Chapter 2
Hygrothermal Risk

One of the factors that contribute most directly to the degradation of the built heritage is the water from rain or soil in its liquid or vapour form.

Thus, hygrothermal behaviour of the building elements are an important risk factor for the monumental heritage buildings once they strongly influence its degradation. Hygrothermal behaviour is directly related to climatic conditions to which the heritage element is subdued, particularly in terms of precipitation, relative humidity, temperature, wind and sunshine.

Climate change is certainly a new risk that must be taken into account. The intensity and frequency of extreme events such as floods and droughts, possibly associated with climate change, have countless implications in contemporary societies, becoming increasingly pressing the prevention and mitigation of their effects, including regarding our built heritage.

Floods have always devastated large areas of Portugal, however, in recent years, there seems to be a trend of increased frequency and severity of their presence, giving rise to growing concerns about the exposure and the vulnerability of populations and heritage with this phenomenon. It is true that the floods have always existed as a natural phenomenon, after all, the presence of very intense or very long periods of precipitation have contributed to the intensification of floods, which rose exceptional frequent in many regions.

Portugal, due to its geomorphology, has a large and complex river system, increasing interest in the study of floods and the risk they pose to the built heritage.

Therefore, regarding our subject "the built monuments", we analysed three major hygrothermal phenomena which, directly or indirectly, are related and dependent on changes and the presence of water.

2.1 Importance of Hygrothermal Behaviour

Once there is a vast and complex river network in Portugal, a lot of great heritage buildings are located close to water lines. Nevertheless, when the buildings are in equilibrium with the terms of the atmosphere, they can remain in good condition for hundreds of years. When this balance is affected by changing the internal conditions

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for border changes or significant changes in terms of external stresses, such as is the case of the occurrence of floods/droughts and fluctuations in the water table, degradation is inevitable.

The problem of moisture in buildings has always attracted great interest. However, the complexity of the phenomena involved do not always make easy the scientific explanation of various forms of events in which these problems are associated.

Moisture, in its various forms, is one of the primary causes of the degradation observed in buildings. Therefore, the development of studies aimed at identifying qualitative and quantitative rules for heritage protection is of great importance.

Normally, in practice there is not an isolated event, but the superposition of one or more forms of different events, either in liquid phase or in vapour phase. In this project we focus our attention only on the rising moisture that occurs in the liquid phase on the hygroscopicity of the materials and the dimensional variation that relate with the vapour phase.

2.2 Risk Associated to the Proximity of a Water Line

Natural flooding are extreme and temporary phenomena caused by moderate rainfall and permanent or sudden rainfall and intensity. This excess precipitation increases the volume of rivers, leading to extravasation of normal bed and flooding the banks of the river and adjacent areas.

Except in case of sudden flooding caused by intense and sudden rainfall associated with atmospheric instability difficult prediction, in general it is possible to provide a flood. This forecast is possible with the observation of meteorological comments and knowledge landfills dams, to try to minimize their impact quickly informing the population.

The public will be informed, however the built heritage cannot be moved, being the buildings subject to direct aggression of the flood by flood or by varying the water table. Thus it is necessary to create direct measurements in heritage to prevent or minimize degradation.

The envelope of the built heritage is the protective barrier of the building, and is subject to external aggression and internal stresses. The risk of the nearby heritage with water lines, is not only associated with the direct flooding due to flooding, but also, and more significantly shape, with the change of water level, or by the effect of flooding or by drought effect.

Parts in contact with the ground, generally used in this kind of building constructions, have great moisture transfer capacity, mainly due to capillary action, thus being subject to a series of downgrades by the moisture effect, due to the phenomenon of rising damp.

Moisture conditions of the building envelope condition the relative humidity of the indoor environment. If the change is significant, moisture equilibrium of

Fig. 2.1 Some examples of heritage degradation by hygrothermal behaviour (Guimarães et al. 2011)

materials can be seriously affected, such as in the case of wood, can handle a degradation of materials, coatings or even sculptures.

Figures reflect the following examples of impairments that built heritage is subdued due to hydrothermal origin actions (Fig. 2.1).

In this work we intend to give a contribution to knowledge, developing various studies in the following areas:

- Rising damp;
- Indoor materials hygroscopicity;
- Dimensional changes of the building materials.

2.3 Rising Damp in Building Heritage

Rising damp, a world-wide phenomenon, is a major cause of decay of masonry materials such as stone, brick and mortar. The conservation of historical buildings assumes, nowadays, a considerable importance and it has had a great development in the last few years (see Fig. 2.2).

The height that moisture will reach through capillary action depends upon factors such as the quantity of water in contact with the particular part of the building, surface evaporation conditions, wall thickness, building orientation and the presence of salts (Torres 2004; Torres and Freitas 2006). When atmospheric conditions are constant, the thicker the wall, the greater the height reached by the damp, as a greater quantity of water is absorbed (see Fig. 2.3).

