, linear shrinkage, in tangential and radial directions ($\beta_{t,max}$ and $\beta_{r,max}$, respectively), coefficient of linear shrinkage (k_t and k_r, respectively), volumetric shrinkage ($\beta_{v,max}$), and coefficient of volumetric shrinkage (k_v). Coefficients of linear shrinkage were calculated with the ratio between $(l - l_{min})/(l_{min} x W)$, in which l is the dimension of specimen at the end of shrinkage process, l_{min} is the dimension of oven dried specimen and W is the moisture content of specimen also at the end of shrinkage process with moisture content values between 13-15%. Coefficient of volumetric shrinkage was calculated similarly using the volumetric dimensions of specimens.

The results obtained for both linear shrinkages in the case of Maritime Pine and Scots Pine specimens were lower than the values collected in literature. Awoyemi [18] reported that linear shrinkage of Scots Pine is 6.14% and 8.29%, while this study shows values of 4.32% (CoV=19.6%) and 6.97% (CoV=13.3%) in radial and tangential direction, respectively. Pinto [22] reported a radial linear shrinkage for Maritime Pine of 5.0% and 8.5 % for the tangential linear shrinkage, while the present experimental program obtained values of 2.75% (CoV=18.6%) and 5.45% (CoV=21.7%), in radial and tangential direction, respectively. However, for Spruce the results obtained were within the expected range from the literature. Gryc et al [21] indicate a range of values for Spruce: radial shrinkage should be between 4.23% and 5.70% and tangential shrinkage should be between 7.16% and 10.36%. The results of present study are within this range presenting values of 5.55% (CoV=6.1%) and 10.05% (CoV=9.0%), in radial and tangential direction, respectively. Despite the differences between the results obtained in this experimental program and those reported by some literature for Maritime Pine and Scots Pine, the ratios between the tangential and radial shrinkage are similar to the value suggested by literature in all cases, around 2.0 [1]. Scots Pine is the softwood specie with the lower ratio between tangential and radial shrinkage, equal to 1.61 while Maritime Pine and Spruce had presented values of 1.98 and 1.81, respectively.

Assuming obtained volumetric shrinkages, Maritime Pine looks to be the one with lower shrinkage (8.30%) while Spruce is the one with higher shrinkage (13.91%). Scots Pine is in an intermediate position as regards volumetric values (10.38%).

The results obtained for coefficients of linear shrinkage in tangential (k_t) and radial (k_r) directions, present in Table 1, classify Maritime Pine as a “low shrinkage” wood, while Spruce and Scots Pine are classified as “medium shrinkage” woods [23].

Despite the difference between moisture content values obtained at the end of stabilization periods (shrinkage or swelling), EMC was calculated with the average of final moisture content values of dried and saturated specimens. FSP was calculated through volumetric shrinkage values.

$$FSP = \frac{\beta_{v,max}}{\sigma_v} \quad (4)$$

As expected, results show that the three softwood species evaluated have an EMC around 12% and an FSP around 30%. Maritime Pine has the highest EMC (12.8%) and highest FSP (32.7%) while Scots Pine has the lower values (12.1% and 26.6%, respectively). Spruce has an EMC of 12.2% and a FSP of 30.4%.

Differently to values obtained for dimensional variation and linear shrinkage, density of reference and moisture content presents lower and more constant values for coefficients of variance (CoV). Density of reference was obtained through the methodology and formula suggested in [24]:

$$\rho_{12} = \rho_W \left[1 - \frac{(1-k)(w-12)}{100}\right] \quad (7)$$

ρ_{12} is the specimen density with W% of moisture content, W is the moisture content of specimens, in percentage and k is the coefficient of volumetric shrinkage.

The three softwoods studied have quite different reference values for the density, but all of them are within the range established by the literature (0.32 – 0.72g/cm^3) [1]. Maritime Pine is the heaviest one with a density of reference of 0.659g/cm^3 (CoV=2.0%); Spruce is the lightest with a density of reference of 0.470g/cm^3 (CoV=1.2%); and Scots Pine has a density close of Spruce with a density of reference of 0.502g/cm^3 (CoV=1.6%).

