

The role of chemical transport in the brown-rot decay resistance of modified wood

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Chemical modification of wood increases decay resistance but the exact mechanisms remain poorly understood. Recently, Ringman and coauthors examined established theories addressing why modified wood has increased decay resistance and concluded that the most probable cause of inhibition and/or delay of initiation of brown-rot decay is lowering the equilibrium moisture content. In another recent study, Jakes and coauthors examined moisture-induced wood damage mechanisms, including decay and fastener corrosion, and observed that these mechanisms require chemical transport through wood cell walls. They proposed that chemical transport within wood cell walls is controlled by a moisture-induced glass transition in interconnected networks of hemicelluloses and amorphous cellulose. This paper shows how these models jointly suggest mechanisms by which wood modifications can inhibit brown-rot. Alternative mechanisms are also discussed. These models can be used to understand and further improve the performance of wood modification systems.

Keywords: Wood modification; Brown-rot decay; Diffusion; Chemical transport; Percolation theory; Glass transition temperature

Introduction

As a building material, wood is a renewable resource that sequesters carbon during the life of the building (Falk 2009). Furthermore, wood has an excellent strength-to-weight ratio and is frequently cited as having a warm, pleasing appearance (Rice, Kozak, Meitner and Cohen 2006). However, the interaction of wood with moisture can cause a host of undesirable consequences that, in part, limit the usefulness of wood as a building material. When the moisture content within the wood is sufficiently high, it is susceptible to biotic attack and becomes corrosive towards embedded metal fasteners. Furthermore, repeated large changes in the hygroscopic range of wood moisture content cause dimensional instability, which can lead to the formation of splits and checks within the wood and failures at wood-adhesive bond lines. When non-durable wood and wood-based products are selected for an application where it will become repeatedly wet in-service, preservative (biocidal) treatments are frequently specified. These treatments protect the wood by excluding fungi or insects that attack the wood through repellent, biostatic, or biocidal actions. However, almost all

preservative treatments are regulated pesticides, and their use may be curtailed as pesticide regulations change (Lebow 2004). Over the last 50+ years, wood modifications have been developed as a potential alternative to preservative treatments for use when wood will be exposed to damp conditions.

In contrast to preservative treated wood, where biocidal chemicals (mainly heavy metals) are injected into the wood, wood modification is defined as non-toxic (Hill 2006). The modification treatment leads to a change in the wood structure resulting to improvements to the dimensional stability and decay resistance of wood. However, there are differences between the treatments in their ability to resist decay (Lande, Eikenes and Westin 2004; Temiz, Terziev, Jacobsen and Eikenes 2006; Rowell, Ibach, McSweeney and Nilsson 2009; Verma, Junga, Militz and Mai 2009; Thybring 2013). Several possible mechanisms have been proposed for how wood modifications protect wood (Papadopoulos and Hill 2002; Hill *et al.* 2005; Rowell 2005; Boonstra and Tjeerdsma 2006; Boonstra, Van Acker, Kegel and Stevens 2007; Rowell *et al.* 2009). Testing these hypotheses and identifying how wood modifications enhance durability are the keys to finding the preferred uses for modified wood as well as refining the modification processes for optimum performance, environmental effect, and cost.

This study synthesises recent advances in the understanding of brown-rot decay, wood modification, and chemical transport in wood and shows how these advances are interrelated. The potential mechanisms by which decay resistance occurs in modified wood are then discussed in light of these recent advances. With

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each potential mechanism, testable hypotheses are highlighted so that future work can address these. Finally, the paper highlights the most crucial open questions that can be used to determine the mechanisms resulting in the decay resistance of modified wood.

