A REVIEW ON PROMISING APPROACHES FOR LIQUID PERMEABILITY IMPROVEMENT IN SOFTWOODS

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Abstract. The low liquid permeability of refractory wood species such as Norway spruce [*Picea abies* (L.) Karst.] and white Fir (*Abies alba*) is related mainly to the aspiration of bordered pits during wood drying. The resulting low permeability complicates treatments with liquid preservatives or wood modification substances. This article provides a literature review on various mechanical and biotechnological approaches that were developed for improving liquid permeability. In this context, we focus on the incubation of Norway spruce wood with a white rot fungus, *Physisporinus vitreus* (Pers.) P. Karst. The process is termed "bioincising" and results in a significant increase in wood permeability. This is most probably caused by the selective degradation of bordered pit membranes and simple pits of xylem ray parenchyma during the initial period of wood colonization. Subsequently, we discuss how bioincising could be a potential pretreatment method for wood preservation and selected wood modification substances. Considering that these wood modification systems require specific penetration depths for optimal performance, we discuss the capability of bioincising to enhance permeability at the required penetration depths. In this regard, we propose a terminology for better differentiation of penetration depths by liquid substances into the wood.

Keywords: Bioincising, impregnation, penetration depth, permeability improvement, wood modification.

INTRODUCTION

Permeability represents a material property that is of specific importance for different technical processes in the wood industry. Not only for preservative impregnation, but also for pulping and wood drying, the permeability of wood to gases and liquids influences the design of industrial wood processing procedures. Furthermore, the application of substances to enhance selected wood properties such as hardness, UV stability, water and vapor repellency, dimensional stability, and fire resistance requires a movement of liquids into the wood to different depth levels.

Permeability determines the flow of liquid or gaseous phases through a solid medium. Siau (1984) defines permeability as a measure of the ease with which fluids are transported through a

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porous solid under the influence of a pressure gradient. The pore size and distribution, but even more so, the degree of pore interconnectivity (tortuosity), influences the material permeability.

In softwoods, bordered pits act as interconnecting pathways between adjacent tracheids. During wood drying, a large number of the bordered pits are aspirated. This occurs as a result of pressure differences between the tracheids. Hence, the liquid permeability of, for example, Norway spruce [*Picea abies* (L.) Karst.] is reduced to 1 – 5% of that of green wood (Messner et al 2003). Although this so-called pit aspiration is an efficient response of the living tree to counteract embolism in the water-conducting sapwood, it presents an undesirable obstacle for treatment of the wood with liquid substances. To overcome the problem, ample research on transport processes, pit aspiration mechanisms, and permeability improvement on Norway spruce has been conducted (Liese and Bauch 1967; Petty 1970; Palin and Petty 1981; Flynn 1995; Hansmann et al 2002). Besides numerous mechanical incising and drilling techniques for reopening the wood structure for subsequent impregnation, several biotechnological approaches have been developed on the basis of bacterial, enzymatic, or fungal activity (Militz 1993b; Nijdam et al 2001; Messner et al 2003; Reinprecht and Pánek 2008). One of the latest approaches is the incubation of Norway spruce with the white-rot fungus *Physisporinus vitreus* (Pers.) P. Karst over a period of approximately 6 wk (Schwarze et al 2006). During its initial period of colonization, this fungus apparently selectively degrades the pit membranes. The permeability is significantly improved without severe strength losses by “bioincising.”

In this article, we give an overview of the mechanisms that lead to a reduction of permeability in softwoods. Fundamentals of flow in porous media like wood are briefly discussed before we present different techniques for the improvement of wood permeability. The bioincising process is then outlined as a potential technique to improve the permeability to specific depths of the wood substrate. Regarding this differentiation, we suggest that certain wood modification systems require specific penetration depths. For example, substances for UV and visible light protection have to penetrate only the subsurface area, whereas substances for dimension stability have to penetrate the wood at much deeper levels for positive effects. When adapted to these specific requirements, bioincising can be a potential technique to customize the depth of penetration for the target property, which can be improved by the subsequent treatment. Therefore, bioincising is discussed in the context of permeability improvement to specific levels of depth and selected wood modification techniques. To provide an understanding for discussion, we further suggest terminology for the precise differentiation of penetration depths in the wood.