To assess the possibility that wood suffers irreversible changes on their ability to shrink/swell after consecutive shrinkage/swelling processes, a comparison between OD specimens and SD specimens was performed. Figure 6 shows that besides RH and temperature, the EMC of wood depends on its moisture history. In fact, drying (desorption) from a saturated state in certain climatic conditions yields a higher EMC than moistening (adsorption) from a dry state to the same conditions [25].

Specimens that were only dried presented higher values for the linear radial and tangential swelling in comparison with the ones that were saturated before drying. In other words, specimens that were only dried showed greater capacity to recover initial dimensions, while the specimens that were subjected to the entire humidity cycle showed greater difficulty to restore the initial dimensions. Differences between rates of linear shrinkage (β) can be significant. Scots Pine and Spruce are the softwood species that exhibit greater losses in radial and tangential direction: Scots Pine had presented losses of 0.51% and 0.69%, and Spruce presented losses of 0.45% and 0.65%, respectively. Maritime Pine is the species with lower losses: 0.25% on radial direction and 0.47% in tangential direction.

5. CONCLUSIONS

As a hygroscopic material, wood responds to changes in environmental humidity by changing its geometry, i.e. it swells during wetting and shrinks during drying, until EMC is not reached. The experimental work developed confirms that EMC of wood depends on RH, temperature and its moisture history. As expected, saturated specimens have the greater variations between 24 and 36 hours (when the moisture content becomes lower than FSP) while dried specimens presented most of the geometric variation during the first 12 hours due to the higher capacity of wood absorb water when it is in the anhydrous state.

Analyzing the results of both experimental campaigns, the following main conclusions can be pointed out:

- Maritime Pine is the wood species with lower ability to shrink and swell (k_v=0.24%), higher EMC (12.8%) and FSP (32.7%). It is the heaviest wood specie with a reference density value of 0.659g/cm^3;
- Spruce is the more sensitive to shrink and swell (k_v=0.51%) wood specie, and it is the lightest one with a density of reference of 0.470g/cm^3;
- There is a relation between density and dimensional variation of wood: the lightest wood species have demonstrated large shrinkage/swelling ability;
- Spruce and Maritime Pine has the higher differences between tangential and radial swelling/shrinkage, resulting on the higher ratio between tangential and radial linear shrinkage. This can mean that these species have a higher tendency to develop defects;
- Scots Pine and Spruce are the wood species that presented higher tendency to lose swelling ability when subjected to entire humidity cycles (including desorption and adsorption).

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TABLE CAPTIONS

Table 1 – Main results obtained derived from the second phase of the experimental program (average values)

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Softwood species	$\beta_{t,max}$ [%]	$\beta_{r,max}$ $[\%]_r$	k_t [%]	k_r [%]	$\beta_{v,max}$ [%]	k_v [%]
Maritime Pine (MP)	5.45	2.75	0.17	0.07	8.30	0.24
Spruce (S)	10.05	5.55	0.31	0.19	13.91	0.51
Scots Pine (SP)	6.97	4.32	0.25	0.17	10.38	0.43

FIGURE CAPTIONS

Fig. 1: Fixed and non-fixed measurement systems.

Fig. 2: Linear shrinkage (β) and swelling (α) in time in radial and tangential directions of larger experimental campaign with standard deviation bars. (a) dried specimens [D] in radial direction; (b) dried specimens [D] in tangential direction; (c) saturated specimens [S] in radial direction (d) saturated specimens [S] in tangential direction

Fig. 3: Reliability of hygrometer when compared with weighing (

Fig. 4: Linear Shrinkage (β) and Swelling (α) in time in radial and tangential directions calculated during smaller experimental campaign, with standard deviation bars. (a) only dried specimens [D] in radial direction; (b) only dried specimens [D] in tangential direction; (c) saturated and dried specimens when saturated [S] in radial direction (d) saturated and dried specimens when saturated [S] in tangential direction

Fig. 5: Moisture content (W) and its relation with time

Fig. 6: Evolution of linear swelling in time representing loose of elastic capacity of wood when dried after saturation. (a) Maritime Pine in radial direction; (b) Maritime Pine in tangential direction; (c) Spruce in radial direction; (d) Spruce in tangential direction; (e) Scots Pine in radial direction; (f) Scots Pine in tangential direction

