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Studies on the sound absorption properties of wood-based pulp

fibre foams

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ABSTRACT

Acoustic behaviour of wood fibres depends on material properties on different hierarchical structural levels, including molecular, microscopic, and macroscopic. In this paper, we present comprehensive studies on the effect of the hierarchical structure of wood pulp fibres on acoustical properties. In the molecular level, structural polymers of wood and their arrangement in the cell wall are crucial in determining the material properties of the fibres. In the microscopic level, wood fibres are characterised by an irregular morphology and present average fibre lengths and widths ranging from 0.4 - 6 mm and $10 - 50 \mu$ m, respectively. In the macroscopic level, the porous structure of a 3D-fibre network formed by means of foam-forming technique depends on the raw fibres as well as on the foam forming procedure used. The studied pulp fibre foams achieve comparable sound absorption properties to those of conventional synthetic porous materials. Increasing use of wood based materials in buildings contribute to reduce CO₂ from the atmosphere by binding CO₂ into the building structure for decades.

Keywords: Sound, Insulation, Transmission

1. INTRODUCTION

The current market of porous sound absorbing materials is dominated by mineral wool and plastic based products. Emissions from the production processes of these materials have been reduced during the last years by means of a more sustainable use of energy as well as the use of recycled raw materials for their production. However, their production processes are still highly energy intensive which aggravate environmental degradation of the planet. Thus, use of acoustic materials with low-carbon emissions is needed to reverse the current role of buildings and mitigate climate change. In this study, we propose wood-based pulp fibre foams to be used as sound absorbing building materials. The production processes of wood based pulp fibres are highly efficient and release low emissions of CO_2 (1). Additionally, wood based pulp fibres are carbon negative raw materials as wood fibres sequester more CO_2 from the atmosphere than their production processes release.

Sound absorption properties of wood fibres depend on material properties on different hierarchical structural levels, including molecular, microscopic, and macroscopic. In the molecular level, structural polymers of wood fibres and their arrangement in the cell wall are crucial in determining the material properties of the fibres. Furthermore, mechanical properties of wood fibres, flexibility among others, change with varying moisture content. This is mainly attributed to rearrangement of structural polymers as moisture gets into wood fibres, as well as variation in the dimensions of the fibres due to swelling.

As reported in (2), at low frequencies, the ability to dissipate sound energy of fibrous materials is sensitive to fibre flexibility. In contrast, at high frequencies, the movement of fibres is null, and therefore sound absorption due to fibre flexibility can be neglected. It should also be considered that in fibrous porous materials, fibre contact and bonding influences the flexibility of fibres and freedom of movement, and thus, they also influence the ability of the material to dissipate sound energy. Moreover, dislocations, microcompressions, curling, crimps, and kinks are induced during the pulping process. All these artefacts tend to increase the flexibility of pulp fibres (3). In the microscopic level, wood fibres are characterised







Figure 1 The hierarchichal structure of wood at multiple scales. a) The cell wall consists of the lumen (the void space in the middle of the cell), the primary wall and the secondary wall, which, in turns, is divided in three sublayers: S1, S2 and S3. Cellulose, hemicellulose and lignin are the three main components that form the cell wall. b) The cross- and longitudinal sections of cells show that microfibrills (MFCs) are embedded in a matrix of hemicellulose and lignin. The figure also shows that microfibrils contain crystalline (highly ordered) and amorphous (disordered) regions. Adapted from (6).

by their irregular morphology, and their length and width vary considerably with species. Average length and width of softwood fibres range between 2–6 mm and 20–50 μ m, respectively. Whereas length and width of hardwoods range between 0.4–1.4 mm and 10–40 μ m (10–300 μ m for vessel elements) (4).

Three biopolymers are the main components of wood fibres: cellulose, hemicellulose and lignin. The proportion of these biopolymers in wood fibres depends on tree species. In general, the cellulose content of hardwoods is 40% - 50%, hemicellulose content 23% - 40%, lignin is 19% - 23%, and extractives around 5% - 10% extractives. Whereas, for softwoods, cellulose content is 40%, hemicellulose 23% - 30%, lignin 27% - 33%, and extractive 5% - 10% (4). The main elements of wood fibres are cellulose microfibrils (CMF) which are formed by the aggregation of cellulose chains that are bonded by hydrogen bonds and Van der Wall forces. The width of CMF is 3-4 nm whereas the length is in the micro-scale, although it strongly depends on the tree species. The walls of wood fibres consist of CMFs embedded in a matrix of hemicelluloses and lignin, where lignin acts as the cementing component (4). Figure 1 presents an illustration of the hierarchical structure of wood at multiple scales.