Brown-rot decay resistance in modified wood

Among wood decay agents found in buildings and other structures, brown-rot fungi stand out as the most efficient, widespread and destructive and can cause a rapid loss in serviceability. Failure analyses conducted between 1985 and 1988 by the Forest Products Laboratory at VTT in Finland found that 85% of damaged wood structures were caused by brown-rot fungi (Viitanen and Ritschkoff 1991). Brown-rot decay is characterised by significant reductions in strength even at low mass loss (Eaton and Hale 1993; Green and Highley 1997; Ibach 2005). In brown-rot fungi belonging to the orders *Gloeophyllales*, *Polyporales*, and *Boletales*, the degradation process has been described schematically as being divided into two parts: (i) chelator-mediated Fenton (CMF) degradation, in which hydroxyl radicals depolymerise polysaccharides in addition to modifying lignin, and (ii) enzymatic degradation, in which cellulases and hemicellulases hydrolyse the polysaccharides (Goodell et al. 1997; Baldrian and Valášková 2008; Arantes, Jellison and Goodell 2012). Ringman, Pilgård, Brischke and Richter (2014) recently conducted a review of theories of how modification imparts decay resistance to wood and presented four different potential mechanisms:

(i) There may not be enough easily accessible nutrients, such as hemicelluloses, in the modified wood material to provide energy for initial degradation, since hemicelluloses are degraded or heavily modified in e.g. thermally modified and acetylated wood (Boonstra et al. 2007; Rowell et al. 2009). It has also been argued that arabinose is a potential trigger of wood degradation (Rowell et al. 2009). However, Ringman et al. pointed out, based on Aro, Pakula and Penttilä (2005) and Baldrian and Valášková (2008), that celluloses and hemicelluloses are degraded by the same mechanisms so if there are no hemicelluloses, the fungi would most probably degrade cellulose instead. Furthermore, this mechanism would not inhibit CMF degradation.

(ii) The fungal metabolism process may be disrupted by wood modification through modification of the wood polymers so they are unable to be broken down by fungal enzymes (Rowell 2005). This mechanism also seems unlikely to be solely responsible for the enhanced durability of modified wood since brown-rot fungi are able to break down wood primarily through CMF degradation (Koenigs 1974; Goodell et al. 1997; Arantes et al. 2012).

(iii) Wood modification may close micropores in the wood cell wall preventing enzymes to enter the cell wall. However, Hill et al. (2005) showed that for acetylated wood, the entire size range of micropores is accessible to CMF degradation agents in highly modified wood even though the total volume of micropores has decreased.

(iv) Diffusion of fungal CMF degradation agents may be inhibited since wood modification reduces the equilibrium moisture content by decreasing the free volume within the cell wall (Papadopoulos and Hill 2002;

Boonstra and Tjeerdsma 2006). Taking the brown-rot degradation process into account, Ringman et al. (2014) concludes that out of the four established theories, this is the most plausible one. However, mechanisms 2 and 3 may reduce the rate of the enzymatic breakdown.

The authors concluded that inhibition of diffusion through the wood cell wall due to moisture exclusion is the most probable theory, since it also explains how the initial CMF degradation is inhibited.

The remainder of the paper focuses on the relationship between wood moisture content and intra-cell-wall diffusion to show how wood modifications may inhibit diffusion at a given moisture content and how by reducing the moisture content generally, there is a reduction in diffusion.

Chemical transport in wood cell walls

A mechanism recently proposed to control the onset of degradation in wood was the percolation of rubbery regions in hemicelluloses and amorphous cellulose networks that facilitate the necessary transport of CMF degradation chemicals through wood cell walls (Jakes et al. 2013). This onset mechanism was developed based on the observations in the literature that:

(i) In CMF degradation, chemical transport must occur through wood cell walls because the onset 20–25% MC for wood decay is below fibre saturation (Griffin 1977; Viitanen and Paajanen 1988; Carll and Highley 1999), suggesting free water is not readily present in the wood structure to facilitate chemical transport.