Another important factor to take into account is the presence of salts, which also increases the height achieved by rising damp. The salts are dissolved when the relative humidity of the air rises and they crystallise again when this humidity declines. This crystallisation/dissolution process causes the materials to decay. There are various water-soluble salts in the walls of buildings, contained in the building materials or emanating from the soil. These dissolved salts are transported

Fig. 2.2 Example of rising damp in a historical building

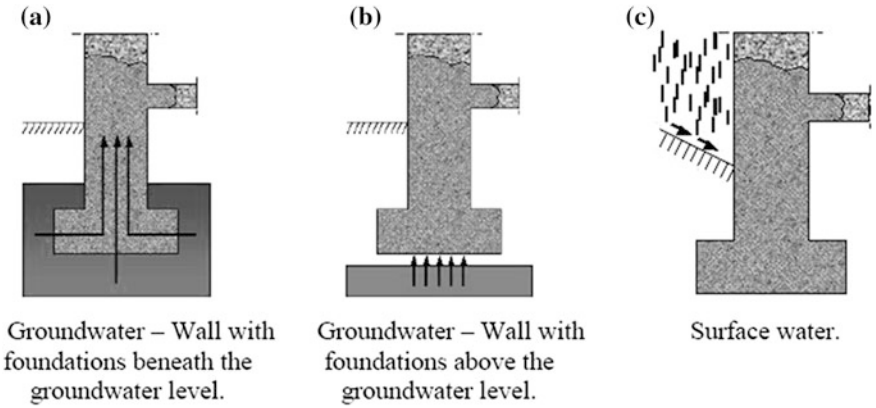

Fig. 2.3 Humidification of walls by groundwater and surface water

to the wall surface where they crystallise in the form of fluorescences or crypto fluorescences, depending upon whether the crystallisation takes place on the surface of the wall or beneath the wall renderings (Hens 2007).

Rising damp depends upon the following factors (Freitas et al. 2008):

- Ambient climate (temperature and relative humidity);
- Solar radiation;
- The presence of salts;
- The porosity and porometry of building materials;
- Wall thickness;
- The kind of materials used for wall renderings.

2.3.1 Climatic Conditions

The climatic conditions affect the drying process and exert great influence upon the level achieved by rising damp. In places with high relative humidity, evaporation is more difficult and there will consequently be greater progression of the damp front. Conversely, when relative humidity is low, evaporation will be greater and the damp front will progress more slowly. The drying flow may be defined by the following equation:

$$g = \beta.(C'_s - C'_a) \tag{2.1}$$

where:

g is the flow density ($kg/(m^2s)$)
β is the surface moisture transfer coefficient (m/s)
C_s' is the water vapour concentration at the surface (kg/m^3)
C_a' is the water vapour concentration in the air (kg/m^3).

Where there is no great temperature difference between the air inside the building and the inner surface of the wall, for high relative humidity, the concentration difference $C_s'-C_a'$ tends to zero, as does the drying flow.

2.3.2 Solar Radiation

In a building with identical climate conditions throughout, the progression of the damp front may vary in accordance with the orientation of the building and amount of solar radiation received. Solar radiation and the radiation absorption coefficient alter the surface temperature and temperature distribution, bringing consequences for the drying process.

2.3.3 Salt Attack

Salt crystallization is one of the main mechanisms involved in stone degradation. This degradation mechanism is based upon the pressure exerted by salt formation in the porous structures, with an increase in volume. It is dependent upon the types of salts involved, their size and the arrangement of the pores.

Temperature may have some influence in the process, because salt solubility depends upon it.

When the pressure exceeds the material's resistance capacity, and, particularly, when the salt formations result in cycles of crystallisation and dissolution in response to humidity fluctuations, there will typically be material losses.

The most characteristic salts are:

- Chlorides, which absorb large amounts of water;
- Nitrates of organic origin, of which the most common is calcium nitrate, which crystallises at 25 °C and 50 % relative humidity;
- Sulphates, which are hygroscopic and soluble, and which increase in volume upon crystallization. The most common are sulphates of calcium, sodium and magnesium.

Anomalies caused by the presence of salts may result in a variety of symptoms of degradation in wall renderings. These include: surface alterations (fluorescences or damp patches); cracking; the formation of crusts; the separation of building materials into layers (delamination, exfoliation, the detachment of coatings, etc); loss of cohesion (eg. pulverulence of ceramic or stone brick elements, arenization of mortars, etc…), and the formation of voids (such as alveolization).

2.3.4 Porosity and Porometry

A material's porosity may be defined as the ratio between the total volume of voids (pores and channels) and its total apparent volume. Practically all building materials are characterised by open porosity, and their moisture imbibitions capacity is directly related to porosity. In the case of closed porosity, when there is no intercommunication between pores, the material is impermeable and water cannot penetrate.

Materials with closed porosity are of interest for the prevention of rising damp, as they may be used to form a water barrier. Materials with open porosity, on the other hand, conduct the moisture by capillary action. Capillarity increases the smaller the diameter of the pores. Thus, porometry studies are useful, as they enable the size of the pores to be assessed.

2.3.5 Wall Thickness

The progression of rising damp stabilises when the flow through the absorbent section is equal to the total wall evaporation; that is to say, the amount of water that enters the wall through absorption is the same as the amount of water that leaves through evaporation.

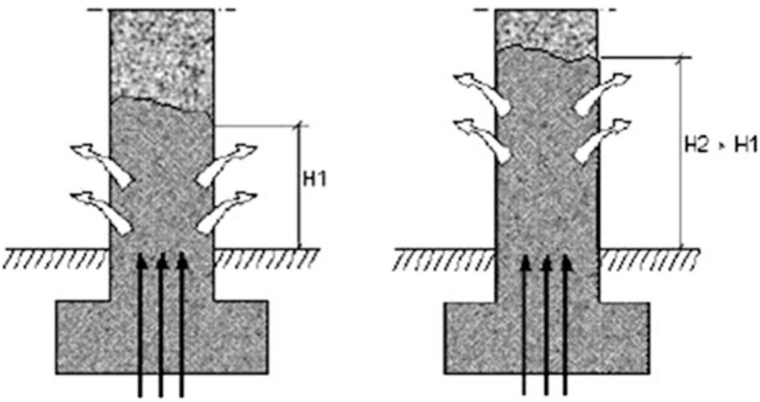

Fig. 2.4 Influence of impermeable materials placed on the wall surface at the level achieved by rising damp

2.3.6 Wall Renderings

The damp-proofing of walls generally reduces the evaporation conditions, which increases the level of rising damp, until a new equilibrium is achieved. This is shown in Fig. 2.4 as a schematic representation.