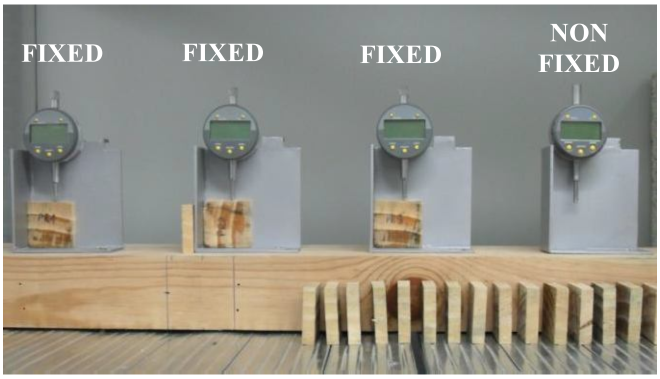
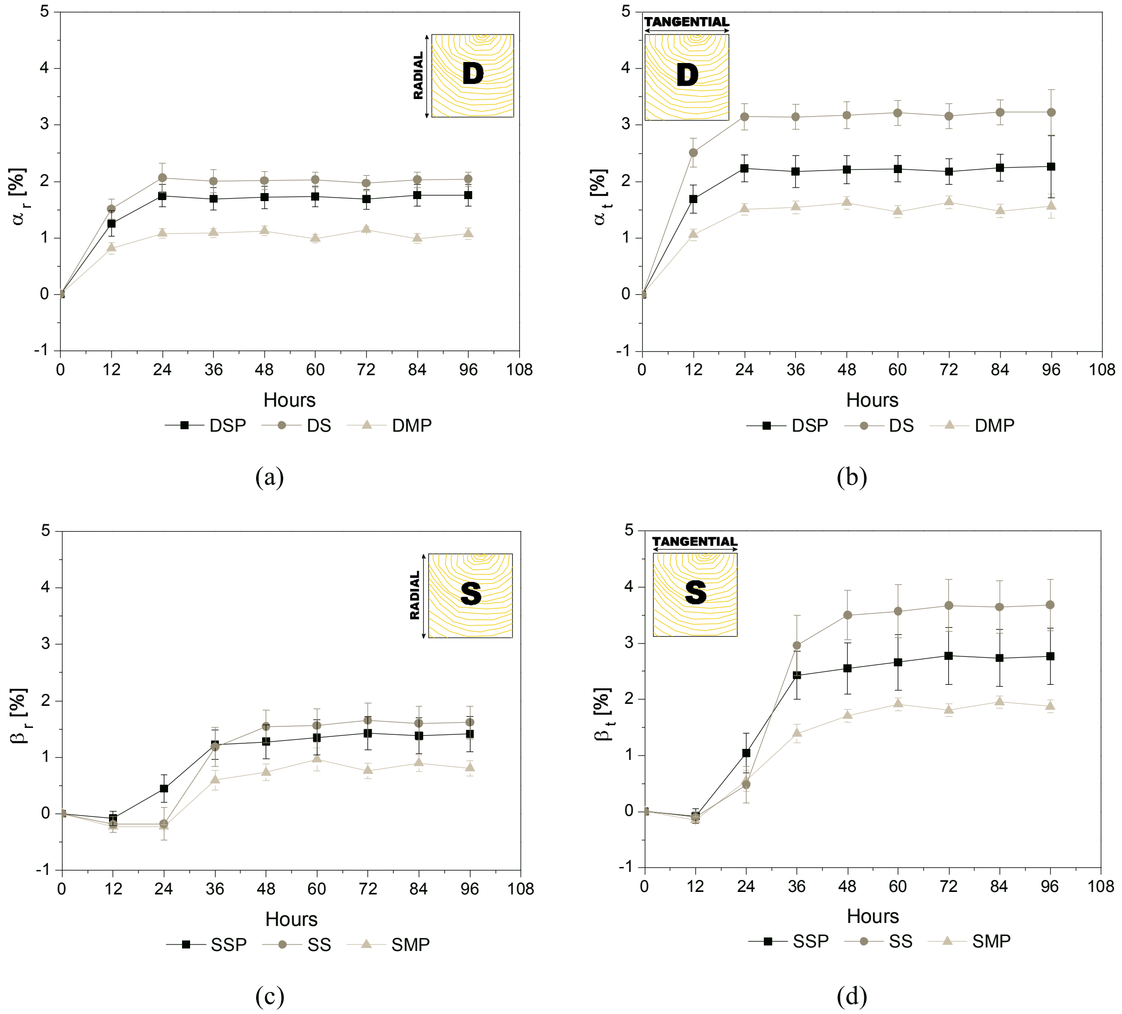
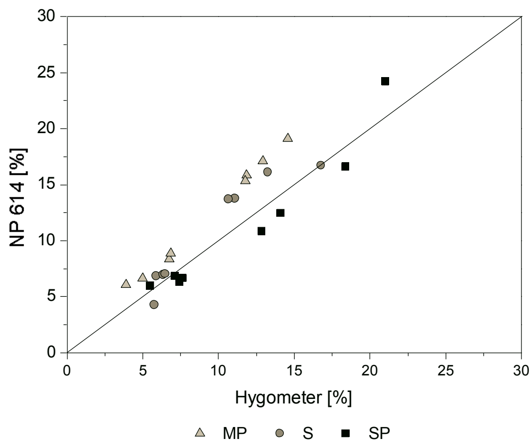