(ii) Hemicelluloses and amorphous cellulose are proposed to form interconnected networks in wood cell walls. Glucomannan is mechanically associated with cellulose microfibrils (Åkerholm and Salmén 2001) and may create a sheath around the microfibrils (Terashima et al. 2009) or even be present within a single microfibril (Salmén and Fahlen 2006). Additionally, xylan forms networks both parallel (Stevanic and Salmén 2009) and perpendicular (Terashima et al. 2009) to the cellulose microfibrils in secondary wood cell walls. Hemicelluloses are also embedded as an irregular, interconnected network in lignin to form the middle lamella (Hafren et al. 2000).

(iii) The moisture-induced glass transition of hemicelluloses occurs at lower moisture content than wood decay. Dry hemicelluloses have a glass transition temperature (T_g) much higher than room temperature; estimates of T_g range from 150 to 220°C (Back and Salmén 1982; Kelley, Rials and Glasser 1987). Water plasticises the hemicelluloses and lowers the glass transition temperature. The T_g decreases with increasing moisture content and with enough added moisture, the T_g drops below room temperature. It is estimated using mechanical spectroscopy that the T_g of hemicelluloses drop below room temperature when the environment is between 60 and 80% relative humidity (RH) (Cousins 1978; Kelley et al. 1987; Olsson and Salmén 2004). This corresponds with a wood moisture content of approximately 11–15%.

(iv) Ionic conduction in polymers is much higher in the rubbery state above their glass transition than in the glassy state below their glass transition (Ferry 1980).

(v) Ionic conduction in wood as a function of moisture content can be fit with a percolation threshold at 16% MC (Zelinka, Glass and Stone 2008).

A schematic of the proposed formation of percolated regions of softened hemicelluloses in the secondary cell wall and middle lamella is shown in Fig. 1. An experiment to test the proposed mechanism and effects of moisture on ionic diffusion in wood cell walls was recently developed using synchrotron-based X-ray fluorescence microscopy (XFM) (Zelinka et al. 2015). In these experiments, a sharp concentration gradient of ions was implanted into thin sections of wood and the RH controlled *in situ* during imaging to allow the observation of humidity thresholds for ion diffusion. It was observed that the threshold MC for observable diffusion depended on the ion (Cu, Zn, K or Cl), cell wall layer (S2 or middle lamella), and orientation (longitudinal or transverse). The threshold for diffusion was found to be as low as 60% RH (ca. 10% MC) for K and Cl ions and potentially be as high as 90% RH (ca. 19% MC) for Zn ions in the longitudinal direction. This range of humidity corresponds to the proposed 60–80% RH range for the hemicelluloses passing through their moisture-induced glass transition, supporting the theory that percolated networks of rubbery hemicelluloses and amorphous cellulose are responsible for ion transport through and in wood cell walls. Additionally, for all experiments a low RH bound was observed over which no ion diffusion could be observed during the experiment (~10 minutes). The difference in onset RH for different ions might relate to size requirements to the diffusion pathways in the percolated network.

If CMF reagents behave similarly to the ions examined in the XFM experiments, it suggests that there may be a moisture threshold for diffusion of CMF degradation chemicals that limits wood decay. It follows that XFM experiments could then potentially be a valuable tool to predict the efficacy of a wood treatment on decay resistance. However, it is also possible that the diffusion of CMF degradation chemicals is not a rate limiting step in the decay process. The next section examines potential mechanisms of decay resistance in modified wood and presents a series of potential experiments to test these mechanisms.

Discussion – potential mechanisms of decay resistance in modified wood based upon transport theories

Even with these recent advances in understanding transport and decay in modified wood, there is not yet enough information to know the exact mechanism or mechanisms. Three potential mechanisms by which modified wood may inhibit brown-rot decay are presented. Along with each mechanism, testable hypotheses are given.

Transport of fungal CMF degradation agents is inhibited by preventing softening of the hemicelluloses

The percolation model of Zelinka et al. (2008) and extended transport model of Jakes et al. (2013) both suggest that a *threshold moisture content* exists below which diffusion of at least some chemical species does not occur. One possible mechanism for the decay

resistance of modified wood is that diffusion of CMF degradation compounds are inhibited because the percolation threshold has not been reached. In this case, a percolating network would not be achieved because the hemicelluloses remain in their glassy state.

