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STRUCTURE AND PROPERTIES OF FIR (ABIES BORISII – REGIS MATTF.) AND SPRUCE (PICEA EXCELSA LINK) AND THEIR INFLUENCE ON WOOD IMPREGNABILITY*

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ABSTRACT

Spruce and fir wood is important for Greek and Bulgarian forestry and wood industry. Durability of spruce and fir mature heartwood is low and both species are refractory to impregnation - spruce wood is poorly or not permeable, while fir wood is poorly to moderately permeable. The low permeability and the resistance of fir and spruce wood to impregnation are attributed to its specific anatomical – characteristics and properties. This work presents the structural characteristics and properties, summarises those anatomical characteristics which are related to impregnation processes and looks for new methods to improve fir and spruce wood permeability. Surface drilling of wood by laser beams might improve their permeability to preservatives and widen the uses of fir and spruce in exterior conditions.

Key words: spruce, fir, wood structure, wood properties, permeability

INTRODUCTION

Fir (*Abies borisii-regis* Mattf.) grows in Bulgaria (Pirin, Rhodope), Greece (Macedonia to Peloponnesus) and east and northern Turkey with common names as Bulgarian fir, hybrid fir or Nordman fir. It reaches 40 –50 m in height and up to 1.5 m in trunk diameter. It is a natural cross hybrid between Greek fir (*Abies cephalonica*) and European white (silver) fir (*Abies alba*) - *Abies cephalonica* x *Abies alba*, populus hybridogenus (Tsoumis and Athanasiadis 1981). The genus *Abies* is distributed over the whole of Europe. The color of wood is white with a little tendency to grey-violate. Heartwood is slightly distinct from sapwood in dry wood (Passialis and Tsoumis 1984) (Fig. 1). The texture is fine to medium according to growth rate. There is no resin in the wood. The wood is similar to spruce: soft, low in weight with low to medium density (0.40-0.45 g/cm^3. Strength properties are good. Sawing, machining and assembling are easy. Fir has a slight tendency to split when nailed (Blaskova 2009).

Spruce (*Picea excelsa* Link) grows in Europe, including western Russia, also in Canada and USA. It reaches a height of 24–36 m and trunk diameter of 0,6–1,2 m. The wood is similar to fir wood. It has no odor and heartwood is light in color, indistinct from sapwood; Grain appearance is fairly even to moderately uneven and the early/latewood transition is gradual; Resin canals are small, relatively few and variable in distribution, solitary or up to several in tangential groups (Tsoumis 1991, Blaskova 2009).

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Figure 1: Distinction of heartwood from sapwood in freshly cut fir logs (*Abies borisii-regis*). This distinction becomes lighter when the wood dries.

Fir and spruce wood are often mixed for structural end uses, indoors and outdoors: general carpentry, interior construction, windows, doors and floors, poles and posts, wooden boxes, musical instruments, pulp and paper, particleboards and fiberboards.

The permeability of wood to liquids and gases plays an important role in many technical processes (Kakaras and Philippou 1996). Permeability is a key issue in evaluation of impregnating or drying processes. It is influenced by structure and properties of wood, which represents a heterogeneous capillary system consisting of makro- and mikro-capillaries, through which liquids can flow. Impregnability of wood depends on its anatomical structure. The opened or closed state of the pits in the tracheids has a dominant effect on the impregnability of conifers. Fir and spruce wood has low permeability after the aspiration of tracheid bordered pits, which usually occurs during the tree growth (in heartwood zone) or during drying of the wood after cutting (sapwood zone) (Blaskova 2009). Mechanical surface drilling of wood improved its permeability to preservatives (Kakaras and Voulgaridis 1992, Ruddick 1986). The use of laser beams for surface drilling of spruce and fir wood seems to be a promising method for improving their permeability.

EXPERIMENTAL METHODS

Microscopic and anatomical characteristics were observed and measured in a light microscope with digital camera. The physical and mechanical properties were determined, when measured, according to European standards (DIN 52186: 1992, ISO 3787: 1976). For mechanical properties the SHIMATZU and AMSLER testing machines were used.

