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TEST OF WOOD PROPERTIES IN OAK SPECIES (*QUERCUS ROBUR* L., *QUERCUS PETRAEA* (MATTS) LIEBL. AND *QUERCUS PYRENAICA* WILLD.) FOR WINE AGING. PART III: POROSITY VERSUS VOID RATIO

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ABSTRACT

The study on wood physical properties of *Quercus robur* L., *Quercus petraea* (Matts) Liebl., and *Quercus pyrenaica* Willd., to use in wine aging was also founded on the relationship between porosity and void ratio to assess its variation in the oak species under study. A total of 45 oak trees were chosen in 15 oak stands of the Lugo and Ourense provinces (Galicia, northwestern Iberian Peninsula). Altogether, were obtained forty-five fine slices of wood at 60 cm tall on the trunk, and 194 wood test specimens' parallelepipeds of 20 × 20 × 40 mm ± 1mm.

On average, oak species in Galicia have lower porosity than oaks of the French regions of Limousin and Vosges. With a width of growth ring and age similar, *Quercus pyrenaica* has porosity slightly lower than *Q. robur* and *Q. petraea*. Our objective is to carry out a complete description on the wood physical properties of the studied species for its possible use in the cooperage industry and wine aging. For that, the aim of this work was to estimate the porosity versus the void ratio.

KEYWORDS: NW Iberian, Galician oaks, wine aging, wood properties.

INTRODUCTION

Sustainable, ecologically-based management of oak forests requires forestry to integrate several treatments to emulate historic disturbance processes. These forestry practices were developed in European countries where thousands of hectares of oak forests have been managed for hundreds of years (Bary-Lenger and Nebout 1993). However, as a consequence of the diverse use and conservation, the oak forests in Galicia, present a wide set of ages and qualities (Diaz-Maroto et al. 2010).

Galician oak forests were exploited from centuries employing forestry methods inadequate (i.e., pollarding and felling of the best trees). Now, as a consequence of rural depopulation and socioeconomic necessities, there was a radical change trend from overexploitation to total lack of use (Diaz-Maroto and Vila-Lameiro 2007). As indicated by the Habitats Directive 92/43/EEC, Council Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora, these ecosystems are habitats of Community Interest, being essential in many regions to put into practise a rural sustainable development.

The area occupied by native deciduous broadleaved forests in Galicia has significantly increased. According to the published last data, belonging to the IV National Forest Inventory, the forests of native broadleaves occupy a 31% of the forest area, 441,289 ha, standing out the area covered by *Quercus robur* L. with 246,446 ha, 17.4% of the forest cover (Diaz-Maroto 2019).

Today, forest management virtually does not exist and the use of its wood is only for firewood. The oak wood is little used by the forest industry because the existence of numerous small plots of many owners does not promote its use (Diaz-Maroto et al. 2005). The overall objective of the current research was to study the anatomical and physical characteristics of the Galician oak wood for making wine barrels and assess its main properties for cooperage industry as key to sustainable rural development. For this, Image J software has been very useful. It is a digital image processing computer program which is focused at different science field. It is a public domain, open source software developed in Java at the USA National Institutes of Health. It includes powerful built in tools to edit, process, and analyse every type of image in diverse formats. However, the main feature is its flexibleness, because functionalities can be widened to solve most of the situations found in digital image processing through macros, scripts and, specially, plugins programmed in Java thanks to the Image J API (Sánchez 2014). The particular aim of this paper is to determine the porosity versus the void ratio to understand its fluctuation in the oak tree wood.

MATERIAL AND METHODS

Study area and sampling method

The study area is located in Galicia, northwestern Spain. The average altitude is about 500 m, with slopes of more than 20% in the middle of the land. The lithology is varied, but there is a dominance of siliceous substrates; the climate is Humid Oceanic with a Mediterranean effect in the south. Annual rainfall varies between 600 and < 3000 mm, and the average temperature is nearly to 13°C (Diaz-Maroto et al. 2006a).

