

DEPENDENCE ON SHRINKAGE AND SWELLING IN CHEMICAL COMPOSITION AND ANATOMICAL STRUCTURE – AN OVERVIEW

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ABSTRACT

When the water content changes, the wood undergoes serious changes in its dimensions and volume. The processes of shrinkage and swelling are mutually reciprocal and associated with large energy changes in the different directions of the stem. These changes are due to the fact that wood is formed from polymers that contain hydroxyl groups. Dimensional changes during drying of raw wood begin when the water content falls below the fibre saturation point. Shrinkage is different for different wood species. Shrinkage is also different in different directions of the wood.

The article examines research conducted on different wood species and at different levels of the chemical composition and anatomical structure of the wood, with the aim of explaining the processes of drying and swelling.

Key words: wood, anatomical structure, chemical composition, cellulose, hemicelluloses, lignin, shrinkage, swelling, early wood, late wood.

INTRODUCTION

As a physical body, wood is composed of cell walls, intercellular spaces, and cell cavities. For different types of cells, these indicators are different. They differ even within the annual ring (Enchev, E.At. 1984; Bluskova, G.St. 2009).

Wood is a natural polymer made of cellulose, hemicellulose and lignin. They have hydroxyl groups that attract water (Olek W. et al., 2015; Cresswell R., et al., 2021). Among the main components of wood, hemicelluloses have the highest absorption capacity, followed by cellulose and lignin (Kollmann, F.F.P., Cote A.W.Jr., 1968). The amount and structure of these chemical compounds is not the same in different parts of the cell wall and intercellular space.

Wood is a complex and hierarchically organized material. It is characterized by an architecture of hard crystalline cellulose fibrils parallel to each other and surrounded by a soft matrix composed of hemicelluloses

and lignin. The bound water is also placed in this matrix. When water is absorbed, the matrix swells and provides a source of internal stress (Barbetta A., 2017). Cellulose fibers are able to attract and bind water molecules due to their high concentration of hydrophilic functional groups, mainly hydroxyl (OH) (Thybring E.E., et al., 2020).

Considered in an other way, wood can be considered a cellular anisotropic biocomposite whose cell walls consist of heteropolymers with a unique supramolecular structure. Thus, wood properties can be interpreted at different levels of organization (scale) (Bonarski J.T., et al. 2015).

The size at which wood shrinkage depends on factors such as: wood type, density, extractive content, tracheid length, lignin content and percentage of rays, annual ring sizes, percentage of early and late wood, differences between heartwood and sapwood, the presence of juvenile wood, the rate of tree

growth, the position in the stem (Barcenas-Pazos G., et al., 2000).

In raw cut wood, the cells have two types of water: free water ($MC > 30\%$), which is located in the cell cavities, bound water ($MC = 0-30\%$), which is located in the cell walls (Enchev, E. At. 1984; Bluskova, G. St. 2009). In addition, dry wood is hygroscopic and has the ability to absorb moisture from the environment, and wet wood to release moisture. During these processes, the dimensions and mass of the wood details change, and hence their properties (Penttila P.A., et al., 2021).

Wood shrinks differently in different directions of the tree. The change in dimensions is the smallest in the longitudinal direction – on average 0.4% (0.1-0.6%), much larger in the radial direction – 4.3% (2.3-6.8%) and even greater in the tangential direction – 8.2% (6.0-11.8%). As a result, volume shrinkage varies around 12.9% (8.5-18.8%) (after Tsoumis, 1991).

In addition to the determination of the absolute values of shrinkage, for practical purposes a coefficient of shrinkage is also calculated. It shows by what percentage the size of the wood will decrease in the corresponding direction if the water content decreases by 1%. An anisotropy coefficient is also determined, which is a ratio of shrinkage values in the tangential and radial direction (Bosshard H.H., 1982, Siau J.F., 1984, Ugolev, B.N., 2007).

These physical parameters have been studied in detail and used to compare the wood of different tree species (Wagenführ, R. Chr. Scheiber, 1996).

CHEMICAL COMPOSITION

At the polymer level, cell walls consist of cellulose, hemicelluloses and lignin, which are accompanied by minor amounts of extractives and minerals. The cell wall is an

interconnected network or, in other words, a 3D biopolymer composite (Rowell et al. 2005). These polymers have different hygroscopic properties due to their chemical composition as well as ultrastructural organization (Bonarski J.T., et al. 2015).