To be able to utilise wood fibres they need to be isolated from wood. The methods to separate wood fibres are classified into mechanical or chemical pulping. Among all the existing methods, the kraft process (chemical pulping) is the most popular. The kraft process aims to completely eliminate lignin from the cell wall (4).

In this study, foam forming technique (5) was used to produce porous sound absorbers from softwood and hardwood pulp fibres with varying chemical composition and ultrastructural properties. The sound absorption coefficients of the produced materials were measured using an impedance tube. We studied the influence of pulp fibre dimensions and chemical composition on the acoustic behaviour of the produced foams. In addition, this study also presents results on the influence of moisture on the mechanical properties of pulp fibres, and in turn, on the acoustical properties of the foams. The results provide valuable insight for the optimization of bio-based sound absorbing materials.

2. MATERIAL AND METHODS

2.1 Materials

Industrial hardwood (HW) and softwood (SW) kraft and dissolving pulps were provided by Finnish mills. Kraft pulp samples were obtained from three different stages of the pulping and bleaching process: before and after oxygen delignification, and after bleaching. The pulps were either used as never-dried or as machine-dried.

2.2 Preparation of sound absorbing foam samples

Sound absorbing foams samples were prepared using foam-forming technique following the method described in (5). Pulp, water and sodium dodecyl sulphate (SDS) were axially agitated at a rotational speed ca. 3000 rpm in a cylindrical container of dimensions 67 cm length and 27 cm diameter. The mixer was built according to (7). A variation of fibre consistencies were used (2.5 % and 3.5 %) to achieve foams with varying densities. The dosage of SDS was 0.5 g/L. The dry pulps were soaked in 10 L of tap-water for 1 day at room temperature. Before the addition of SDS, the suspension of pulp in water was mixed for 5 minutes to disperse fibres. Then SDS was added and the foaming continued until the initial volume of the mixture doubled. The fibre foam was poured in a square mould of dimensions 40 cm x 40 cm x 50 cm with two stainless steel nets located at the bottom, and then left to gravity drain for over 15 minutes. The top net had an opening mesh of 0.16 mm, while the net below had a mesh opening of 5 mm. The latter served as a support for the top net to avoid curvature of the bottom surface of the samples being produced. The foams was dried with heated air flow at 40 - 50 C° for three days.

Circular samples were cut from the produced foamed materials with the help of a bench drill. The produced samples had variable inner density, with a higher density at the bottom. In order to attain more homogeneous samples in terms of density, layers of fibres were removed from both sides of the samples with the help of a sharp blade.

2.3 Determination of carbohydrates and lignin

Pulp carbohydrates and lignin were determined according to standard NREL/TP-510-42618. The content of cellulose and hemicelluloses were determined applying the Janson formula (8). Soluble lignin was measured in a UV-Visible spectrophotometer (UV-2550, Shimadzu).

2.4 Fibre morphological properties

Morphological properties of the different pulp fibres were characterized using a Kajaani FiberLab optical fibre analyser (Metso automation, Finland). The following properties were measured: fibre length, width, curl (degree of non-straightness of fibre), kink (degree of sharp bends along the fibre), fines (small particles detached from pulp fibres), fibres per unit weight, and cell wall thickness (CWT).

2.5 Handsheets and fibre mechanical properties

Handsheets were prepared according to ISO 5269-1. Tensile strength, stiffness, and stretch indices as well as modulus of elasticity were measured in the longitudinal direction according to ISO 1924-2 with the help of a L&W tensile tester with fracture toughness SE 064. The results are given by the average results of ten test pieces obtained from four different handsheets. Grammage of handsheets was determined and their thickness was measured according to ISO 534 using a thickness tester L&W micrometer SE 250d. Handsheets were conditioned for one day at 50% relative humidity and 23 C°. The conditioning was kept throughout the test.