STRUCTURE OF FIR AND SPRUCE WOOD

In fir (Fig. 2), the growth rings are well outlined. The late wood takes up 20–25 % of their width. The transition between earlywood and latewood within one growth ring is gradual, sometimes tending to abrupt. The early tracheids are rectangular or pentagonal, thin-walled with a wall thickness of 2,2 to 5,1 μm. The size of their cell lumen is 21,1 to 52,4 μm. The latewood tracheids are rectangular, thick-walled with a wall thickness of 6.6 to 12.3 μm. The mean dimensions of the double cell wall of two adjacent cells and cell lumen of earlywood tracheids are 3,7 and 34,6 μm, and of the latewood ones 9,0 and 16,2 μm, respectively. The mean length of tracheids is 4300 μm, and their relative volume is about 90,4 % of the wood (Blaskova 2009, Seckin 2012).

The rays are homogeneous, one-row, composed in height of 1 to 40 (50) cells or they have a height of 90 to 430 µm. They take up about 9,6 % of the wood. They are not seen with the naked eye. In the cross field, 1 to 4 small taxodioid cross-field pits are found. Crystals of calcium oxalate are, also, found. There are no resin canals in the wood of fir, which may be an essential sign during its identification. The wood parenchyma is rare (Esteban *et al*. 2009, Blaskova 2009).

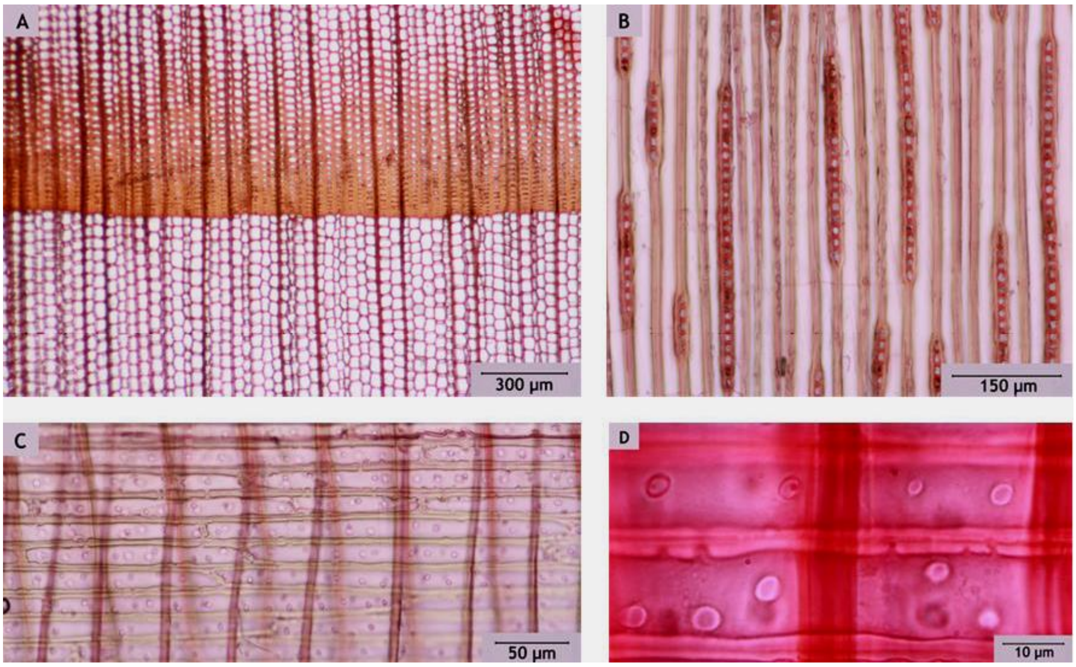

Figure 2: Microstructure of Abies sp. A: No resin canals in wood; B: average ray with height of 15–25 (sometimes up to 60) cells, C: Rays homocellular, D: taxodioid cross-field pits in early wood rays (Seckin 2012).