PERMEABILITY OF SOFTWOODS

Role of Pits for Fluid Transport in Wood

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). 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 (Wardrop and Davies 1961; Liese and Bauch 1967; Comstock and Coté 1968; Comstock 1970; Richter and Sell 1992; Matsumura 1999; Usta and Hale 2006). Flow in the tangential and radial directions is much less than in the longitudinal direction (Lihra et al 2000; Usta and Hale 2004; Tarmian and Perré 2009). The spreading of fluids from xylem ray elements to longitudinal tracheids (and vice versa) is still under discussion (Olsson et al 2001). Characteristics of the cross-field pits and the structure of ray tissue vary greatly among softwood species; hence, the transverse permeability depends on the number and size of ray parenchyma and ray tracheids. Simple pits between the ray parenchyma cells restrict fluid transport because the pit membranes can only be penetrated by diffusion or through plasmodesmata (Fujikawa and Ishida 1975). Moreover, deposited extractives are believed to reduce permeability of ray parenchyma cells (Olsson et al 2001). Some authors have shown that the transport in ray parenchyma is important (Wardrop and Davies 1961; Keith and Chauret 1988), whereas others state the contrary (Bailey and Preston 1969). The ray tracheids on the outermost position of the ray tissue have been found to act as important transport paths during impregnation (Liese and Bauch 1967; Olsson et al 2001). Similarly as between longitudinal tracheids, fluid transport in ray tracheids occurs through bordered pits.

The bordered pits of the longitudinal tracheids substantially determine the permeability of a softwood species. In reaction to different pressure levels in adjacent tracheids during the drying of wood, the pit is aspirated with the margo and torus attached to the inner wall of the pit opening (Fig 1). Aspiration is considered irreversible because of the formation of hydrogen bonds between the torus/margo and the pit opening. These forces are seldom overcome by high pressures during processing (Liese and Bauch 1967; Thomas and Kringstad 1971).

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, MC in the heartwood of the living tree is reduced, resulting in some level of pit aspiration. Furthermore, depositions of hydrophobic organic wood extractives occlude the pit membranes (Comstock 1965; Bamber and Fukazawa 1985; Mantanis and Young 1997).

After drying wood, the latewood regions commonly have a higher permeability than the earlywood (Kininmonth 1971; 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 (Liese and Bauch 1967; Erickson 1970; Flynn 1995; Hansmann et al 2002).

Resin canals and intercellular spaces also play a certain role in softwood impregnation, because fluids penetrate the void spaces and then enter the adjacent tracheids (Koran 1989). Although

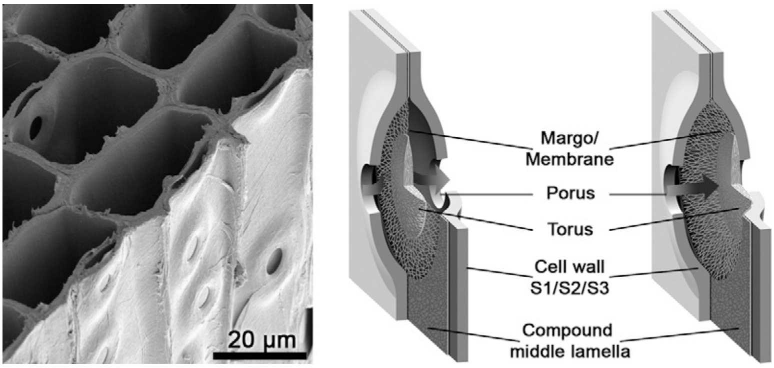

Figure 1. Bordered pits act as interconnecting voids between adjacent tracheids. After aspiration, the torus restricts fluid flow.

pit interaction is not directly involved, we mention these pathways at this point to complete the description of fluid movement through softwoods.