2.4 Materials Hygroscopicity

Hygroscopic moisture is moisture which a porous substance can absorb from the air and then release it into the air. The humidity will achieve balance with its environment, which means that the substance has hygroscopic balance moisture.

The hygroscopic qualities of building materials vary greatly. Wood-based materials are very hygroscopic; mineral-based materials are not very hygroscopic. The ability of a building material such as insulation to bind and release moisture is called the moisture capacity, and it is highly significant for the moisture-technical functioning of the structure. Large moisture capacity balances changes in moisture and reduces the risk of moisture damage.

Many materials and objects that are part of the internal heritage buildings are particularly sensitive to indoor relative humidity variations, being mainly affected by extremes, high or low relative humidity values. A low relative humidity can lead to contraction of the materials which in the case of small movements or objects consisting of different layers, implies the occurrence of tensions in an extreme case, may cause the cracking of the building material. The high relative humidity can lead to expansion of the material, involving tension, accelerates the reactions of degradation and makes favourable development organizations (mould and algae).

Once humans have the ability to sustain Relative humidity in a wide range of values, the concern of control occurs only in special-use buildings, such as museums. The use of coating materials with appropriate hygroscopic inertia, can help control the relative humidity of the indoor environment variations. The hygroscopicity reflects the hygroscopic behaviour of materials, which is characterized by the ability to bind water molecules adsorption and return them to the environment in which it is located, based on changes in relative humidity thereof. Hygroscopic material says if the amount of water that is capable of retaining adsorption is relatively large. Figure 2.5 shows the typical form of a porous hygroscopic material curve, which defines its ability to store water.

The practical application of the "hygroscopic inertia" concept in building design demands for a simple prediction strategy of the impact of interior renderings and furnishings. Significant aspects of the evaluation of finishing materials contribution to the hygroscopic inertia are presented.

On the NORDTEST Workshop on Moisture Buffer Capacity (Rode et al. 2003), the issue of how to characterize the ability of materials and structures to accumulate moisture was widely discussed. Although some definitions like moisture effusivity, available water and penetration depth, that hold an acceptable theoretical background, are available for characterizing building materials, they can't be easily used for structures or even coated materials. On that workshop, the MBC number was referred as a good alternative for the aimed characterization.

Based on the suggestions of the NORDTEST Workshop on Moisture Buffer Capacity—Summary Report (Rode et al. 2003), a laboratory test was prepared, where a specimen is submitted to a square wave in relative humidity, with 12 h steps, and constant temperature. This experiment simulates the cyclic variations in moisture loads and relative humidity levels that can be found in bedrooms, for instance, where during the night, there will be an increase in relative humidity due to vapour production by occupants. Some of the results of this work have already been presented (Ramos and Freitas 2004).

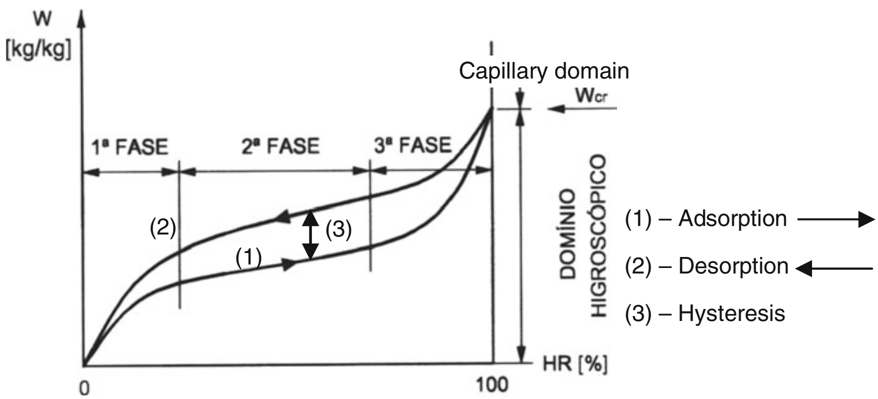

Fig. 2.5 Hygroscopic behaviour of building materials with relation to relative humidity

The specimens used in the tests were stabilized inside a climatic chamber at 20 °C and 65 % relative humidity. Afterwards, each specimen was tested for a few days period with a square wave of relative humidity, with 12 h steps, and constant temperature. The high value used for relative humidity was 85 % in the presented experiments. We can see in Figs. 2.6, 2.7, 2.8, 2.9 and 2.10 the mass variation of the

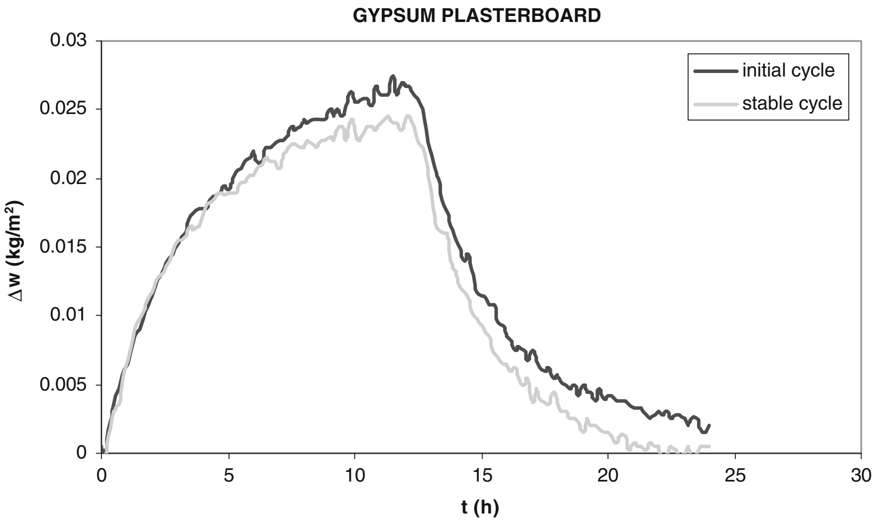

Fig. 2.6 Mass variation of the gypsum plasterboard specimen during laboratory tests