Fig. 1: Fixed and non-fixed measurement systems.



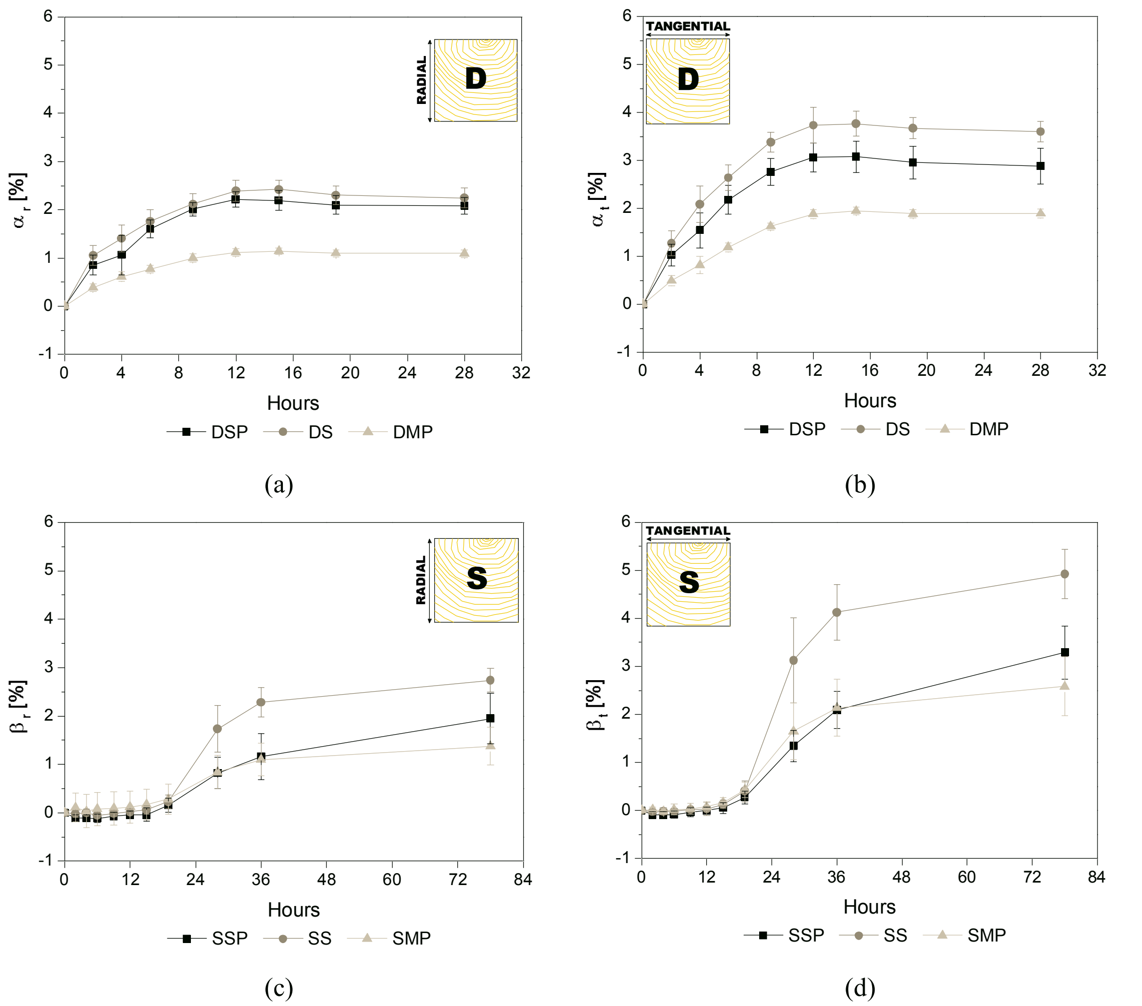
SMP – Saturated Maritime Pine; SS – Saturated Spruce; SSP – Saturated Scots Pine; DMP – Dried Maritime Pine; DS – Dried Spruce; DSP – Dried Scots Pine