Mechanism of decay resistance

This mechanism provides decay resistance by inhibiting the transport of CMF degradation compounds. Chemical modifications that increase the humidity required for hemicelluloses to pass through a glass transition should improve decay resistance. A modification that prevents a hemicelluloses glass transition under water saturated conditions should be an effective wood protection treatment because the initial CMF degradation mechanisms are prevented.

Testable hypotheses of this mechanism

If decay resistance was imparted by inhibiting diffusion by stopping the moisture-induced glass transition of the hemicelluloses, then there would be no observable diffusion at high moisture contents and the hemicelluloses would be stiffer than in untreated wood at high moisture contents. Previously, XFM was used to examine the diffusion thresholds for unmodified wood (Zelinka et al. 2015); this work could be extended to study whether the *threshold moisture content* changes in modified wood. Furthermore, mechanical spectroscopy of unmodified and modified wood across a range of moisture contents could determine if the moisture-induced glass transition in hemicelluloses tracked with the diffusion threshold.

Transport of fungal CMF degradation agents is inhibited by preventing percolation

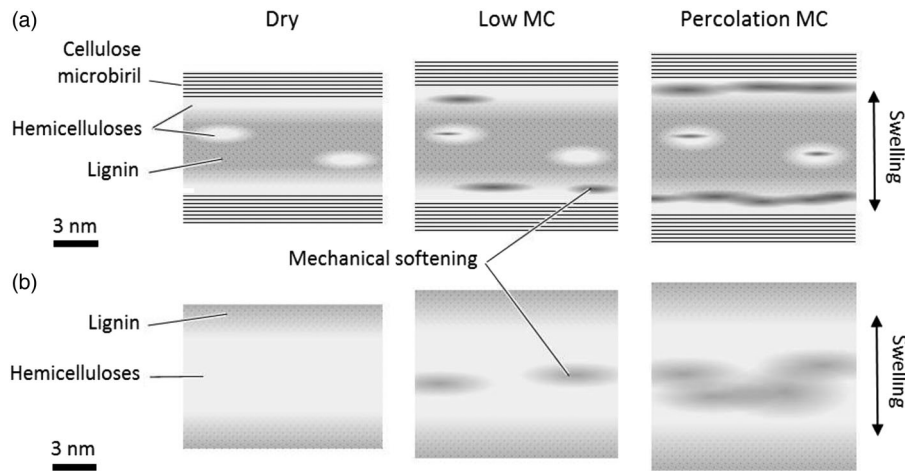
Another possibility is that there is softening of the hemicelluloses, but a percolating network does not form in modified wood. The transport mechanism presented by Jakes et al. showed correlation between percolation and the softening of hemicelluloses but did not prove causation. Therefore, it is possible that chemical modifications do not affect the glass transition of hemicelluloses but do prevent percolation and diffusion. In this case, even though the hemicelluloses may have softened, the heavy presence of embedded entities from the modification (e. g. acetyl groups in acetylated wood) may prevent a continuous, percolating network through which diffusion can occur.

Mechanism of decay resistance

In this case, the mechanism of decay resistance is the same as in the previous section; the diffusion of fungal CMF degradation compounds is inhibited. However, in contrast to the previous mechanism, this lack of diffusion is not related to vitrified hemicelluloses, but instead comes from lack of percolation.

Testable hypotheses of this mechanism

Similar to the previous mechanism, testing this mechanism would require testing both whether or not diffusion can occur in modified wood as well as testing whether or not the moisture-induced glass transition of the hemicelluloses changed. In this case, diffusion would not be observed, but the hemicelluloses would be softened.