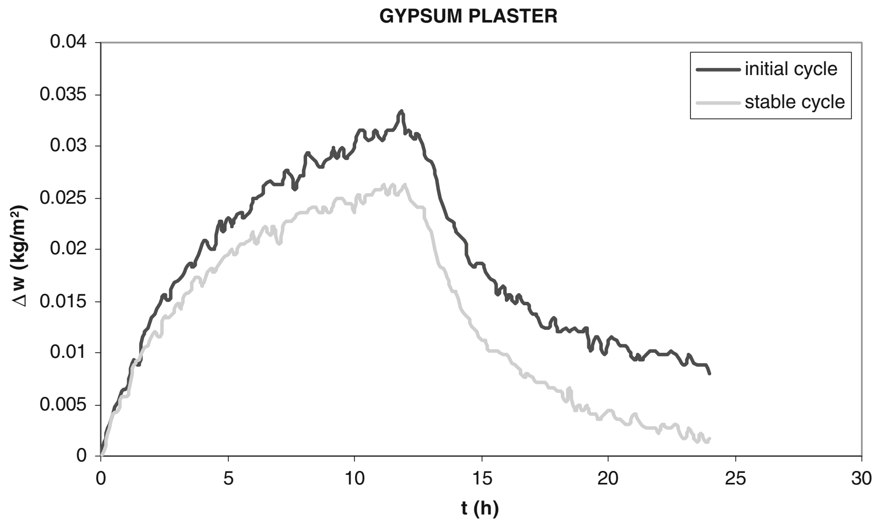

Fig. 2.7 Mass variation of the gypsum plaster specimen during laboratory tests

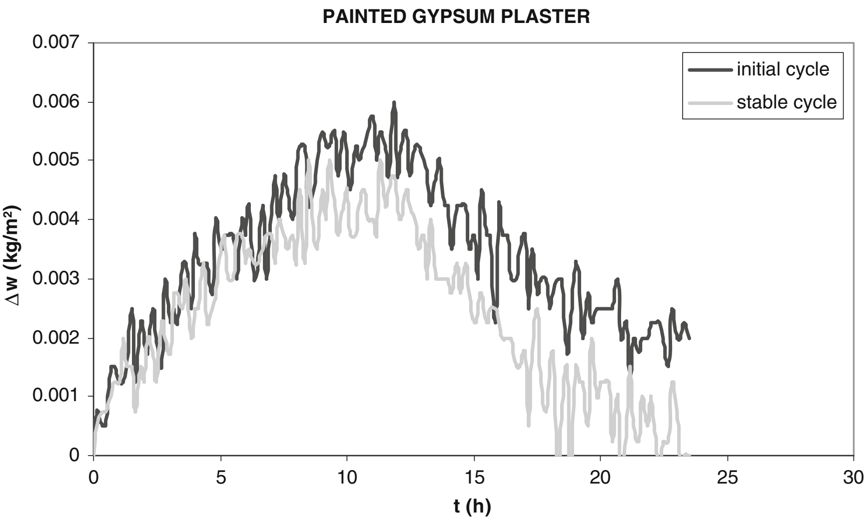

Fig. 2.8 Mass variation of the painted gypsum plaster specimen during laboratory tests

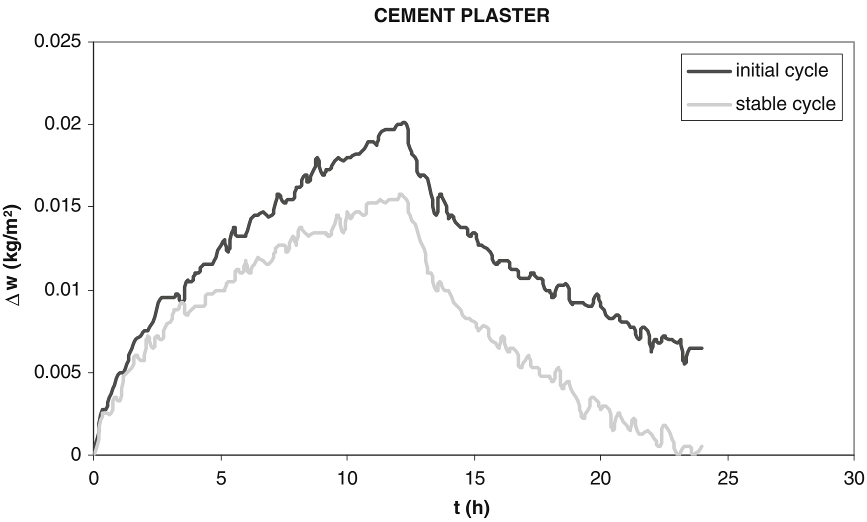

Fig. 2.9 Mass variation of the cement plaster specimen during laboratory tests

specimens, for the initial cycle and for what could be called the stable cycle, where the mass variation after its full length is zero.