Fig. 2: Linear shrinkage (β) and swelling (α) in time in radial and tangential directions of larger experimental campaign with standard deviation bars. (a) dried specimens [D] in radial direction; (b) dried specimens [D] in tangential direction; (c) saturated specimens [S] in radial direction (d) saturated specimens [S] in tangential direction



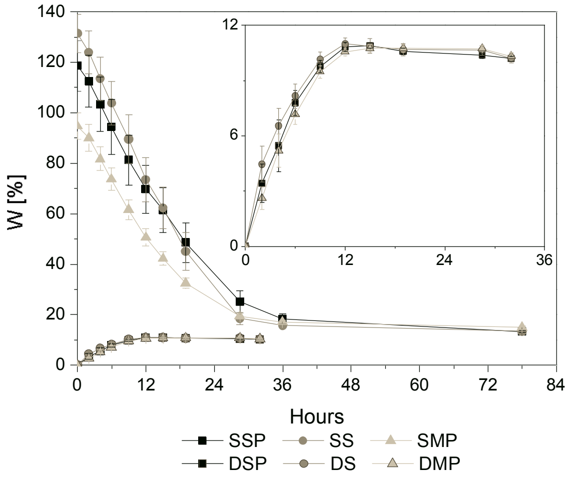
MP – Maritime Pine; S –Spruce; SP – Scots Pine

Fig. 3: Reliability of hygrometer when compared with weighing (method suggested in [19]).



ODMP – Only Dried Maritime Pine; ODS – Only Dried Spruce; ODSP – Only Dried Scots Pine; SDMP – Saturated and Dried Maritime Pine; SDS – Saturated and Dried Spruce; SDSP – Saturated and Dried Scots Pine.