The area under study was considered as a single unit, where the locations for sampling were selected. A sufficient number of oak stands were included on the basis of the Forest Map of Spain. The minimum area ranged between 0.5 and 1 hectare, which avoided problems of the edge effect. Finally, 45 oak trees were chosen on 15 stands of the eastern provinces of Galicia, Lugo and Ourense, i.e., we have cut 45 wood slices at 60 cm tall on the trunk, and obtained a total of 194 test tubes with a parallelepiped shape and dimensions of 20 × 20 × 40 mm ± 1mm.

Since 69% of Galicia land is above 600 m of altitude, a lot of the forests are located on steep slopes. This fact is a problem because strong slopes encourage the formation of the tension wood. This wood type has a heart off centre, which not appropriate to cooperage industry.

Tab. 1 shows the physical characteristics –quality– of the wood slices regarding to growth ring of trees felled (from normal tree to heart strongly off centre) (Vila-Lameiro and Diaz-Maroto 2005).

Tab. 1: Physical features –quality– of the wood slices from trees felled.

Type of tree heart	*Q. robur*	*Q. petraea*	*Q. pyrenaica*	Total
Normal	7	6	5	18
A little off centre	4	-	2	6
Heart off centre	4	8	3	15
Strongly off centre	2	1	3	6
Total wood slices	17	15	13	45

Statistical testing: Image J software

In the field of forest science, by means of Image J software, we can calculate, among other features, the area of each of the parts of the tree trunk, namely the bark, sapwood and heartwood, as well as their proportion. The high precision allows using a large wooden sample, in addition to reflecting the uniqueness of each sample. Image J is multithreaded, so time-consuming procedures such as image file analysis can be done together with other. It can estimate area and pixel value statistics of user-defined options. Also, can calculate distances and angles and generate density histograms. It supports standard image processing functions, e.g. contrast management, sharpening, smoothing, edge recognition and median filtering. Spatial calibration is available to supply measurements in mm (Diaz-Maroto and Tahir 2016).

Porosity versus void ratio

Wood density is one of its most main features since it correlates well too many other properties (Knapic et al. 2007). Long, winemakers know oak wood should be suitably porous to allow exchange slow and continuous oxygen. One of the first studies on the passage of oxygen through the staves was conducted by Vivas et al. (2003). The porosity is directly related to the proportion of void compared to the total volume:

$$\varepsilon = V_0 / (V_1 + V_0) \quad (\%) \tag{1}$$

where: ε - porosity, (%)
V_0 - void volume (cm^3),
V_1 - solid timber volume (cm^3).

Nepveu (1987) has linked infradensity to porosity using the relationship established by Siau (1984), such as Vivas et al. (2003) cited in his work on the exchange of oxygen through staves:

$$\varepsilon = (1 - (ID \times 0.001 / 1.53) \times 100\ (\%) \tag{2}$$

where: ID – infradensity (g·cm^{-3}),
1.53 - density of the dry timber (g·cm^{-3}) (Usta, 2003).

Wood is a cellular/porous material constituted of cell wall substances and cavities containing air and extractives (Bakour 2003). Without cavities and intercellular spaces the relative density of the cell wall materials is practically constant for all timbers with a wood density (or specific gravity) equal of 1.53 g·cm^{-3}, on an oven dry mass and volume basis (Pasztory et al. 2014). The gravity of 1.53 g·cm^{-3} is an ideal physical value for a lignified cellulosic cell wall which is completely nonporous (Harvald and Olesen 1987, Usta 2003).

RESULTS AND DISCUSSION

Spatial scale and polygon selection

Initially, we have taken digital pictures of the test tubes by means of a camera Canon EOS 550D, which manages a unique structure to ensure optimal light and also an invariable distance between the camera and the samples –test tubes–. The first step is to specify the spatial scale of the image so all measurements can be obtained in standardized units, in our case, centimetres. Before operating the scale command, we need to make a line selection corresponding to a known distance. Image J software will have automatically filled in the distance in pixels founded on the length of the line selection (Diaz-Maroto and Tahir 2016, Sánchez 2014).