In Fig. 2.11 the maximum weight variation in each cycle is presented. We can see that there's always a decrease of that value from the initial cycle to the stable one. Also that decrease is different for each specimen. We believe that the stable

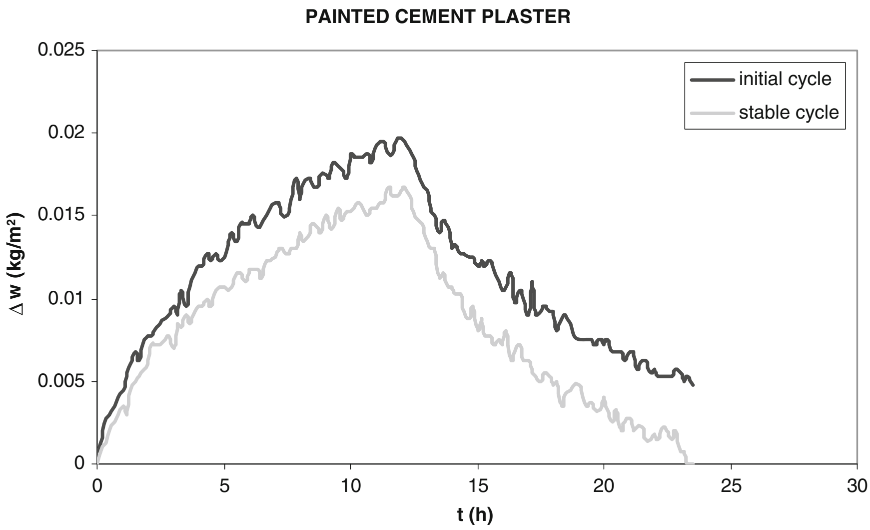

Fig. 2.10 Mass variation of the painted cement plaster specimen during laboratory tests

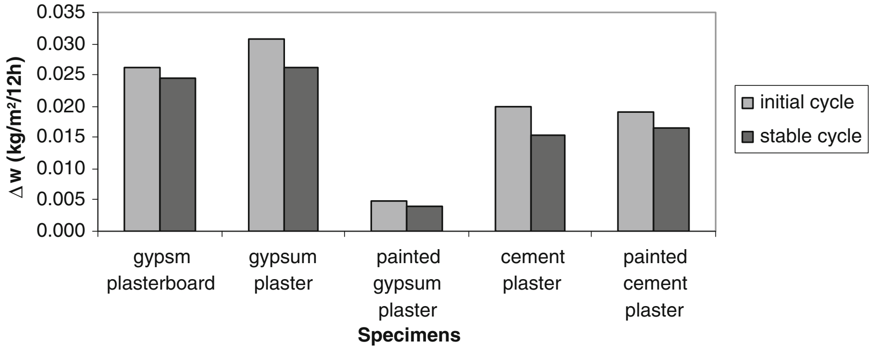

Fig. 2.11 Maximum weight variation

cycle should be the reference for the definition of a rendering's Moisture Buffer Capacity.

2.5 Dimensional Changes of Building Materials

Moisture is one of the most important causes for building pathology. Material's behaviour degradation can be affected by the presence of water both in vapour and liquid phase. Wood is a hygroscopic substance and this ability to absorb or to lose water is dependent on the temperature and the humidity of the surrounding atmosphere. This moisture relationship has an important influence on wood properties and performance. Many of the challenges of using wood as an engineering material arise from changes in moisture content or an abundance of moisture within the wood.

As a consequence, the amount of moisture in wood fluctuates with changes in the atmospheric conditions around it. All physical and mechanical properties of wood are greatly affected by the fluctuations of the quantity of water vapour present in wood. In using wood as a raw material, it is therefore essential to be able to evaluate its moisture content, and to understand where the moisture is located and how it moves through the wood.

Wood is dimensionally stable when moisture content is greater than the fiber saturation point. Below this point, wood changes dimension as it gains moisture (swells) or loses moisture (shrinks), because volume of the cell wall depends on the amount of bound water (Bergman et al. 2010). With respect to dimensional stability, wood is an anisotropic material. It shrinks or swells most in the direction of the annual growth rings (tangential), about half as much across the rings (radial), and only slightly along the grain (longitudinal). As with all wood properties, shrinkage is highly anisotropic, i.e., tangential shrinkage is 1.5–2.5 times greater than radial shrinkage.

2.5.1 Theory

An important variable that should be analysed is the rate of dimensional change. It is well-known that below the fiber saturation point, the rate of shrinkage can be expected to be directly proportional to moisture adsorption. The rate of dimensional change can be described by the initial linear rate (Mantanis et al. 1994) or by the two-parameter asymptotic regression model (Rypstra 1995), as

$$\frac{dy}{dt} = k(y_{\max} - y) \tag{2.2}$$

Integrating this equation for the initial and end conditions $t = 0$ to $t = t$ and $w = 0$ to $w = w$, Eq. (2.2) may be rearranged for linearized data plotting as shown by Eq. (2.3):

$$\ln\left(1 - \frac{y}{y_{\max}}\right) = -k.t \tag{2.3}$$

The isothermal adsorption data measured is given in Fig. 2.10. Several equations (GAB model, modified Oswin model and Hansen equation) were used to fit experimental data for water activity in the range between 0.33 and 0.91 (Machado 2006).

The three models referred above were applied to experimental data using SPSS 14.0 program and Levenberg-Marquardt algorithm, with no statistical relevant differences observed. The quality of the models was tested by using the "root mean square" (RMS, %):

$$RMS = \sqrt{\frac{\sum \left[(M^{\text{exp}} - M^{\text{calc}})/M^{\text{exp}}\right]^2}{N}} \times 100\,\% \tag{2.4}$$

The results obtained were very similar and the authors decided to use the model proposed by Hansen (1986) and given by the following expression (Tables 2.1 and 2.2).

$$u = u_h\left(1 - \frac{\ln\phi}{A}\right)^{-1/n} = u_h \exp\left[-\frac{1}{n}\ln\left(1 - \frac{\ln\phi}{X_1}\right)\right] \tag{2.5}$$

The results of parameter estimation, for the experimental data, are summarized in Table 2.3. The fittings of the proposed model are very satisfactory for the examined building materials.