1 Mechanism of transport proposed by Jakes et al. where transport occurs in interconnected regions of softened hemicelluloses in the (a) S2 layer and (b) middle lamella

Transport of CMF degradation agents is not inhibited

In unmodified wood, the diffusion threshold ($\sim 16\%$ MC) (Zelinka et al. 2008) is well below the *threshold moisture content* at which brown-rot decay is first observed ($>20\%$ MC) (Griffin 1977; Viitanen and Paajanen 1988; Carll and Highley 1999). Clearly diffusion is a necessary but not sufficient condition for brown-rot decay to occur. Furthermore, it is unclear what other changes are occurring to the wood between the percolation threshold and the decay threshold that makes decay possible.

Previous research on modified wood has found linkages between the moisture exclusion efficiency (MEE) and decay resistance across various wood modifications (Thybring 2013) with completely different chemistry and mode of action (bulking, grafting, cross-linking). MEE is a measure at how effectively wood modifications reduce the equilibrium moisture content below fibre saturation. The relationship between MEE and decay resistance for modifications which presumably has a diverse effect on the hemicelluloses softening, suggests that decay resistance may be directly controlled by the amount of water inside cell walls, although the exact mechanism is yet unclear.

One possibility is that it is not the diffusion threshold that is important to the fungi, but rather, a minimum rate of diffusion that is needed to produce a favourable decay reaction. In this case, while there may be sufficient moisture to create a percolating system, the diffusion rate is not high enough to sustain the degradation process. In terms of modified wood, it could be that even at the highest possible moisture content within cell wall diffusion is simply too slow for decay to occur (note that this does not exclude the possibility that percolation occurs in modified wood).

Conversely, it is also possible that diffusion is freely able to occur and that the decay resistance of modified wood is caused by an as yet undetermined mechanism that may or may not be related to the wood moisture content. For example, the reactions leading up to the formation of hydroxyl radicals in the CMF degradation are pH sensitive and may therefore be inhibited by the altered pH in some modified wood materials.

Mechanism of decay resistance

In this case, it is unclear the exact mechanism of decay resistance. It could be that while there is diffusion, it is not fast enough to sustain decay, or it could be that the mechanism of decay resistance is not linked to transport.

Testable hypotheses of this mechanism

If diffusion experiments show transport in decay resistant modified wood, then clearly diffusion of fungal agents is not excluded and an alternative mechanism must be responsible for the decay resistance of modified wood.

Conclusions

In this paper, we discuss newly published findings on chemical transport in wood and brown-rot decay in modified woods. These new findings jointly suggest that transport of low molecular weight compounds in wood cell walls play an important role in the decay process and theories of chemical transport suggest some potential mechanisms by which transport might be inhibited. However, at this stage, there is not enough research to definitively identify the role of chemical transport in the decay resistance of modified wood. Based on the current understanding, we suggest there are three possibilities: (1) that diffusion is inhibited by making the hemicelluloses glassy at high wood moisture contents (2) that diffusion is inhibited even though the hemicelluloses are softened because they do not form a percolated network, and (3) that decay resistance is not related to chemical transport. We presented several testable hypotheses to differentiate between these mechanisms with the hope that future research will be able to more clearly identify the mechanism of decay resistance in modified wood.