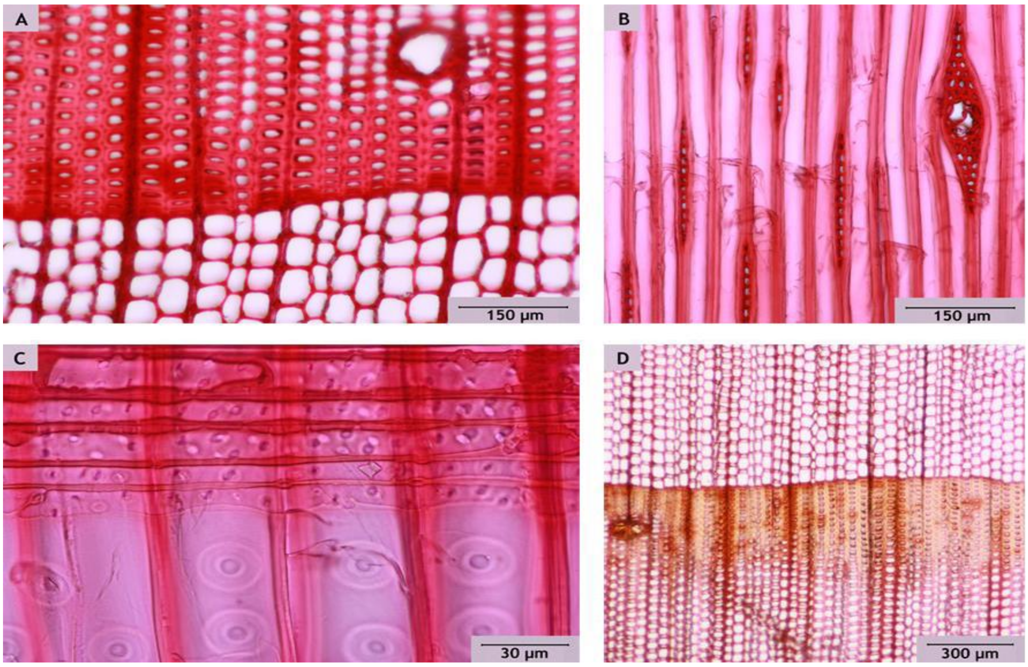

Figure 3: Microstructure of Picea sp. A: Cross section with axial resin canal in latewood, B: Tangential section showing uniseriate rays and radial resin canal in a fusiform ray, C: Radial section with bordered pits in axial tracheids and piceoid cross-field pits, D: Cross section with gradual transition of earlywood to latewood (Seckin 2012).

In spruce (Fig. 3), the growth rings are 1 to 5 mm wide and clearly outlined. The transition between earlywood and latewood is gradual. The rays are heterogeneous, one-row and fusiform. The one-row rays are predominant and composed in height of 1 to 30 cells or they have a height of 100 to 190 μm. The fusiform rays are rarely found and contain in the middle one horizontal resin canal covered by 4 to 8 (10) epithelial cells. The rays take up about 4,7 % of the wood. The tracheids of the earlywood are rectangular, with wall thickness of 1,9 to 4,9 μm. Their cell lumens are wide, with diameter of 16 to 45 μm. The tracheids of the latewood are rectangular, radially flattened, with wall thickness of 9,3 to 11,6 μm. Their cell lumens are narrow – 6,4 to 22 μm. The mean dimensions of the of the double cell wall of two adjacent cells and cell lumen cell of earlywood tracheids are 3,5 and 32 μm, and of the latewood ones 10,7 and 17,4 μm, respectively. The tracheids are 1300 to 4300 μm long (on the average 2800 μm) and take up about 95,3 % of the wood. The ray tracheids are with smooth walls or finely dentate. In the cross field, 2 to 6 small piceoid cross-field pits are found. The resin canals are 30–150 μm in diameter, single or in pairs and are covered with 4–8 thick-walled epithelial cells. They are seen with the naked eye in very smooth cross-section as light dots, and in longitudinal section – as very small yellowish stripes. The wood parenchyma is about 1,5 % (Blaskova 2009).

PHYSICAL AND MECHANICAL PROPERTIES

The pysical and mechanical properties of fir and spruce are shown in Table 1 and compared to those of Scots pine because all these forest species are utilized competitively for many uses. There are no substantial differences between fir and spruce but Scots pine wood is a little denser and has better mechanical properties than fir and spruce. It is worthy to mention that Scots pine is easily impregnated by preservatives but fir and spruce wood is resistant to impregnation.