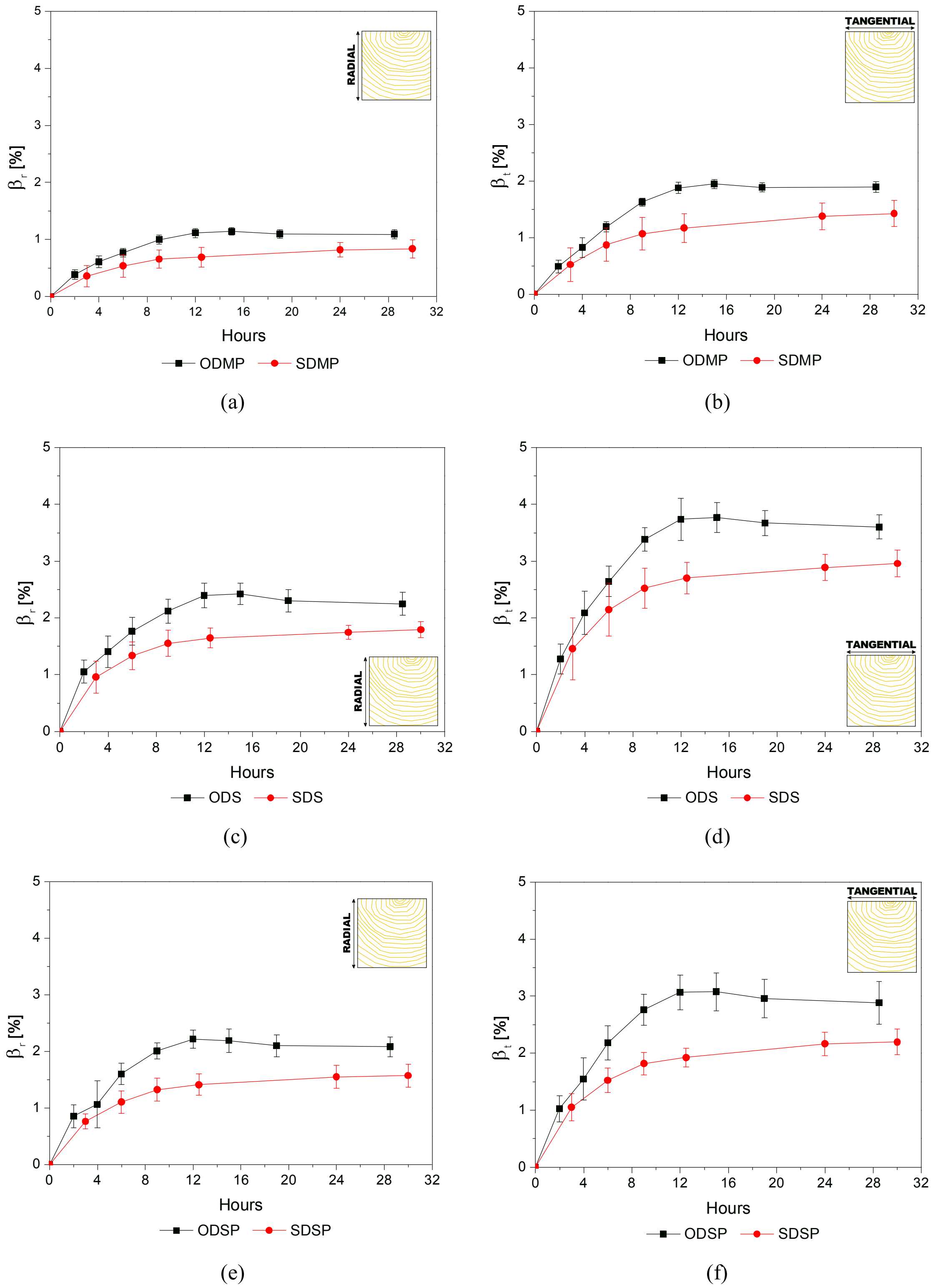
Fig. 4: Linear Shrinkage (β) and Swelling (α) in time in radial and tangential directions calculated during smaller experimental campaign, with standard deviation bars. (a) only dried specimens [D] in radial direction; (b) only dried specimens [D] in tangential direction; (c) saturated and dried specimens when saturated [S] in radial direction (d) saturated and dried specimens when saturated [S] in tangential direction



(a)

SdMP – Saturated and Dried Maritime Pine when Saturated ; SdS – Saturated and Dried Spruce when Saturated; SdSP – Saturated and Dried Scots Pine when Saturated; sDMP – Saturated and Dried Maritime Pine when Dried; sDS – Saturated and Dried Spruce when Dried ; sDSP – Saturated and Dried Scots Pine when Dried

Fig. 5: Moisture content (W) and its relation with time during smaller experimental campaign



SDMP – Saturated and Dried Maritime Pine; SDS – Saturated and Dried Spruce; SDSP – Saturated and Dried Scots Pine; ODMP – Only Dried Maritime Pine; ODS – Only Dried Spruce; ODSP – Only Dried Scots Pine

Fig. 6: Evolution of linear swelling in time representing loose of elastic capacity of wood when dried after saturation. (a) Maritime Pine in radial direction; (b) Maritime Pine in tangential direction; (c) Spruce in radial direction; (d) Spruce in tangential direction; (e) Scots Pine in radial direction; (f) Scots Pine in tangential direction