A clear linear relationship between lignin content and wood shrinkage is established. For example, as the lignin content increases from 14 to 26%, tangential shrinkage decreases from 12 to 4% (Barcenas-Pazos G. et al., 2000).

According to many authors, hemicelluloses are the most strongly influencing swelling. They contain the largest number of active sorption sites in their macromolecules. Thus, they make the greatest contribution to wood dimensions in the hygroscopic range (Bosshard H.H., 1982, Siau J.F., 1984, Ugolev, B.N., 2007). Furthermore, it is suggested that the ultrastructural organization of hemicelluloses reveals a different character in radial and tangential cell walls (Olek W. et al., 2015).

Water has been shown to play an important role in the hemicellulose-cellulose bond. After significant molecular shrinkage caused by dehydration, the original molecular structure is not fully restored after rehydration. Changes include xylan, which becomes more tightly and irreversibly bound to cellulose, and some mannan, which becomes more mobile and changes structure (Cresswell R., et al., 2021).

In wood, xylan is bound to lignin, while glucomannan is more closely bound to cellulose. These results suggest that the mechanical interactions between the cellulose microfibril and the matrix substance induce longitudinal pressure and transverse tension in it during drying (Abe K., H. Yamamoto, 2006).

Since the swelling and shrinkage processes are related to the amount of bound water in the wood, it is reasonable to expect that

the extractives will also affect the amount of shrinkage. Their removal with hot water, alcohol and organic solvents cause excessive shrinkage (Choong El.T., S.S. Achmadi, 1989).

ULTRASTRUCTURE OF THE MAIN CHEMICAL COMPOUNDS THAT MAKE UP WOOD

It is difficult to give an exact boundary between the chemical composition of wood and the ultrastructure of the compounds that make it up. The wood cell consists of a cell wall and a cell cavity, which have a direct influence on water-related processes in wood (Bosshard H.H., 1982, Siau J.F., 1984, Ugolev, B.N., 2007).

The wood cell wall consists of a primary and a secondary wall, the latter of which consists of three layers (S_1 , S_2 and S_3), with S_2 being predominantly the thickest with about 80% of the entire cell wall volume. This layer consists of microfibrils assembled from a cellulose matrix and amorphous regions enveloped by hemicelluloses and lignin. Here cellulose and its crystalline regions are significantly more compared to the primary cell wall (Bosshard H.H., 1982, Siau J.F., 1984, Ugolev, B.N., 2007).

The physical properties of the cell wall are governed by the S_2 layer, in which the microfibril angles are small (they are almost parallel to the cell axis), while the microfibril angles of the S_1 and S_3 layers are irregular and they are almost perpendicular to the longitudinal direction of the cell. The swelling of the S_2 layer is differently limited in the peripheral direction from the S_1 and S_3 layers with their different cell wall architecture (Nakano T., 2018).

The crystalline cellulose of wood cell walls has a limited capacity to absorb water molecules, as well as to change its length or

cross-section. On the contrary, the amorphous matrix formed by lignin and hemicelluloses readily binds or releases water and exhibits a distinct tendency to swell or shrink out. Matrix shrinkage is particularly restricted in a direction parallel to the microfibril axis (Bonarski J.T., et al. 2015).

Since the longitudinal mechanical behavior of wood with a small angle of microfibrils is strongly influenced by the stiff cellulose microfibril, the longitudinal shrinkage increases suddenly at about 10% moisture content, resulting in the drying process showing non-linearity. Some researchers have theoretically discussed nonlinearity in the longitudinal shrinkage process and assumed in their theories that cellulose microfibrils are not affected by moisture absorption. (Abe K., H. Yamamoto, 2006).

Despite the anisotropy, wood shrinkage also depends on the microstructural and molecular characteristics of the cell wall and mainly on the microfibrils angle. Changing the matrix swelling potential has a large effect on tangential shrinkage at low microfibril angle, while the same is true for longitudinal shrinkage at high microfibril angle. The conclusion is that the correlation between shrinkage and microfibril angle is strong only in a narrow range (30° – 40°) (Leonardo M., et al., 2009).