The second step is to make use of the polygon selection tool to generate polygons irregularly shaped, demarcated by a network of linear segments. To construct a polygon it is necessary to click time after time with the mouse to select linear segments corresponding to the perimeter of different areas, although Image J has an automatic selection tool -wand tool-. The identification of the bark is the most complicated, because its border is irregular, and at times it's complex to distinguish the correct limit (Gelhaye and Guilley 2000, Fernandez-Parajes et al. 2005, Vila-Lameiro and Diaz-Maroto 2005).

Results and explanation on the wood density

The selection method of the test tubes was as follows:

1. Three species of Galician oak used for wine aging: *Quercus robur*, *Q. petraea*, and *Q. pyrenaica*.
2. Three different types of wood: sapwood, heartwood, and juvenile wood.
3. Three types of tree trunk regarding to growth ring: rotten heart, off-centre heart, and normal heart.

The sample division according to the wood type and the species is show in Tab. 2, and the Tab. 3 shows the test tubes distribution by tree trunk type and species. Only the slices from *Q. petraea* have a rotten heart which is a peculiarity of the area where the trees were felled. Mostly, they are located on steep slopes where soil depth is scarce (Deret-Varcin 1983, Diaz-Maroto et al. 2006b).

Tab. 2: Distribution of the sample by species and wood type.

Species/Wood type	*Q. robur*	*Q. petraea*	*Q. pyrenaica*	Total
Sapwood	33	19	29	81
Heartwood	27	27	34	88
Juvenile wood	8	6	11	25
Total	68	52	74	194

Tab. 3: Distribution of the test tubes by tree trunk type and species.

Tree trunk type/ Oak species	Rotten heart	Off-centre heart	Normal tree	Total
Quercus robur	0	19	49	68
Quercus petraea	17	0	35	52
Quercus pyrenaica	0	16	58	74
Total	17	35	142	194

In each of the plots, three trees were felled as a general rule. The slopes of great magnitude stimulate the presence of off-centre heart trees. This wood type is not suitable for the manufacture of barrels (Vivas 2000, Pot et al. 2013). This is the cause why sometimes there are only one or two trees without off-centre heart per plot for the measurement of wood porosity. For each individual tree, different test tubes were obtained of sapwood and heartwood in function of its ratio.

Wood density of 142 test tubes from 18 "*normal oak trees*" (Tab. 1), i.e. without rotter heart and/or off-centre heart, show an average of 648 kg·m^{-3}, coefficient of variation (CV) of 7%, and a range between 498 and 906 kg·m^{-3} (Tab. 4). Gelhaye and Guilley (2000), obtained a mean value equal of 553 kg·m^{-3} by wood density, in a total of 90 test tubes of *Q. robur* and *Q. petraea* in the forest of Little Charnie (France), and Bakour (2003), asserts to have achieved a comparable value in different French forests, within a set of 588 test tubes, 530 kg·m^{-3}.

By contrast, Deret-Varcin (1983) got a lower value of the wood density, 450 kg·m^{-3}, on a set of 140 test tubes of the same species in the forest of Morimond, France. However, the data of Vivas (2000) in a *Q. robur* forest of the northern Portugal were higher, 650 kg·m^{-3}, and like to ours, because the procedure of measurement was the same and the site is similar (Lebourgeois et al. 2004). Moreover, the average oven-dry wood density of *Q. robur* and *Q. petraea* was 584.3 kg·m^{-3} and 672.7 kg·m^{-3}, respectively, in floodplain *Q. robur* forests of South Moravia (Czech Republic) and *Q. petraea* forests from highland (Vavrčík and Gryc 2012). Reading these researches allows us to observe the variability of the density of oak wood according to the geographical provenance and maybe the measurement method (Guilley et al. 1999, Fromm et al. 2001).

Factors affecting the variability of the density of oak wood: geographical origin, species, growth ring width, age and wood type

As we mentioned before, wood density is one of its most important characteristics since it correlates well too many other physical and mechanical properties. Therefore, wood density is a suitable feature for estimation other timber properties (Hacke and Sperry 2001, Usta 2003).