The elastic modulus of well-bonded handsheets of long straight fibres is governed by the properties of the fibres as described by Eq. (1) (9).

$$E_p = \frac{1}{3}\phi E_f \tag{1}$$

Where E_p is the sheet elastic modulus, E_f is fibre modulus, and ϕ describes the efficiency of the fibre to transfer stress in a sheet ($\phi = 1$ for sheets of long, well-bonded fibres). For lower bonding degrees or for shorter fibres, the sheet modulus is smaller than that given by Eq. (1) because of the inefficiency of stress transfer along the fibre length. Nevertheless, the effect of fibre length on sheet modulus is only relevant at very low densities (10). The density of the ordinary sheets prepared in this study is sufficient to make a very high number of inter-fiber bonds, thus only a small fraction of the total fibre length does not transfer stress.

2.6 Dynamic vapor sorption (DVS)

Water sorption was measured with an automated sorption apparatus (DVS intrinsic, Surface Measurement Systems, UK). Pulp samples were placed on the sample chamber at a constant temperature of 25 C°. A constant nigrogen flow (grade 5.0, B 3 ppm H2O) of 200 sccm was used to control the RH within the sample chamber. Sorption isotherms were measured starting from the dry state with 10 distinct relative humidity steps (0, 5, 15, 25, 35, 45, 55, 65, 75, 85 and 95%). Each relative humidity step was maintained until the sample equilibrium moisture content (EMC) was reached with a mass change per minute (dm/dt) less than 0.0005 over a period of 10 min. The slope in a 10 min window was used to calculate the change in mass with respect to time (dm/dt).

2.7 Measurements of sound absorption coefficients

The normal incidence sound absorption coefficients of the samples were determined using the impedance tube transfer-function method defined in ISO 10534-2. The impedance tube used was a Brüel & Kjaer type 4206. To study the effect of moisture on the sound absorption properties of wood-based pulp fibre foams, foams samples of varying density were prepared and they were exposed to varying relative humidities (0%, 10%, 32%, 75% and 99%) for two days. This period of time was sufficient for the samples to reach equilibrium moisture content. The different relative humidity conditions were created by preparing salt solutions and pouring them into sealed containers. The prepared aqueous salt solutions and expected relative humidities were: NaOH 50 wt%, MgCl₂ 35.2 wt%, and NaCl 26.5 wt% to create 10 %, 32 % and 75 % RH. Temperature was 20° - 25°. 99 % RH conditions were created by adding water to the sealed box (11). Samples were first dried overnight at 80° and their sound absorption properties were measured after drying. Immediately after taking sound absorption measurements the samples were exposed to 10% relative humidity for two days, and then they were measured in impedance tube. The same process was repeated for all the relative humidities. It is noted that samples were outside the desired humidity conditions only for 1-2 minutes maximum, the time it took to conduct the sound absorption measurements.

The dimensions of the foam samples used to study the influence of moisture on the sound absorption properties of wood-based pulp fibre foams were 100 mm diameter and 60 mm thickness. This size of samples allowed measurements of sound absorption coefficients in the frequency range 50 Hz - 1600 Hz. The dimensions of the samples used to study the influence of pulp fibre dimension and chemical composition on sound absorption were 29 mm diameter and 40 mm thickness. This size of samples allowed measurements of sound absorption coefficients in the frequency range 500 Hz - 6000 Hz.

3. Results and Discussions

3.1 Chemical composition and morphological properties of fibres

Pulp	Fib/mg (pcs/mg)	Length (mm)	Width (µm)	$\begin{array}{c} \textbf{Kink} \\ (m^{-1}) \end{array}$	Curl (%)	Fines (%)	CWT (µm)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
HWunblch	12600	0.96	20.03	602	7.8	1.5	6.27	67.0	29.3	3.7
HW _{ox}	14400	0.86	20.28	1258	12.9	1.2	5.97	68.8	28.9	2.3
HW _{blch}	12600	0.80	20.71	1702	17.1	2.1	6.02	70.2	28.8	1.0
HW _{diss}	19700	0.73	16.32	2409	17.7	1.6	4.05	93.9	5.4	0.7
SWunblch	5300	2.11	28.31	432	9.3	2.4	8.51	73.7	18.7	7.6
SWox	5800	1.88	27.49	881	14.5	3.1	7.98	76.4	19.9	3.8
SW _{blch}	5400	1.97	25.36	984	15.4	3.3	7.03	82.7	16.5	0.9
SW _{diss}	5900	1.73	23.83	1440	18.8	2.3	6.38	92.5	6.7	0.8

Table 1 Chemical composition and morphological properties of pulp fibres.