Flow Through Porous Media

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 with liquid preservatives, 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 (tortuosity).

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:

$$k = \frac{Flux}{Gradient} = \frac{Q/A}{\Delta P/L} = \frac{QL}{A\Delta P} \qquad (1)$$

where k = permeability ($m^4/N\cdot s$), Q = volumetric flow rate (m^3/s), L = length of specimen in the flow direction (m), A = cross-sectional area of specimen perpendicular to the flow direction (m^2), and ΔP = pressure differential (Pa).

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 require an adaptation of Eq 1 for a realistic determination of wood permeability. Several works present an overview on determining permeability of wood (Resch and Ecklund 1964; Banks 1981; Siau 1984; Hansmann et al 2002).

TECHNIQUES FOR THE IMPROVEMENT OF LIQUID PERMEABILITY

Mechanical Opening of the Wood Structure

Incising of refractory wood species such as Norway spruce is a well-established technique to mechanically open the wood structure for subsequent impregnation or drying (Keith and Chauret 1988; Richter 1989; Morris et al 1994). Different perforation systems using needles, drills, slit discs, lasers, and water jets have been reported (Richter 1989). However, visible marks on the wood surface and strength losses are considered to be disadvantageous for certain wood products. Microwave treatments have also been attempted (Terziev 2002; Li et al 2005; Merenda and Holan 2008). In this technique, the induced destruction of bordered pits facilitated the penetration of liquids, but the mechanical properties were presumably negatively altered. In North America, mechanical incising technologies are widely used for the pretreatment of sawn wood, whereas in Europe, they are mostly limited to the air–soil zone treatment of poles.

Reversing Pit Aspiration

The irreversibility of bordered pit aspiration is considered to be caused by strong forces induced by hydrogen bonding between the margo/torus and the adjacent cell wall (Thomas and Kringstad 1971). Fujii et al (1997) and Matsumura (1999) described the positive effect of steam treatment or hot water extraction on gas permeability, in which the hydrogen bonding in the aspirated pits may have been reduced. Exchanging the moisture in green wood with a less polar or nonpolar solvent before drying (solvent-exchange drying) reduces the degree of pit aspiration (Hayashi et al 1966; Siau 1984; Hansmann et al 2002). Bao et al (2001) showed that a low level of aspirated pits in the sapwood results when wood goes from green to a dry state by ethanol-exchange drying. In general, deaspiration is promoted when the solvent has lower swelling characteristics than water and/or when it lacks the ability to form hydrogen bonds. Fluids conducive to this process typically contain benzene or pentane.

Biological Treatments

The controlled use of microbial decomposition is a biotechnological method that can be used for wood modification [see Mai et al (2004) for a review]. Biological concepts that enhance the permeability of softwoods have been developed using enzymes, bacteria, and fungi.

Bacteria. Bacterial activity is considered to be the main cause of improvement in softwood permeability during ponding (storing logs in water over a long period) (Adolf et al 1972; Unligil 1972; Kobayashi 1998; Nijdam et al 2001). Wood exposed to bacterial degradation showed lower pectin contents, pit membranes were destroyed, and substances encrusting the cell lumina and pit chambers were partly removed. However, the necessity for prolonged treatment and inhomogeneous variations of permeability has ruled out further commercial use.

Enzymes. The improvement of softwood permeability by means of enzymes was investigated by Nicholas and Thomas (1968) and Militz (1993a, 1993b), among others. The activity of pectinases, cellulases, and hemicellulases resulted in the partial degradation of pit membranes. The permeability of Norway spruce heartwood and sapwood was improved with a mixture of different enzymes. However, similar to bacterial treatment, several weeks of incubation were required to obtain an enhanced permeability, and localized differences in enzyme activity led to inconsistent results. The introduction of bacteria and enzymes into dried wood is difficult because the aspirated pits counteract rapid and uniform ingress of microbial suspensions. Moreover, the processes are difficult to control and scaling up to industrial application has been unsuccessful.