Numerous variables have an influence on what be known as "geographical origin/provenance". In our research on "Autecology of *Quercus petraea* in the north-west Iberian Peninsula" (Diaz-Maroto et al. 2006b) cited more than different sixty parameters: climatic, soil and physiographic. Now, our goal is to research how the geographical origin influences generally in the wood density of the Galician oaks. To appropriately interpret the obtained results, the data were analysed by species tree and wood type because the distinction between sapwood and heartwood involves differences between 12 and 20% which should not be attributed only to the geographical provenance (Alanon et al. 2011a). Although it is difficult to establish a trend because of the small number of measures, in Tab. 4 shows as for similar increase ring width and age, the wood density varies significantly: e.g. there is up a difference to 132 kg·m^{-3} in *Q. pyrenaica* test tubes.

Only samples of *Q. petraea* possess values extraordinarily near. This circumstance could be justified by the geographical proximity of the sampling plots as well as the similar climatic and physiographic characteristics (Alanon et al. 2011b). However, Guilley et al. (1999) studied the variability of wood density in *Q. petraea* and they evidenced that geographical, site quality, and silvicultural effects only explained a very few part of the total variation of wood density. Therefore, we can assume that the relationship between the density of the wood and the radial growth is not modified according to the sampled localities neither according to the different qualities of the sampled sites (Gelhaye and Guilley 2000, Vila-Lameiro and Diaz-Maroto 2005, Vavrčík and Gryc 2012).

Tab. 4: Wood density, growth ring width and age by oak species and type of wood.

Oak species	Wood type (Test tubes)	Growth ring width (mm)	Age	Wood density ($kg \cdot m^{-3}$)		
				$\bar{x} \pm \sigma$	Range (Min.–Max.)	Coefficient variation (%)
Q. pyrenaica	Sapwood (25)	5.94	45	584 ± 55	498 – 678	9
	Heartwood (26)	5.82	45	716 ± 61	584 – 825	9
	Juvenile wood (7)	6.13	45	732 ± 47	673 – 811	6
[Total] / Weighted average	[58]	5.91	45	661		8
Q. robur	Sapwood (27)	7,38	43	610 ± 72	486 – 744	12
	Heartwood (17)	5,97	49	695 ± 68	622 – 906	10
	Juvenile wood (5)	5,47	51	677± 27	626 – 703	4
[Total] / Weighted average	[49]	6,70	46	646		8
Q. petraea	Sapwood (15)	3,98	67	583 ± 31	532 – 628	5
	Heartwood (15)	4,00	67	671 ± 15	650 – 712	2
	Juvenile wood (5)	4,08	64	640 ± 16	608 – 652	3
[Total] / Weighted average	[35]	4,00	67	629		3
TOTAL	142			648		7

In this context and in accordance with the before authors, it is remarkable to observe the coefficient of variation values within the same plot (Tab. 5); usually, wood density values show low variation at the plot level. *Q. pyrenaica* has the highest wood density, 661 $kg \cdot m^{-3}$, followed by *Q. robur*, 646 $kg \cdot m^{-3}$, and *Q. petraea*, 629 $kg \cdot m^{-3}$ (Tab. 4). These values are in line with the obtained by Fernandez-Parajes et al. (2005). However, Vavrčík and Gryc (2012) achieved a value of the average oven-dry wood density in *Q. robur* and *Q. petraea* of 584.3 $kg \cdot m^{-3}$ and 672.7 $kg \cdot m^{-3}$, respectively. The found data also disagree with those obtained by other authors (Deret-Varcin 1983, Bakour 2003), especially for *Q. petraea*, where the resulting values were higher. The wood test tubes of this species tree come from a mountain range with an elevation greater than 1200 m and abrupt slopes. The environment –growth– conditions are complex and affect the ring width, only 4 mm of average, which is the lowest average of growth ring width.