PERMEABILITY OF SOFTWOODS

Permeability represents a material property that is of great importance in the wood industry. It determines the flow of liquid or gaseous phases through a solid medium and is defined as a measure of the ease with which fluids are transported through a porous solid under the influence of a pressure gradient (Siau 1984). As with other properties permeability of wood differs with the anatomical direction. The pore size and distribution, but even more so, the degree of pore interconnectivity, influences the permeability of wood. The permeable the wood the more easily it can be processed or treated. Permeability of wood to gases and liquids is not only important for preservative impregnation, but also for pulping and wood drying, influencing the design of industrial wood processing procedures. Furthermore, the application of substances to enhance selected wood properties such as hardness, UV stability, water and vapour repellency, dimensional stability, and fire resistance requires a movement of liquids into the wood to different depth levels.

In the xylem of living softwoods, fluid transport occurs primarily in the longitudinal direction through the axially oriented tracheid lumina that are interconnected with fields of bordered pits in their tapered end walls (Hacke *et al.* 2004). A subsidiary role is played by resin canals and longidudinal parenchyma, which are also longitudinally oriented. Axial flow in softwood involves a series of three components: tracheid lumina, pit apertures, and pit membrane pores. During preservative treatment or drying of wood, the same pathways are used for fluid transport in longitudinal and transverse directions. In these directions, flow paths are controlled by the bordered pits, whereas the horizontally aligned rays constitute the main pathways for flow in the radial direction during impregnation (Usta and Hale 2006). It has been shown that flow in the tangential and radial directions is much less than in the longitudinal direction (Usta and Hale 2004) while the spreading of fluids from xylem ray elements to longitudinal tracheids and vice versa is still under discussion (Olsson et al. 2001). The transverse permeability depends on the number and size of ray parenchyma and ray tracheids. These characteristics (cross-field pits, structure of ray tissue) vary greatly among softwood species. Yet it is not clear if transport in ray parenchyma is important or not. Transport in ray tracheids occurs through bordered pits as in the case of longitudinal tracheids. Other lateral pathways of minor importance include intercellular spaces and cracks. Cell walls are penetrated from the cell lumina and the movement into the cell walls of the vertical tracheids occurs through longitudinal and radial flow. Longitudinal cell wall permeability is more important than the radial one as most of the cell wall capillaries in the S2 layer run parallel to the longitudinal axis. To summarise, the pit structure is the most relevant factor controlling permeability at the laminar flow level. For diffusion, the combined path of vapour movement through the cell lumens in series with bound water movement in the cross walls are of primary importance for both transverse and longitudinal movement.

Table 1. Physical and mechanical properties of fir (*Abies borisii- regis*) and spruce (*Picea excelsa*) compared to pine (*Pinus sylvestris*) (Passialis/Tsoumis 1984 for fir, Tsoumis 1991 for spruce and pine, Voulgaridis 2006)

№	Property	Fir (*Abies borisii- regis*) HW SW	Spruce (*Picea excelsa*)	Scots Pine (*Pinus sylvestris*)
1	Density ρ12 ..15(g/cm³)	0,41–0,45, 0,41–0,45	0,41–0,47	0,53–0,59
2	Shrinkage (%): Axial Radial Tangential Volumetric	 3,5 3,7 8,4 8,6 11,7	0,3 3,6 7,8 12,0	0,4 4,0 7,7 12,4
3	Shrinkage anisotropy (Tangent. / Radial)	2,4 2,3	2,2	1,9
4	Permeability: Axial ($cm^2 s^{-1} atm^{-1}$) Radial Tangential	H:1,6	H: 0,42 0,04 0,001	H: 2,1, S: 7,4 0,17 0,012
5	Static bending strength (N/mm²) : MOR	67 (78*)	60 (70*)	98
	MOE	10,780 10,458 (8,500*)	9,100 (9,050*)	11,760
6.	Compression strength-Axial (N/mm²)	38,5 39,1(30,0*)	30 (29,3*)	54
7	Tension strength (N/mm²): -along fibers -across fibers	78 1,4	84 1,5	102 2,9
8	Hardness (N/mm²) : Lateral Axial	20,9 20,6 32	15 26	24 30
9	Shear along the fibres (N/mm²)	5,5	5,3	9,8
10	Toughness (J/ cm²)	5,9	4,9	6,9
11	Durability (resistance to fungi and insect attack)	Non-durable	Non-durable	Little durable
12	Resistance to impregnation (sapwood)	poorly to moderately permeable	poorly or not permeable	Permeable
13	Moisture content of wood of standing trees (%)	77–89 129–153	100–150	65–152