Fungi. In contrast to isolated enzymes, hyphae of white rot fungi are able to transport their specific enzymes deep into the wood substrate during colonization. The hyphae largely follow the nutrient-rich parenchyma cells and rays and grow from there into the adjacent tracheids primarily through simple or bordered pits or even by creating bore holes in the cell walls. During the first period of substrate colonization, the excreted enzymes alter the chemical structure of the pit membranes and contribute to their selective degradation with almost no negative effect on the strength properties of the wood matrix (Messner et al 2003). Investigations on Norway spruce infected with strains of *Trichoderma, Dichomitus,* and *Phanerochaete* resulted in an enhanced permeability of the sapwood, whereas the effect on the heartwood remained negligible (Rosner et al 1998). In contrast, incubation of Norway spruce and white fir for 6 wk with a white rot fungi (*Physisporinus vitreus*) revealed significant permeability improvement in both sapwood and heartwood (Schwarze et al 2006). At the same time, impact bending strength was reduced negligibly. The process was subsequently patented (Schwarze 2006) and termed "bioincising." In the following section, we focus on the bioincising process and discuss its potential for permeability improvement in refractory species.

THE BIOINCISING PROCESS

The studies of Schwarze et al (2006) revealed an enhanced liquid uptake of 200 – 400% for bioincised heartwood of Norway spruce and Fir. As illustrated in micrographs by the authors, membranes in bordered pits of the tracheids and in simple pits of the ray parenchyma cells were most likely selectively degraded by the enzymatic activity of *P. vitreus* during the first period of substrate colonization. Schwarze et al (2006) suggested the excretion of polygalacturonase and oxalic acid by *P. vitreus* during incipient wood decay as promoting factors for the hydrolysis of the pectin-rich bordered pit membranes.

P. vitreus is known to have high tolerance to very wet conditions and has been isolated from wood in cooling towers. Considering this aspect, the selective degradation of pit membranes during the first period of substrate colonization has been interpreted as a strategy of *P. vitreus* to indirectly influence the MC of the wood (Schmidt et al 1997; Schwarze and Landmesser 2000). The biodegradation of pit membranes results in an increase of wood MC and favors an efficient and rapid distribution of hyphae in the substrate. Once the pit membranes are removed and a high MC is established, the distribution of lignolytic enzymes is facilitated. In a second period, degradation of the cell wall matrix occurs and weight and strength losses have been recorded. Therefore, fungal activity during the bioincising process must be restricted to the first period of substrate colonization to avoid severe damage to the wood matrix and exclusively limit changes to those that increase the permeability for gases and preservatives.

Schwarze et al (2006) conducted their investigation on specimens of relatively small dimensions [100 × 10 × 15 mm and 100 × 25 × 15 mm (l × t × r)]. When incubation with *P. vitreus* was repeated with larger specimens of Norway spruce, fungus activity turned out to be heterogeneous across the substrate (Fig 2). The samples (500 × 50 × 50 mm) were obtained from an entire trunk to provide a comprehensible visual impression of differences between sapwood and heartwood. Radial or tangential grain orientation could of course not always be maintained. Checking of the bioincised specimens occurred during drying at 105°C.

Impregnation of the bioincised samples with stained water revealed that permeability was preferentially improved in sapwood. Also, fungal activity could be documented in heartwood, but the permeability improvement occurred in local regions and activity was rather heterogeneous.

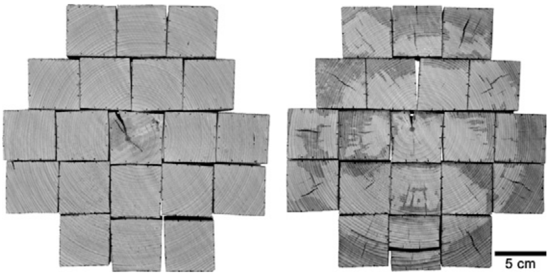

Figure 2. Liquid uptake of Norway spruce (left) and after 6 weeks of bioincising (right) demonstrated by vacuum impregnation (20 min, 0.7 mbar) with stained water. Note checking of the bioincised samples resulted from drying at 105°C (photographs from test series for Schwarze et al 2006).