There were differences in average values and variability of annual ring width in relation to oak species. According to decreasing ring width with the age of the tree it is noticeable that higher density should be in the central part of tree trunk of ring-porous species as oaks (Vavrčík and Gryc 2012). A lower ring width in the oak species proves in a lower texture (Vila-Lameiro and Diaz-Maroto 2005), being the percentage of early wood more significant than of the late wood (Pasztory et al. 2014). The oak wood has an initial porous part since it has many vessels in the early wood (Bary-Lenger and Nebout 1993, Ghazil 2010). Therefore, a lower texture contains more vessels on the slice surface, giving rise to a lower wood density (Usta 2003, Pot et al. 2013). Also, the higher average ages of *Q. petraea* have an effect on wood density (Fromm et al. 2001, Bakour 2003, Pasztory et al. 2014).

The positive correlation between growth ring width and density of wood is shown in the Eqs. 4, 5, and 6. A high density agrees with a maximum of wood and a small proportion of vessels. In the oak trees, this small proportion of vessels results in an important proportion of late wood, i.e. a strong texture (Gelhaye and Guilley 2000, Knapic et al. 2007, Lehringer et al. 2008).

The slope model for *Q. pyrenaica* is more considerable than for *Q. robur* and *Q. petraea* because to the higher density detected in this species (6). The low value of the Pearson coefficient of *Q. petraea* is due to the non-existence of sufficient data, only 35 test tubes against 58 for *Q. pyrenaica* (Tab. 4), combined with a large range of ages.

Regarding to the relationship between wood density variability and the age, we don't even need to note at the Pearson coefficient to understand this model does not work. Bakour (2003) demonstrated a negative correlation between age and wood density for *Q. robur* (3). Modelling on 123 trees makes it possible to obtain the equation following:

$$\text{Wood density} = -0.564 \times age + 600.498;\ R^2 = 0.262 \tag{3}$$

The slope of the model is only −0.564. However, in our research the slope of the relationship between growth ring width and wood density is 24,482 for *Q. robur* (4). Consequently, we can deduce the influence of age on wood density in this species is less important that the influence of width of growth ring.

$$\textit{Quercus robur}: y = 24.482\,x + 561.79;\ R^2 = 0.3972 \tag{4}$$
$$\textit{Quercus petraea}: y = 21.219\,x + 581.99;\ R^2 = 0.1844 \tag{5}$$
$$\textit{Quercus pyrenaica}: y = 36.296\,x + 533.39;\ R^2 = 0.2116 \tag{6}$$

To conclude this point on the factors that affect the density of oak wood, with respect to the type of wood (Tab. 4 and 5); regardless of the species, the sapwood has the lowest density with values between 12 and 20% lower than the average density of the heartwood and juvenile wood (Deret-Varcin 1983, Lehringer et al. 2008). Also, it is interesting to note the sapwood has the higher CV, although the difference with the heartwood is not significant (Tab. 4 and 5); it is a tree region with comparatively variable density (Vila-Lameiro and Diaz-Maroto 2007, Lehringer et al. 2008, Pasztory et al. 2014).

From an anatomical standpoint, the heartwood only contains dead cells because it has been submitted chemical and sometimes physical alterations (Vermaas 1988, Higuchi 1997, Hacke and Sperry 2001). The ways of sap flow can be closed (closing bordered pits of conifer "tracheids") or become blocked (blocking of vessels broadleaved trees by membrane extensions called "tyloses") (Ghazil, 2010). Microscopic studies (LM –Light Microscope, and Scanning Electron Microscope –SEM) showed that the "tylosis" formation increased with the degree of damage by fungal infections, in earlywood vessels as well as latewood vessels. Whereas the heartwood vessels were generally sealed by tyloses, as was expected, the degree of tylosis formation in the sapwood was considerably different (Kaus et al. 1996).

Therefore, we can assume that these heartwood obstructions leave less space for air and water, which explains a higher density than in the sapwood (Vermaas 1988). However, sapwood be composed of living cells, the non-obstruction of the vessels are critical to the flow of sap. To close, it is very complicated to conclude on the density of the juvenile wood. By species to remark that *Q. robur* and *Q. petraea* have a slightly lower density in the sapwood. And, the wood density of *Quercus pyrenaica* wood is slightly higher than in the other species (Tab. 4).