The chemical composition and morphology of the wood-based pulp fibres are presented in Table 1. As expected, the proportion of cellulose and hemicelluloses differs between hardwoods and softwoods fibres, having hardwoods greater content in hemicelluloses. Lignin content is very low in both types of pulp fibres and it further decreases in each of the stages of the bleaching process. This is because the kraft process aims maximising the removal of lignin while minimising removal of cellulose and hemicelluloses. As can be observed from Table 1, the main difference between dissolving and bleached

kraft pulps is the content in cellulose and hemicelluloses. The main objective of dissolving pulp is the removal of hemicelluloses, and thus, dissolving pulps are pulps of high cellulose content (>90%). The differences in chemical composition between the two types of fibres make them suitable for different applications. For example, dissolving pulp are preferred in the textile industry whereas bleached kraft pulp is more used for paper applications.

It can be seen (Table 1) that softwoods are considerably longer and wider fibres than hardwoods. Within the group of hardwood pulp fibres, cell wall thickness, fibre length and width generally decrease with removal of lignin and hemicelluloses. The same trend is seen for softwood fibres. Differences within the hardwood pulps and the softwood pulps are rather small, being fibre width between bleached and dissolving fibres the most significant difference.



3.2 Dynamic vapor sorption (DVS)

Figure 2 (2a) Dynamic vapor sorption measurements of kraft bleached and dissolving hardwood and softwood pulps. Glasswood and rockwool were also measured as reference sound absorbing materials; (2b) Moisture content measured from samples used in sound absorption measurements.

Figure 2 presents the sorption isotherms measured for bleached and dissolving hardwoods/softwood fibres. The vapor sorption isotherms describe the relationship between relative humidity of the environment and total moisture content in wood fibres at constant temperature. Sorption isotherms of glasswool and rockwool fibres were also measured as reference materials. It can be seen from Figure 2 that the interaction of water with synthetic fibres, glasswool and rockwool, is much lower than that of pulp fibres. Rockwool and glasswool fibres begin to take some moisture at relative humidities above 60% and 85%, respectively. On the other hand, moisture sorption by pulp fibres immediately begins as relative humidity increases over 0%. Moisture uptake by pulp fibres is mainly due to the number of accessible hydroxyl groups, however, also additional mechanisms may exercise control over water uptake (12). The greater the degree of crystallinity of the fibres, the lower the number of accessible hydroxyl groups, which leads to lower moisture uptake. The degree of crystallinity of cellulose is significantly higher than that of hemicelluloses, which implies that hemicelluloses can adsorb more water than cellulose. Thus, dissolving pulp fibres take less moisture because they are more crystalline than bleached fibres as dissolving pulp fibres contain much more celluloses and less hemicelluloses than bleached fibres.

3.3 Handsheet and fibre mechanical properties

Table 2 presents the measured mechanical properties of the handsheets and calculated fibre Young modulus, both in the longitudinal direction. As can be seen from the table, hemicellulose content is a critical factor determining the mechanical properties of the handsheets. The tensile index and stiffness of hardwoods and softwoods decrease with decrease in hemicellulose content of the fibres. The Young modulus of the different pulp fibres has been calculated according to Eq. (1) and they are shown in Table 2. It is concluded that bleached hardwood pulp fibres are the stiffest ones whereas dissolving pulp fibres show the lowest stiffness. These results are in accordance with those reported in (4).

Pulps		Fibre properties				
	Density [Kg/m ³]	Elongation (%)	Young mod. [Gpa]	Stiffness Ind [kNm/g]	Tensile Ind [Nm/g]	Fibre Young mod. [Gpa]
HW _{blch, M}	491	1.69	1.56	3.17	17.13	4.68
HW _{diss}	402	1.47	0.75	1.86	9.58	2.25
SW _{blch, M}	429	2.73	1.13	2.63	16.76	3.39
SW _{diss}	386	2.45	0.92	2.37	15.21	2.76

Table 2 Handsheet and calculated fibre properties.