Obviously, a range of biotechnological parameters still has to be optimized to enable homogenous and rapid colonization of the sapwood and heartwood with *P. vitreus*. Schubert et al (2009) showed in their study that the water activity and temperature have a strong influence for rapid mycelial growth during early stages of the bioincising process. Moreover, the studies showed that *P. vitreus* is susceptible to microbial contaminants, particularly for *Trichoderma* species during the lag phase. This also can have a negative impact on the homogeneity of colonization.

Currently, a number of investigations are underway to assess bioincising. First, we are evaluating material properties such as permeability, strength, and chemical composition of the bioincised wood. Second, we study the behavior of liquid substances during substrate penetration into the bioincised wood according to anatomical orientation. Finally, we try to estimate the effect of bioincising on the targeted properties for improvement after a subsequent application of wood modification substances. For this purpose, tests with respect to selected properties such as hydrophobicity, UV stability, surface hardness, or flame retardancy have been conducted. Because the results from the mentioned investigations will be the subject of further publications, only one example from preliminary tests will be presented in the following section.

Preliminary Tests

To evaluate the overall performance of the bioincised wood for subsequent treatment with property-improving substances, we conducted preliminary tests for flammability (Lehringer et al 2009). Wood samples (30 × 40 × 15 mm; l × t × r) of Norway spruce were incubated with *P. vitreus* for 6 wk and then treated with three commercial wood modification substances. The substances were applied to the material by brushing, dipping (30 min), and vacuum impregnation (20 min, 7 kPa). To avoid major capillary uptake, the endgrain surfaces were presealed with a polyurethane coating. The substance uptake of the wood modification agents was gravimetrically measured for the three application methods. Flammability was measured by exposing the treated samples horizontally to a propane flame for 3 min. After removing the char, mass loss was determined gravimetrically.

For brushing and dipping, little or no effect of bioincising on the uptake was observed, whereas a clear improvement of penetrability was apparent when the agents were impregnated in a vacuum chamber. Despite an improved uptake of modification substances after impregnation, we found a negative effect of bioincising on the target properties (Lehringer et al 2009). The bioincised samples lost more mass than the control samples. Apparently, the cell wall structure was affected by the fungal activity that promoted the mass loss.

To reduce this type of side effect from *P. vitreus* and to bring the bioincising process in the area of technical application, future work must focus on optimizing the bioincising method.

In the past, wild-type strains of *P. vitreus* with dikaryotic mycelia have been used for the bioincising process. Each dikaryotic cell of *P. vitreus*, a tetrapolar heterokaryon, contains two nonidentical nuclei derived from the fusion of two different, sexually compatible primary mycelia, each bearing a single nucleus per cell. The dikaryotic mycelia of most *P. vitreus* isolates become pigmented in culture, producing brown exudates and darkening some softwoods during colonization. In addition, dikaryons in general have faster growth rates than monokaryons of the same species. These factors suggest that the use of a monokaryon of *P. vitreus* may be preferable to a dikaryon for the development of a biological bioincising system. Monokaryons show a reduced tendency to produce dark pigments in culture and cause less discoloration (Addleman and Archibald 1993). Additionally, because of the reduced growth rates, it may have reduced numbers of isozymes of secreted enzymes such as laccase and manganese peroxidase and consequently may have the potential to degrade bordered pit membranes more selectively. It is expected that monokaryons can enhance wood permeability more effectively than the dikaryons presently used. Moreover, they would provide a much simpler genetic and biochemical system for the elucidation of the bioincising mechanisms because they are more easily genetically modified.