№	Property	Fir (*Abies borisii- regis*) HW SW	Spruce (*Picea excelsa*)	Scots Pine (*Pinus sylvestris*)
14	Absorption(Kg/m³), Penetration(mm) of creosote[1] : H : S Retention (% ovendry weight) Penetration (% of cross sectional area)	40, 2–12 mm 154 ,Complete LW 27,5 78,9 34,5 68,9	67, 0,5–10 mm	320, Complete 432, Complete

**New measurements (05.10.2013) from the material of the project. [1]H:Heartwood, S: Sapwood, LW: Latewood, Lateral penetration, Open tank treatment, Cross section of wood samples: 5 cm X 5 cm, length 1,1 m (Redding 1971).*

The bordered pits of the longitudinal tracheids substantially determine the permeability of a softwood species (Fig. 4). During wood drying, water evaporates from the wood surface and causes a capillary suction in the tracheids (Salin 2006). Air enters the capillary system and causes different pressure levels in adjacent tracheids. In consequence, the elastic pit membrane is deflected and the thickened part of the membrane (torus) attaches to the opening in the cell wall (porus); this closure is called „aspiration". Aspiration is considered irreversible because of the formation of hydrogen bonds between the torus/margo and the pit opening. Permeability is reduced not only during drying process, but also during heartwood formation in the living tree. Inorganic constituents and ligno complex substances incrust the cell walls and the torus and margo of bordered pits. Consequently, moisture content in the heartwood of the living tree is reduced, resulting in some level of pit aspiration. Moreover, wood extractives occlude the pit membranes.

When sapwood is transformed to heartwood, a number of changes occur which lead to decreased permeability of heartwood compared to sapwood. For softwoods, the main structural changed involved is the closure of pits, e.g. pit aspiration. In sapwood of softwoods, permeability decreases probably with distance from the bark. Below fibre saturation softwood permeability generally increases as moisture content decreases, probably because of shrinkage of the microfibrillar strands in the margo of the pit membranes (Siau 1995). After drying wood, the latewood regions commonly have a higher permeability than the earlywood (Siau 1995). Pits in latewood have thicker strands, a tighter margo texture, smaller diameters, a higher degree of lignifications, and denser configuration of the pit chamber, resulting in a higher stiffness. Furthermore, because of the thicker cell walls in latewood, the torus must move a greater distance to aspirate. As a consequence, the necessary forces for deflection and adhesion need to be greater, and fewer pits in the latewood are aspirated during drying. Although dry latewood contains fewer and smaller pits, it is more permeable than seasoned earlywood in which the pits tend to aspirate faster during drying. In the green conditions, this relation is reversed, in which the larger pits in earlywood are not aspirated and permit a higher bulk flow (Hansmann et al. 2002) (Table 2). According to Siau (1984), the transport of fluids can be separated into bulk flow and diffusion. Although bulk flow through interconnected cell lumina is vital for impregnation of wood, the diffusion processes are more important for kiln drying of wood. Bulk flow is mainly determined by permeability, which itself is related to the porosity of a system and the size and quantity of openings that interconnect the single pores. The description of viscous liquid transport through wood is commonly defined by Darcy's law, which states a direct dependency of the media to a pressure gradient. Wood anisotropy, interaction between fluid and substrate, pit aspiration, plugging of pits and pores with bubbles or particles, turbulent flow, occurrence of molecular slip effects, or fluid compressibility are important factors for a realistic determination of wood permeability.