Table 2.1 Variables of Eq. (2.2)

Direction	RH (%)	Sample 1				Sample 2			
		y_{max} (mm)	k (h^{-1})	R^2 (%)	E (%)	y_{max} (mm)	k (h^{-1})	R^2 (%)	E (%)
Tangential	50	0.139	0.005	99.72	2.07	0.129	0.005	99.70	3.68
	75	0.414	0.004	99.95	1.67	0.382	0.003	99.92	2.67
	90	0.618	0.001	99.94	4.09	0.593	0.001	99.94	3.91
Radial	50	0.085	0.006	97.46	10.81	0.089	0.006	99.27	4.80
	75	0.235	0.005	99.22	7.32	0.238	0.005	99.52	4.81
	90	0.279	0.004	99.91	2.26	0.280	0.004	99.89	2.45

Table 2.2 Moisture content of the samples

Test period	Sample 1			Sample 2		
	m_h (g)	m_s (g)	u (%)	m_h (g)	m_s (g)	u (%)
Beginning	53.347	46.742	14.1	53.576	46.746	14.6
RH = 35 %	51.178	46.742	9.5	51.173	46.746	9.5
RH = 50 %	51.890	46.742	11.0	51.899	46.746	11.0
RH = 75 %	53.823	46.742	15.1	53.848	46.746	15.2
RH = 90 %	55.851	46.742	19.5	55.817	46.746	19.4

Table 2.3 Samples dimension in function of relative humidity

Relative humidity (%)	Sample 1		Sample 2	
	l_t (mm)	l_r (mm)	l_t (mm)	l_r (mm)
0	29.03	49.05	58.93	48.78
50	29.17	49.14	29.06	48.87
75	29.44	49.29	29.31	49.02
90	29.65	79.33	29.52	49.06

$$u(\%) = \frac{m_h - m_s}{m_s} \times 100 \tag{2.6}$$

and hygric expansion is given by

$$\varepsilon_h(\%) = \frac{l - l_0}{l_0} \times 100 \tag{2.7}$$

$$\alpha = \frac{\Delta\varepsilon_h}{\Delta u} \times 100 \tag{2.8}$$

$$\rho_{ref} = \rho \frac{(100 + 12)(100 + \alpha_v u)}{(100 + u)(100 + 12\alpha_v)} \tag{2.9}$$

2.5.2 Experiments and Results Analyse

An experimental device was planned and designed for testing wood samples (see Fig. 2.11). Displacement sensors were attached to a supporting tray and the complete set was installed in an existing climatic chamber.

The samples with 50 × 50 × 30 mm were, initially, stabilized at a relative humidity of 35 % and a temperature of 20 °C. At the beginning of each cycle, the samples were weighed and measured in three directions, so that it is possible to determine the curve hygroscopic and density. Figure 2.12 presents the geometry assumed for the specimens based on the NP-615 (1973) recommendations and shows the measurement points of the specimens: two measurements per side, in the axial (A), radial (R) and tangential (T).

The stopping criterion to consider that the wood samples had reached stabilization was to remain unchanged for 5 consecutive days.

Figure 2.13 shows the dimensional change in tangential and radial direction, observed for the 2 samples, in function of the variation of relative humidity (RH): [35,50], [50,75] and [75,90]%.