Tab. 5: Wood density, growth ring width and age depending on geographic provenance.

Oak species	Wood type	Geographic provenance	Trees (test tubes)	Growth ring width (mm)	Age tree	Wood density ($kg \cdot m^{-3}$) $\bar{x} \pm \sigma$	CV (%)
Quercus pyrenaica	Sapwood	Ourense province	1 (3)	1.27	50	609 ± 22	4
			2 (8)	3.26	46	548 ± 16	3
			1 (2)	1.60	48	547 ± 1	0
			1 (4)	3.26	44	523 ± 22	4
			2 (8)	3.42	37	651 ± 26	4
	Heartwood	Ourense province	1 (2)	2.55	50	768 ± 2	0
			2 (8)	3.86	46	661 ± 48	7
			1 (4)	3.45	48	674 ± 27	4
			1 (4)	4.48	44	736 ± 23	3
			2 (8)	4.09	37	729 ± 25	3
Quercus robur	Sapwood	Ourense Lugo provinces	2 (15)	4.62	29	637 ± 87	14
			2 (8)	2.13	59	568 ± 30	5
			1 (4)	1.63	57	598 ± 25	4
	Heartwood	Ourense Lugo provinces	2 (5)	4.51	29	688 ± 123	18
			2 (8)	2.71	59	676 ± 30	4
			1 (4)	3.35	57	740 ± 10	1
Quercus petraea	Sapwood	Lugo province	3 (7)	1.59	80	568 ± 33	6
			3 (8)	1.73	53	596 ± 28	5
	Heartwood	Lugo province	3 (7)	2.34	80	674 ± 17	3
			3 (8)	2.66	53	667 ± 13	2

Galician oak properties for the barrel manufacturing to cooperage industry: porosity vs void ratio

A lot of parameters influence exchange between wine and wood barrel. The species, the wood porosity, the grain, the aging method, the toasting type, the volume of the barrels and the barrel manufacturing process put forward a many possibilities for the aging of quality wines (Feuillat et al. 1994, Alanon et al. 2011b, Ballian et al. 2018). There are different methods to determine the density of the wood within the void volume values (porosity). In all cases, the volume definition has a great effect on the density which varies significantly between species and within species, due to differences in the ratio of cell wall to air spaces (Usta 2003).

The meaning and importance of the porosity of the wood and grain

The width of the growth rings or "grain" determines important properties such as wood porosity (Feuillat et al. 1994) and chemical composition (Vivas 1995). Technically wood grain refers to the alignment, texture and appearance of wood fibres, whereas its shape describes the pattern created by the grain orientation (Guilley et al. 1999, Knapic et al. 2007). The wine aging in wood barrels is an indispensable phase in the obtaining of quality wines. During the period of this procedure, two imperative phenomena occur: i) the oxidation of some compounds of the wine because to the infiltration of oxygen; ii) the dissemination of aromatic compounds, some of which came from the wines themselves and others which came from the oak wood.

Feuillat et al. (1994) describe the barrel as an "active interface" between a liquid (wine) and a gaseous environment (air of the wine cellar) that regulates the exchange phenomena between the two environments. Exchanges take place by the joints of the staves, and also across of the staves themselves (Prida and Chatonnet 2010).

Moreover, the wood fibers must be straight and not be cut to be waterproof. For the same cause, the wood with nodes is also unsuitable for cooperage industry. Coopers use the concept of grain because it is an easy test makes it is possible a fast and reliable visual classification. The criteria most commonly used are the geographical provenance of wood and the grain, that is to say, the width of growth rings and its regularity. Basic grain descriptions and types include (Hill 2015):

- Straight-grain: this performs in a single direction along the cut wood.
- Cross-grain: formed when some cells grow out from the centre of the tree.
- Spiral-grain: this type of grain develops as the trunk of the tree twists during its growth.
- Interlocked-grain: this is a step further than spiral grain and occurs when growth rings in a twisting trunk develop misaligned grain.