3.4 Sound absorption

3.4.1 Influence of fibre dimensions and chemical composition on sound absorption

The influence of pulp fibre dimensions, mainly fibre length and width, and chemical composition on sound absorption has been reported in a previous study (13). The study concluded that dissolving hard-wood pulp fibres provide the greatest absorption. The authors resported that further processed, shorter and thinner fibres move the first peak of the sound absorption curves towards lower frequencies. The effect was attributed to the increase in the number of fibres per unit volume as the dimensions of the fibre decreases. Increasing the number of fibres per unit volume results in more tortuous paths and surfaces for sound energy to dissipate within the materials. These results were in agreement with the results reported in earlier studies (14).

3.4.2 Influence of moisture on sound absorption properties of wood-based pulp fibre foams

The increase in moisture content was controlled for the samples exposed at varying relative humidities and the results are shown in Figure 2a. As can be observed, the results from Figure 2b resemble much those shown in Figure 2a which confirms that the exposition of materials to varying humidities was performed correctly and that the samples reached moisture equilibrium before absorption measurements. It is noted that DVS measurements were taken from fibres that did not go through foam-forming process, whereas the sound absorbing foam samples went through foam-forming and drying process. Foam-forming may cause rearrangement of hemicelluloses in the cell wall (13), whereas drying may cause further hornification of fibres (15), i.e., further closure of pores withing the fibres. This may explain some of the differences found between 2a and 2b.

Figure 3 shows the sound absorption coeff. of bleached and dissolving hardwood and softwood pulp fibres measured at the two extreme relative humidity conditions, 0% and 100%. The results show how the sound absorption of pulp fibres improve at low-mid frequencies with increasing moisture content. Moreover, the increase in absorption properties tend to be slightly greater for denser samples. As expected, glasswool and rockwool fibres did not show changes in their sound absorption at varying relative humidity conditions. This is mainly due to the inherent hygrophobicity of these materials.

In an attempt to explain the influence of moisture on the sound absorption properties of wood fibres we suggest two theories, changes in the mechanical properties of pulp fibres and structural changes of fibres with increasing moisture content. Variations in relative humidity conditions result in changes in the water content of pulps fibres which, in turn, leads to changes in the mechanical properties. A well-known effect of moisture on the mechanical properties of pulp fibres is the decrease of the fibre modulus with increasing moisture content, i.e., fibres become more flexible as moisture content increases (16). The main reason why pulp fibres become more flexible with increasing moisture content is that water molecules get into the fibre matrix and weaken the interfibrillar hydroxyl bondings (17). The increase in fibre flexibility is suggested to be one of the parameters that improve the absorption properties of pulp fibres at low-mid frequencies. This is in agreement with the results reported in (2).

Moisture uptake by wood fibres also causes structural changes in the microfibril bundles that forms the cell wall. Two main structural changes have been suggested to occur at different moisture contents (17, 18). At low moisture content, 0% - 10%, microfibril bundles release stresses and adopt higher degrees of crystallinity. At around 10% - 15% moisture content, water begins to dominate the space between microfibrils and the matrix softens. As the matrix softens it can deform more easily, which



Figure 3 Sound absorption coeff. in third-octave bands measured from bleached and dissolving hardwood and softwood pulp fibres-based foams. Glass- and rockwool were also measured as reference materials. The results are averages of the sound absorption coeff. measured from the two sides of the samples. Dashed and continuous lines represent denser and less dense foams, respectively. Black and magenta colors are used to represents dry foams and foams exposed to 100 % RH, respectively. The thickness of all the samples was 6 cm except for glasswool whose thickness was 4 cm.

leads to expands water channels between microfibrils and swelling of fibril bundles (18). This swelling of fibrils results in increasing width dimensions of pulp fibres which, in turn, modify the porous structure of pulp fibre based samples. The increase in fibre width is suggested to be a second parameter that may influence the sound absorption properties of pulp fibres based foams. The increase in width experienced by pulp fibres with varying moisture content will be studied in future research. Nevertheless, some authors have already reported some results on this question (17, 19, 20). Pulp fibres expanded in width from 2 - 4.5% (depending on the chemical composition of the pulp) after fibre exposure to 75% relative humidity (19). Other authors reported increase in lateral dimensions of pulp fibres up to approx. 20% over the range of relative humidities from 0% to 100% (20).

Pulp fibres, and wood in general, is in constant interaction with the moisture in the surrounding air, i.e., at higher relative humidities wood uptakes water and the uptaked moisture is released when the surrounding air is dryer. This inherent property of wood is convenient to control changes in relative humidity indoors. Additionally, wood fibres do not create problems for indoor air quality, and offer excellent acoustic properties while reducing CO_2 from the atmosphere by binding CO_2 into the building structure during the material operating life.