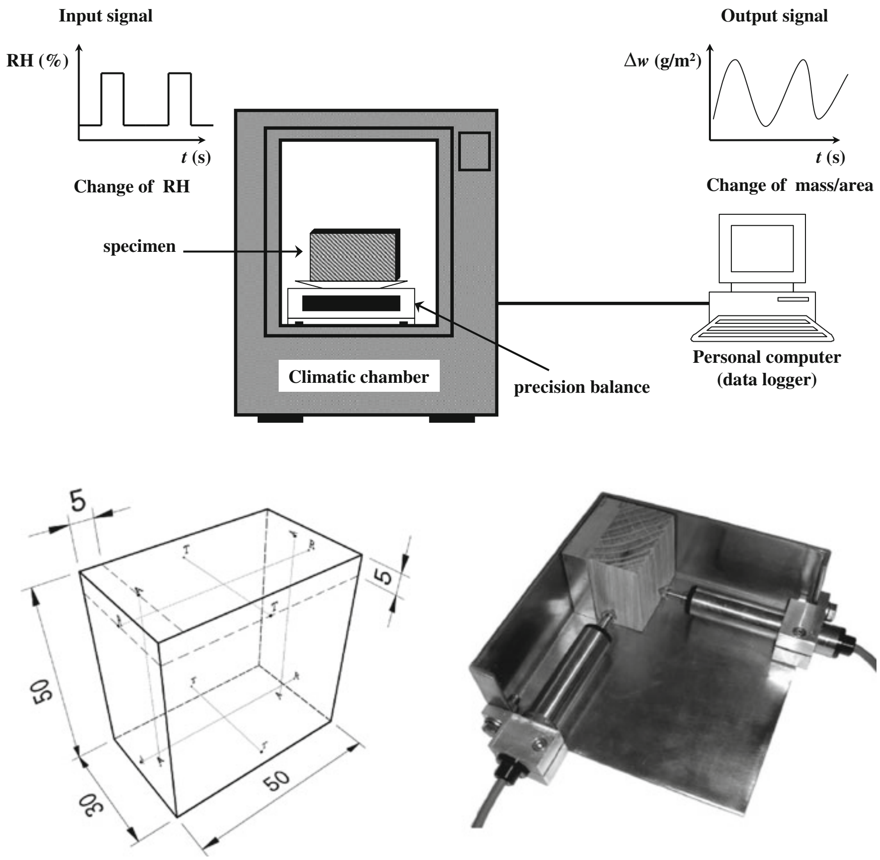

Fig. 2.12 Sketch of experimental set-up

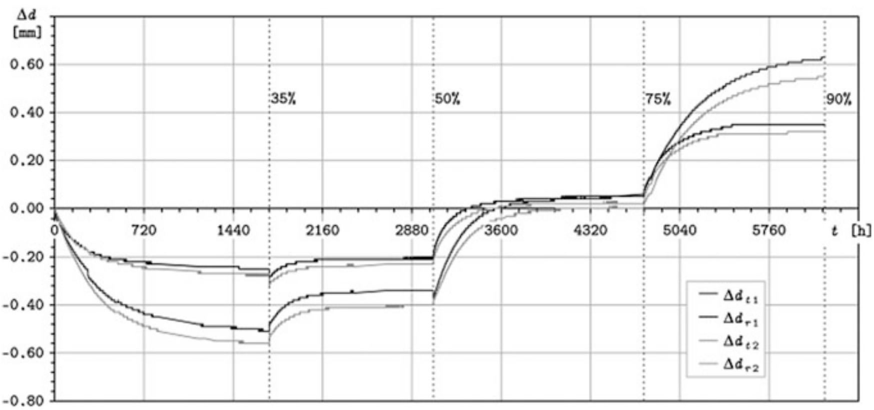

Fig. 2.13 Dimensional change in tangential and radial direction, for each relative humidity plateau

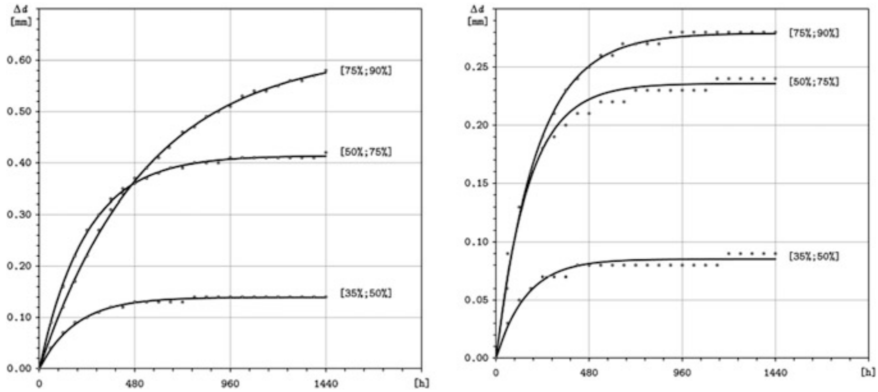

Fig. 2.14 Dimensional change in function of the time and relative humidity, in the **a** tangential and **b** radial direction of sample 1

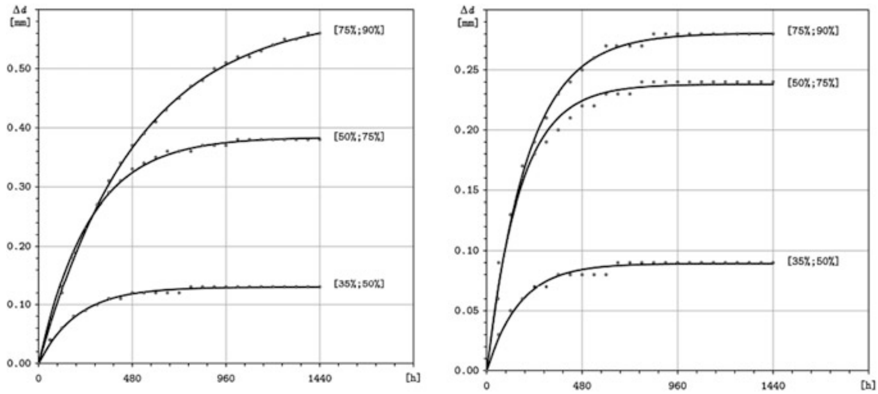

Fig. 2.15 Dimensional change in function of the time and relative humidity, in the **a** tangential and **b** radial direction of sample 2

Figures 2.14 and 2.15 show the wood dimensional change in function of the time at three different relative humidity's (50, 75 and 90 %), for the two samples analysed. Table 2.1 shows the coefficient values of Eq. (2.2) and the average relative deviation module. The analyse of the y_{max} values, of Table 2.1, with the values presented in Fig. 2.13, it is possible to observe that criteria reach 97 % of maximum dimensional variation defined in EN 13006:2000 was also achieved.

The hygroscopic curve was determined using Eq. (2.6). Table 2.2 shows the moisture content observed, for the two samples, at the beginning of the test and for different relative humidity's plateaus. Figure 2.16 shows the hygroscopic curves of the specimens tested for the moisture content values presented in Table 2.2. It is possible to observe that the two samples presenting very similar hygroscopic curves.