In France, coopers usually use the following classification (Vivas 1995):

- Crude-grain: width of growth rings to 5-4 mm.
- Medium-grain: width of growth rings to 4-2 mm.
- Tight grain: width of growth rings to 2-1 mm.
- Very tight grain: width of growth rings less than 1 mm.

The results obtained by Vivas (1995) in different regions of France compared with the results found in our research is show in Tab. 6.

Tab. 6: Comparison of grain wood oak from some French regions (Vivas 1995) and the provinces of Lugo and Ourense, Galicia.

Source	Oak species	Geographical provenance	Trees number	Growth ring width (mm)	Number of rings by cm		
					$\bar{x}$	Heterogeneity (Min/Max)	CV (%)
Vivas (1995)	*Q. robur*	Limousin	180		2.22	0.42	28
	Q. petraea	Vosges			3.44	0.42	29
	Q. petraea	France centre			5.56	0.65	14
Galician oak wood	*Q. robur*	Lugo and Ourense	5	3.5	1.77	0.36	40
	Q. petraea		4	2.2	2.57	0.63	20
	Q. pyrenaica		7	3.5	1.74	0.57	19

The values obtained for the growth ring width, between 2.2 and 3.5 mm, show that the Galician oak wood suitable for cooperage has a medium grain (Vivas 1995). Likewise, the lower average number of growth rings per centimetre indicates a stronger growth of oak species in Galicia, mainly compared to regions of the Vosges and France centre (Tab. 6). Finally, despite the less trees used in our work, heterogeneity and dispersion characterized by CV, are quite similar.

The texture of the grain refers to the size, variation in size, type and arrangement of wood cells and this affects to the appearance of the grain (fine-grain or coarse-grain). The difference between fine-grain and coarse-grain wood is the way that these cells are arranged and the size and distribution of the pores (Hill 2015).

Tab. 7: Values of porosity depending on the oak species and type of wood.

Oak species	Wood type (Test tubes)	Growth ring width (mm)	Age	Porosity (%)		
				$\bar{x}$	Range (Min.–Max.)	Coefficient variation (%)
Q. pyrenaica	Sapwood (25)	5.94	45	62	67 – 56	6
	Heartwood (26)	5.82	45	53	62 – 46	8
	Juvenile wood (7)	6.13	45	52	56 – 47	6
[Total]/ Weighted average	[58]	5.91	45	57		7
Q. robur	Sapwood (27)	7,38	43	60	68 – 51	8
	Heartwood (17)	5,97	49	55	59 – 41	8
	Juvenile wood (5)	5,47	51	56	59 – 54	4
[Total]/ Weighted average	[49]	6,70	46	58		7
Q. petraea	Sapwood (15)	3,98	67	62	65 – 59	3
	Heartwood (15)	4,00	67	56	58 – 53	2
	Juvenile wood (5)	4,08	64	58	60 – 57	2
[Total]/ Weighted average	[35]	4,00	67	59		2
TOTAL	142			58		5

Tab. 7 presents the porosity values depending on the oak species and type of wood. Differences in density and void volume (porosity) may arise simply from differences in the anatomy of the wood and possibly will derive from anatomical differences, such as in cell types and its quantitative distribution, thickness of cell walls and size of cell cavities (Usta 2003). The porosity is very similar in the three oak species, and regarding the wood type the sapwood shows the higher percentage.

CONCLUSIONS

The relationship between porosity and wood density revealed that a higher value of the density, the porosity is lower. Thus, we can assume the following conclusions:

- On average, Galicia oak species have a lower porosity compared to French oak species studied.
- With a growth ring width and age similar, *Q. pyrenaica* has a slightly lower porosity than *Q. robur* and *Q. petraea*.
- The porosity decreases as the width of rings increases.
- The heartwood has a porosity of 7 to 9% lower than the sapwood.
- The number of growth rings per centimetre indicates a greater growth of oak species in Galicia, mainly compared to regions of the Vosges and France centre.

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