Much of the water resides in the spaces between the cellulose microfibrils, where it controls the swelling of the microfibril bundles. It remains to be shown whether water between loosely aggregated cellulose microfibrils is the only type of bound water present in natural wood cell walls (Penttila P.A., et al., 2021).

In their research, different authors have observed unique dynamics of the swelling process. Wood cells swell both outward and inward toward the cell cavity, with no fundamental difference between coniferous, broad-

leaved, and tropical wood species (Nakano T., 2008). Similar behavior is also observed for different wetting dynamics. The swelling of the wood during its rapid and slow wetting is investigated. In one process, the wood cells swell inward, and in the other, they do not (Murata K., M. Masuda, 2006).

SHRINKAGE AND SWELLING OF ANATOMICAL ELEMENTS

The main groups of tree species are separated from each other by their anatomical structure. In some of them (coniferous, ring-porous) there is a clear zoning of the annual ring of early and late wood. The properties and behavior of these zones under different loads is very different (Bardarov, N. 2014).

The behavior of cells at the microscopic level is strongly influenced by their arrangement in the annual ring and in particular by the alternation of early and late wood (Murata K., M. Masuda 2006). Earlywood, which consists of thin-walled cells with large cavities, shrinks differently than latewood, which has thick-walled cells with small cavities (Pang Sh., Al. Herritsch, 2005).

When examining the swelling of individual ring zones, latewood has a slightly higher equilibrium moisture than earlywood at relative humidity below 80%. The higher equilibrium moisture for the latewood is probably due to the higher hemicellulose content compared to the earlywood. However, at relative humidity above 80%, earlywood has equilibrium moisture values 0.2-0.5% higher than latewood (Pang Sh., Al. Herritsch, 2005).

Besides being quantitative, the differences in swelling between early and late wood are also qualitative. It is well known that the transverse drying anisotropy of earlywood is more pronounced than that of latewood (Bonarski J.T., et al. 2015). Thus, it can be concluded that shrinkage at the cellular

level is the result of two related effects: properties of the cell wall (especially its local anisotropy) and cell shape as a result of its formation in the cambium (Almeida G. Et al., 2014).

Although, from the point of view of wood science, sorption and desorption do not fundamentally differ for different groups of structure, there is a difference in their analytical description. If we turn to the theory of diffusion, trying to explain these phenomena, the differential equations describing the diffusion in conifers and broad-leaved species will be different, because of the different shape of the cross-section of the cells that make them up.

When earlywood and latewood are firmly attached to each other, the wood is not free to shrink tangentially and longitudinally as it would if its parts were separated. Therefore, as it shrinks, tension is generated between the two types of layers. Therefore, the measured shrinkage of wood samples containing the entire annual ring differs from that of separated strips of early and late wood (Pang Sh., Al. Herritsch, 2005; Krzemien L., et al., 2015).

Another significant factor responsible for transverse drying anisotropy is the wood core rays. These are transverse-radially located anatomical elements in the wood, for which the radial direction is longitudinal. That is why, other things being equal, they will „oppose” swelling in the radial direction (Bardarov, N. 2014). Moreover, they occupy a significant share in the wood – for example, their volume is up to 17%-22% of the wood tissue of oak and beech (Skaar, 1988). However, Boutelje (1962) denied the importance of rays in this regard in conifers (Bonarski J.T., et al. 2015).

The considerable amount of parenchyma also affects the processes in the wood.

Perhaps not so much the qualitative difference in the structure of the parenchyma (apotracheal and paratracheal) as its quantitative representation in the wood will affect the drying and swelling processes.

Although for us they are deviations, even defects of the wood, the different structures formed in the wood will also affect the drying and swelling processes. As stated above, reaction wood takes center stage in this example. Also important are the inclination of the fibers, the slope grain, burlwood and all that would affect the anisotropy of the wood.

CONCLUSIONS

The anatomical structure is the "book" of wood. In order to draw correct and complete conclusions about its properties, it must be read very carefully.

It is very difficult to distinguish between chemical composition and ultrastructure of the compounds that make up wood. It is also difficult to determine the degree of influence of individual structures on shrinkage and swelling of wood.

The influence of anatomical elements such as wood rays or early and late wood is undoubtedly very strong, but it cannot be isolated and evaluated independently.

The anisotropy of shrinkage and swelling can be explained both by the ultrastructure of the cell wall and by the involvement of different anatomical elements.

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