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References

- Åkerholm, M. and Salmén, L. 2001. Interactions between wood polymers studied by dynamic FT-IR spectroscopy. *Polymer*. **42**(3): 963–969.
- Arantes, V., Jellison, J. and Goodell, B. 2012. Peculiarities of brown-rot fungi and biochemical Fenton reaction with regard to their potential as a model for bioprocessing biomass. *Applied Microbiology and Biotechnology*. **94**(2): 323–338.
- Aro, N., Pakula, T. and Penttilä, M. 2005. Transcriptional regulation of plant cell wall degradation by filamentous fungi. *FEMS Microbiology Reviews*. **29**(4): 719–739.
- Back, E. and Salmén, L. 1982. Glass transitions of wood components hold implications for molding and pulping processes. *TAPPI J*. **65**: 107–110.
- Baldrian, P. and Valášková, V. 2008. Degradation of cellulose by basidiomycetous fungi. *FEMS Microbiology Reviews*. **32**(3): 501–521.
- Boonstra, M. J. and Tjeerdsma, B. 2006. Chemical analysis of heat treated softwoods. *Holz als Roh-und Werkstoff*. **64**(3): 204–211.
- Boonstra, M., Van Acker, J., Kegel, E. and Stevens, M. 2007. Optimisation of a two-stage heat treatment process: durability aspects. *Wood Science and Technology*. **41**(1): 31–57.
- Carll, C. and Highley, T. L. 1999. Decay of wood and wood-based products above ground in buildings. *Journal of Testing and Evaluation*. **27**(2): 150–158.
- Cousins, W. 1978. Young's modulus of hemicellulose as related to moisture content. *Wood Science and Technology*. **12**(3): 161–167.
- Eaton, R. A. and Hale, M. D. 1993. *Wood: Decay, Pests and Protection*. London: Chapman and Hall Ltd.
- Falk, R. H. 2009. Wood as a sustainable building material. *Forest Products Journal*. **59**(9): 6–12.
- Ferry, J. D. 1980. *Viscoelastic Properties of Polymers*. New York: John Wiley & Sons.
- Goodell, B., Jellison, J., Liu, J., Daniel, G., Paszczynski, A., Fekete, F., Krishnamurthy, S., Jun, L. and Xu, G. 1997. Low molecular weight chelators and phenolic compounds isolated from wood decay fungi and their role in the fungal biodegradation of wood. *Journal of Biotechnology*. **53**(2): 133–162.
- Green, F. and Highley, T. L. 1997. Mechanism of brown-rot decay: paradigm or paradox. *International Biodeterioration & Biodegradation*. **39**(2): 113–124.
- Griffin, D. 1977. Water potential and wood-decay fungi. *Annual Review of Phytopathology*. **15**(1): 319–329.
- Hafren, J., Fujino, T., Itoh, T., Westermark, U. and Terashima, N. 2000. Ultrastructural changes in the compound middle lamella of *Pinus thunbergii* during lignification and lignin removal. *Holzforchung*. **54**(3): 234–240.
- Hill, C. A. 2006. *Wood modification: chemical, thermal and other processes*. West Sussex: John Wiley & Sons.
- Hill, C. A., Forster, S., Farahani, M., Hale, M., Ormondroyd, G. and Williams, G. 2005. An investigation of cell wall micropore blocking as a possible mechanism for the decay resistance of anhydride modified wood. *International Biodeterioration & Biodegradation*. **55**(1): 69–76.
- Ibach, R. E. 2005. Chapter 5. Biological properties. In: Rowell R. M. (ed). *Handbook of Wood Chemistry and Wood Composites*, 99. Boca Raton: CRC Press.
- Jakes, J. E., Plaza, N., Stone, D. S., Hunt, C. G., Glass, S. V. and Zelinka, S. L. 2013. Mechanism of transport through wood cell wall polymers. *Journal of Forest Products and Industries*. **2**(6): 10–13.
- Kelley, S. S., Rials, T. G. and Glasser, W. G. 1987. Relaxation behaviour of the amorphous components of wood. *Journal of Materials Science*. **22**(2): 617–624.
- Koenigs, J. 1974. Hydrogen peroxide and iron: a proposed system for decomposition of wood by brown-rot basidiomycetes [*Pinus taeda*, Liquidambar styraciflua, fungus diseases]. *Wood and Fiber*. **6**(1): 66–80.