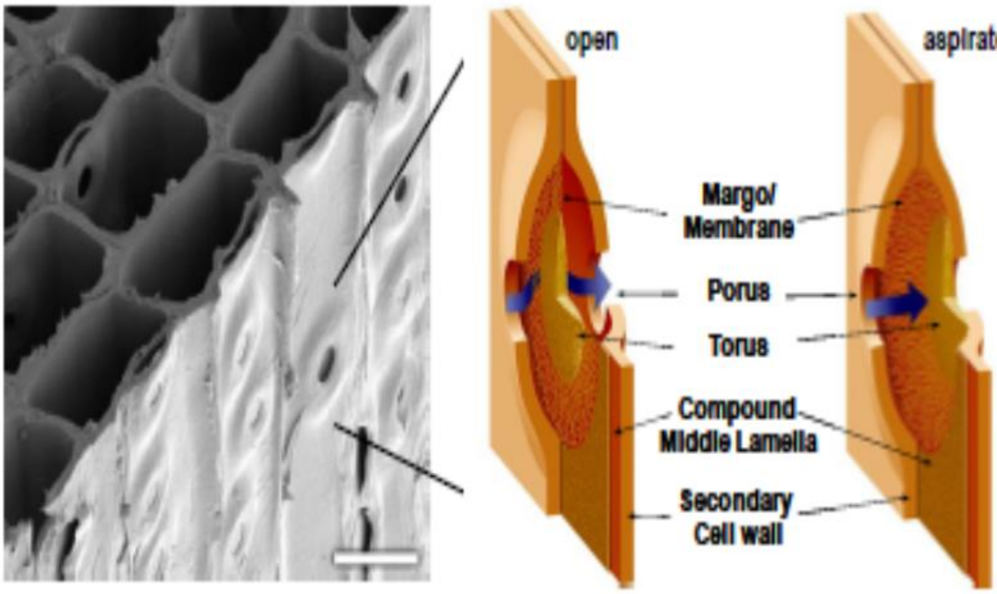

Figure 4: Bordered pits act as pathways voids between adjacent longitudinal tracheids. After aspiration, the torus restricts the flow of fluids. Scale bar 20 µm (Lehnringer *et al*. 2009).

Table 2: Longitudinal air permeability of fir, spruce and pine wood in air dry conditions (MC= 15%) (Smith and Lee 1958)

Property	Fir , Silver	Spruce, Sitca	Scots Pine
• Longitudinal air permeability (c.c./sec cm² atm/cm) • Variation (max/min)	16 max/min = 20	5,5 max/min = 1,3	230 max/min = 39

With a share of 30 % of the technical timber volume produced from Greek state forests, fir and spruce belong to the most important timber species in Greece. Spruce and fir are, also, important conifer species for Bulgarian and European wood industry. As solid wood, fir and spruce are used in a wide range of applications, such as construction material for interior (e.g. roofing, ceilings, furniture) and exterior (e.g. kiosks, wooden houses, fences, railing) situations, for façade claddings or for wood floorings in the form of boards (Wagenführ 2007). But fir and spruce wood have a low natural durability against wood decay fungi, and is assigned to durability class 4 according to EN 350-2: 1994. This requires a chemical wood preservation when the wood is used in structural constructions of utility class 4 (EN 460: 1994, EN 335-2: 2006). In addition, there is a growing interest for a treatment with waterborne surface modification substances that specifically improve selected wood properties of fir and spruce such as UV-resistance, hydrophobicity, hardness and fire resistance. Generally, vacuum-pressure impregnation is used on industrial scale to treat the wood with wood preservatives, e.g. with waterborne metal salts (Richardson 2001). Compared to other wood species, fir and spruce are difficult to be impregnated with wood preservatives and other modifications substances. The refractory behaviour is due to the aspiration of the pit membranes in the tracheid cell walls. Increase of permeability by applying preparatory techniques on wood surfaces of refractory wood species facilitates the impregnation of wood with preservatives in greater depth and increases the service life of exterior and semi-exterior wood structures.

CONCLUSIONS

The conclusions of this work may be summarised as follows:

Fir and spruce are very important conifer species in Greece, Bulgaria and in the whole of Europe producing significant quantities of wood of technical use. They produce wood of similar structure and properties that is used for the same final products after processing. Both species are resistant to impregnation due mainly to pit aspirations that occurred to a great extent during drying. Two important differences between the two species is that spruce wood only has resin canals and it is more resistant to impregnation than fir. By increasing the permeability of these species it is possible to widen their uses in exterior and semi-exterior conditions. The method of surface drilling of wood by laser beams seems to be promising for increasing permeability of these species.

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