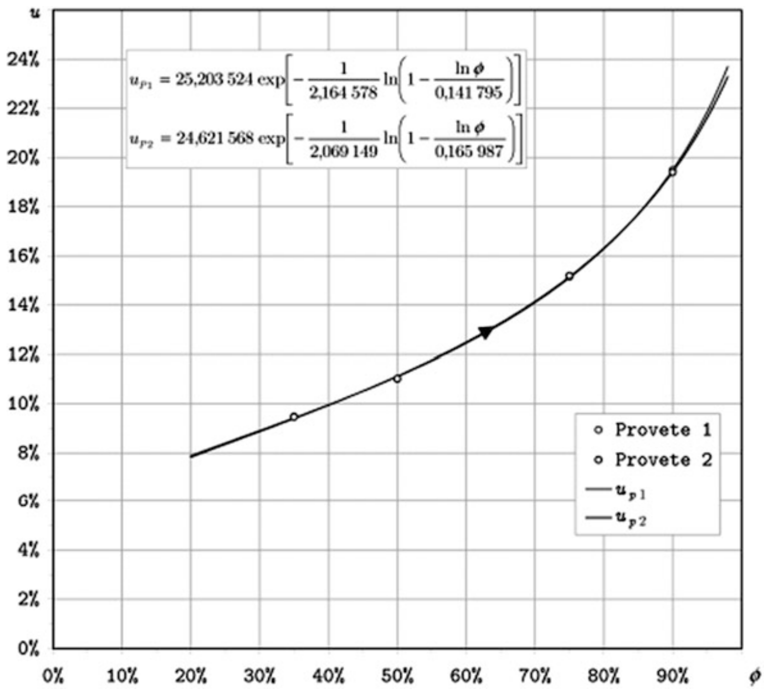

Fig. 2.16 Hygroscopic curve of the samples analysed

Table 2.4 Hygric extension for each relative humidity

Relative humidity (%)	Sample 1			Sample 2		
	u (%)	ε_t (%)	ε_r (%)	u (%)	ε_t (%)	ε_r (%)
50	11.0	0.48	0.17	11.0	0.45	0.18
75	15.1	1.43	0.48	15.2	1.33	0.49
90	19.5	2.13	0.57	19.4	2.05	0.58

Table 2.5 Hygric expansion coefficient determination

RH interval (%)	Sample 1						Sample 2					
	Δu (%)	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_r$ (%)	$\Delta\bar{u}$ (%)	$\alpha_{h,t}$ (%)	$\alpha_{h,r}$ (%)	Δu (%)	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_r$ (%)	$\Delta\bar{u}$ (%)	$\alpha_{h,t}$ (%)	$\alpha_{h,r}$ (%)
[35,50]	1.5	0.27	0.07	10.3	17.9	4.6	1.6	0.24	0.08	10.2	15.4	5.1
[50,75]	4.1	0.95	0.31	13.1	22.9	7.4	4.2	0.88	0.31	13.1	21.1	7.3
[75,90]	4.3	0.70	0.09	17.3	16.2	2.1	4.2	0.73	0.09	17.3	17.2	2.1

Table 2.3 presents the samples dimension in function of relative humidity and Tables 2.4 and 2.5 present the experimental values of hygric extension and hygric

Table 2.6 Density and reference density of the samples analysed

Test period	Sample 1		Sample 2	
	ρ (g/cm^3)	ρ_{ref} (g/cm^3)	ρ (g/cm^3)	ρ_{ref} (g/cm^3)
Beginning (%)	0.711	0.758	0.721	0.772
RH = 35	0.698	0.744	0.703	0.753
RH = 50	0.704	0.750	0.710	0.760
RH = 75	0.713	0.760	0.717	0.768
RH = 90	0.726	0.773	0.729	0.780

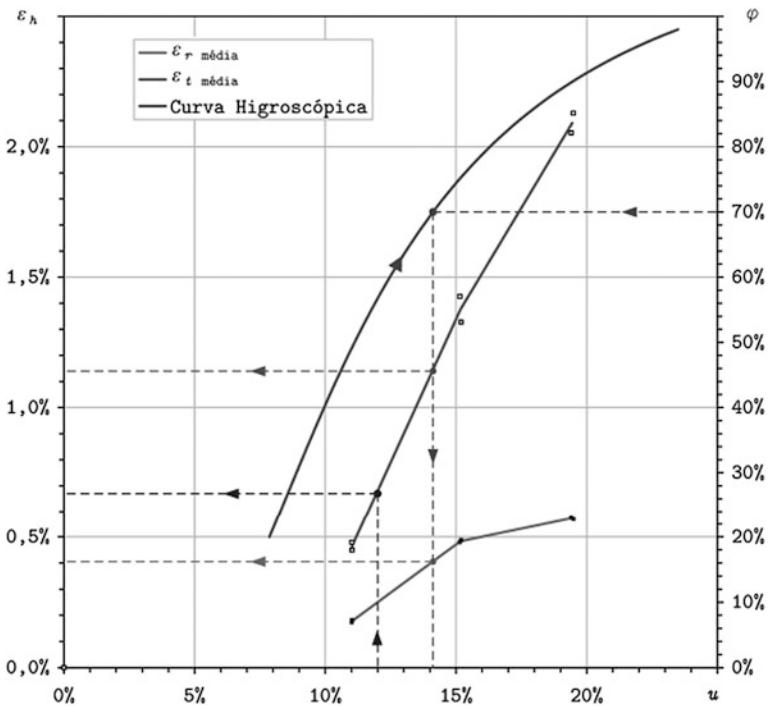

Fig. 2.17 Relationship between dimensional change and the relative humidity and moisture content

expansion coefficients, respectively. Finally, Table 2.6 shows the density values and reference density of the samples analysed (Fig. 2.16).

Above we presented the determination methods of several parameters that characterizing the wood in study. The main goal is to relate the three fundamental parameters of the dimensional variation phenomenon, which are the hygric extension (Eq. 2.7), the environmental relative humidity and the moisture content of the wood. Figure 2.17 presents an abacus with joint representation of those parameters.

This experimental work show the dimensional change of the red oak, an important material used in ceilings, floors and wall finishing's in function of interior moisture change. The experimental campaign resulted in the following conclusions:

- It was developed a prototype for determination of the hygric expansion;
- It was analysed the hygric expansion of the red oak at three different ranges of indoor relative humidity's, 35–50, 50–75 and 75–90 %;
- The hygric expansion coefficient presents a linear variation with the moisture content;
- It was possible to obtain a relationship between the dimensional change and the relative humidity and the moisture content.

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