- Lande, S., Eikenes, M. and Westin, M. 2004. Chemistry and ecotoxicology of furfurylated wood. *Scandinavian Journal of Forest Research*. **19**(sup5): 14–21.
- Lebow, S. 2004. Alternatives to Chromated Copper Arsenate for Residential Construction. Res. Pap. FPL-RP-618. U.S.D.A. Forest Service, Forest Products Laboratory, Madison, WI, pp. 9–9.
- Olsson, A.-M. and Salmén, L. 2004. The softening behavior of hemicelluloses related to moisture. In: *ACS Symposium Series*. Washington, DC: American Chemical Society, 184–197, 1999.
- Papadopoulos, A. N. and Hill, C. 2002. The biological effectiveness of wood modified with linear chain carboxylic acid anhydrides against *Coniophora puteana*. *Holz als Roh-und Werkstoff*. **60**(5): 329–332.
- Rice, J., Kozak, R. A., Meitner, M. J. and Cohen, D. H. 2006. Appearance wood products and psychological well-being. *Wood and Fiber Science*. **38**(4): 644–659.
- Ringman, R., Pilgård, A., Brischke, C. and Richter, K. 2014. Mode of action of brown rot decay resistance in modified wood: a review. *Holzforchung*. **68**(2): 239–246.
- Rowell, R. M. 2005. Chapter 14. Chemical modification of wood. In: Rowell R. M. (ed). *Handbook of Wood Chemistry and Wood Composites*. Boca Raton: CRC Press, 381–420.
- Rowell, R. M., Ibach, R. E., McSweeney, J. and Nilsson, T. 2009. Understanding decay resistance, dimensional stability and strength changes in heat-treated and acetylated wood. *Wood Material Science and Engineering*. **4**(1–2): 14–22.
- Salmén, L. and Fahlen, J. 2006. Reflections on the ultrastructure of softwood fibers. *Cellulose Chemistry and Technology*. **40**(3–4): 181–185.
- Stevanic, J. S. and Salmén, L. 2009. Orientation of the wood polymers in the cell wall of spruce wood fibres. *Holzforchung*. **63**(5): 497–503.
- Temiz, A., Terziev, N., Jacobsen, B. and Eikenes, M. 2006. Weathering, water absorption, and durability of silicon, acetylated, and heat-treated wood. *Journal of Applied Polymer Science*. **102**(5): 4506–4513.
- Terashima, N., Kitano, K., Kojima, M., Yoshida, M., Yamamoto, H. and Westermark, U. 2009. Nanostructural assembly of cellulose, hemicellulose, and lignin in the middle layer of secondary wall of ginkgo tracheid. *Journal of Wood Science*. **55**(6): 409–416.
- Thybring, E. E. 2013. The decay resistance of modified wood influenced by moisture exclusion and swelling reduction. *International Biodeterioration & Biodegradation*. **82**: 87–95.
- Verma, P., Junga, U., Militz, H. and Mai, C. 2009. Protection mechanisms of DMDHEU treated wood against white and brown rot fungi. *Holzforchung*. **63**(3): 371–378.
- Viitanen, H. and Paajanen, L. 1988. The critical moisture and temperature conditions for the growth of some mould fungi and the brown rot fungus *Coniophora puteana* on wood. In: Secretariat I. (ed). *International Research Group on Wood Protection*. Madrid, Spain: International Research Group on Wood Protection, IRG/WP 1369.
- Viitanen, H. and Ritschkoff, A. 1991. Brown rot decay in wooden constructions. Effect of temperature, humidity and moisture. *Rapport-Sveriges Lantbruksuniversitet, Institutionen foer Virkeslaera (Sweden)*.
- Zelinka, S., Glass, S. and Stone, D. 2008. A percolation model for electrical conduction in wood with implications for wood-water relations. *Wood and Fiber Science*. **40**(4): 544–552.
- Zelinka, S. L., Gleber, S.-C., Vogt, S., Rodríguez López, G. M. and Jakes, J. E. 2015. Threshold for ion movements in wood cell walls below fiber saturation observed by X-ray fluorescence microscopy (XFM). *Holzforchung*. **69**(4): 441–448.