4. CONCLUSIONS

In this paper, we presented studies on the different ultrastructural properties of pulp fibres that affect the sound absorption properties of wood-based pulp fibre foams. It was demonstrated that further processed pulp fibres of smaller dimensions contribute to greater sound absorption. Moisture was also shown to affect the sound absorption properties of pulp fibres. The absorption properties of the pulp fibres increased at low-mid frequencies as they were exposed to higher relative humidities. This phenomenon has been attributed to two mechanisms, increasing flexibility and width of pulp fibres with increasing moisture content. However, further research is needed to confirm these results.

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REFERENCES

- 1. Lipiäinen S, Kuparinen K, Sermyagina E, Vakkilainen E. Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden. Sustainable Production and Consumption. 2022;29:421-31.
- 2. Attenborough K. The influence of microstructure on propagation in porous fibrous absorbents. J Sound Vib. 1971;16(3):419 442.
- 3. Page D, DH P, RS S. The elastic modulus of paper. II: The importance of fiber modulus, bonding, and fiber length. Tappi J. 1980;63(10):99-102.
- 4. Sixta H. Handbook of paper and board. Wiley-VCH; 2006.
- 5. Pöhler T, Jetsu P, Isomoisio H. Benchmarking new wood fibre–based sound absorbing material made with a foam-forming technique. Build Acoust. 2016;23(3-4):131-43.
- 6. Chen C, Kuang Y, Zhu S, Burgert I, Keplinger T, Gong A, et al. Structure–property–function relationships of natural and engineered wood. Nat Rev Mater. 2020:1-25.
- 7. Lappalainen T, Lehmonen J. PAPER PHYSICS: Determinations of bubble size distribution of foamfibre mixture using circular hough transform. Nord Pulp Pap Res J. 2012;27(5):930-9.
- 8. Janson J, et al. Calculation of the polysaccharide composition of wood and pulp. Paperi ja puu. 1970;52(5):323-9.
- 9. Seth R, Page D. The stress-strain curve of paper. The role of fundamental research in paper making. 1981;1:421-52.
- 10. Niskanen K. Kraft fibers in paper–Effect of beating. In: Cellulosic Pulps, Fibres and Materials. Elsevier; 2000. p. 249-60.
- 11. O'Brien FE. The control of humidity by saturated salt solutions. Journal of Scientific Instruments. 1948;25(3):73.
- 12. Rautkari L, Hill CA, Curling S, Jalaludin Z, Ormondroyd G. What is the role of the accessibility of wood hydroxyl groups in controlling moisture content? Journal of Materials Science. 2013;48(18):6352-6.
- 13. Cucharero J, Ceccherini S, Maloney T, Lokki T, Hänninen T. Sound absorption properties of woodbased pulp fibre foams. Cellulose. 2021;28(7):4267-79.
- 14. Arenas JP, Asdrubali F. Eco-Materials with Noise Reduction Properties. In: Martínez LMT, Kharissova OV, Kharisov BI, editors. Handbook of Ecomaterials. Cham: Springer; 2018. p. 3031-56.
- 15. Lovikka VA, Khanjani P, Väisänen S, Vuorinen T, Maloney TC. Porosity of wood pulp fibers in the wet and highly open dry state. Micropor Mesopor Mat J. 2016;234:326-35.
- 16. Rhim JW. Effect of moisture content on tensile properties of paper-based food packaging materials. Food Science and Biotechnology. 2010;19(1):243-7.
- 17. Lindner M. Factors affecting the hygroexpansion of paper. Journal of Materials Science. 2018;53(1):1-26.
- 18. Paajanen A, Zitting A, Rautkari L, Ketoja JA, Penttilä PA. Nanoscale Mechanism of Moisture-Induced Swelling in Wood Microfibril Bundles. Nano Letters. 2022.
- 19. Lee JM, Pawlak JJ, Heitmann JA. Dimensional and hygroexpansive behaviors of cellulose microfibrils (MFs) from kraft pulp-based fibers as a function of relative humidity. Holzforschung. 2012;66(8):1001-8.
- 20. Alava M, Niskanen K. The physics of paper. Reports on progress in physics. 2006;69(3):669.