BIOINCISING AS POTENTIAL PRETREATMENT FOR WOOD MODIFICATION

Customized Permeability Improvement

Although certain tasks are obviously still ahead, at this point, we would like to give an outlook of possible technical applications for bioincising. On the basis of the aspects presented, we consider bioincising to be a promising approach for controlled improvement of permeability to different depths of the wood substrate. Depending on the control of process parameters (temperature, nutrient and oxygen supply, substrate humidity, pH, duration of incubation) and an improved selectivity of *P. vitreus*, wood permeability improvement could be customized for subsequent treatment with specific wood modification substances. For example, a treatment for dimension stability requires much deeper penetration into the wood than a treatment for UV protection substances (which are discussed in more detail). Thus, certain penetration depths have to be achieved to ensure 1) an efficient distribution of the modification substance and 2) reaching an optimal effect for the targeted property improvement.

Definition of Penetration Depth

Before we discuss the application of bioincising as pretreatment for subsequent wood modification, it is necessary to define the terminology concerning the penetration depth of liquid substances into the wood surface. Unfortunately, definitions in the literature are imprecise. They do not differentiate between the surface of the material and the zones beneath it. Because of the relatively rough and porous structure of the wood surface, its treatment with liquid

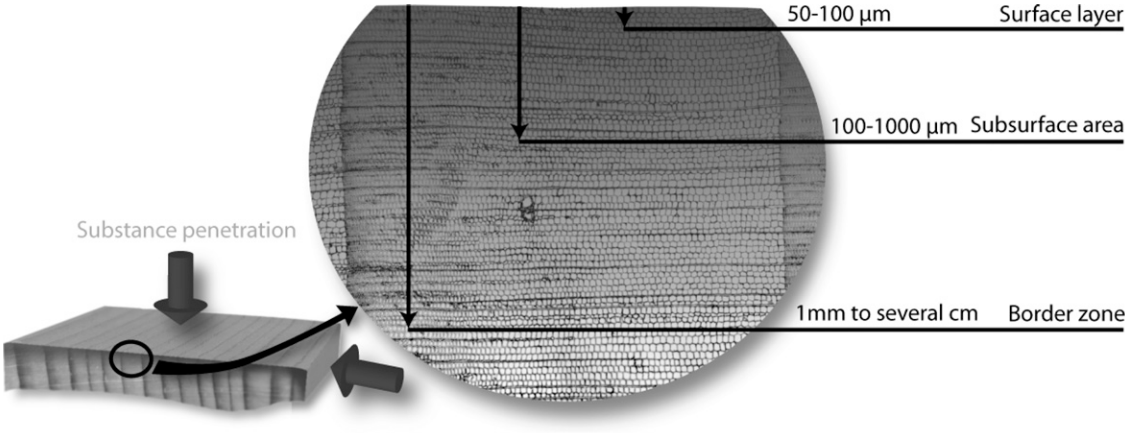

Figure 3. Schema for the differentiation of the wood surface into several zones to obtain a better distinction and description of liquid penetration in radial and tangential directions.

substances typically includes several cell rows in close proximity to the surface area because the substances fill the lumina of truncated cells.

As mentioned previously, penetration depth strongly depends on grain orientation. In practice, however, primarily tangential and/or radial surfaces are exposed to liquid substances. Normally, long pieces of wood are treated, in which those that are primarily transverse sections are comparably small and play a subordinate role for the penetration of liquids into the wood. Considering this aspect, we suggest three different depth zone terms for the radial and tangential orientations.

The term "surface layer" will refer to the zone that extends over approximately 3 – 4 cell rows or a depth of approximately 50 – 100 µm. The zone beyond these first cell rows cannot be regarded as a direct surface and shall be termed "sub-surface area." During brushing or dipping, liquid substances often locally penetrate into this zone—for example, through the ray tracheids and ray parenchyma—which extend to a depth of approximately 100 – 900 µm. For impregnation treatment, higher penetration depths are desired. To define this zone, we propose a third "border zone," which describes the penetration of a wider region to a depth of several millimeters or more. The differentiation of these terms and penetration depths for radial and tangential orientation is illustrated in Fig 3.

Potential Applications for Bioincising

Regarding the proposed terms, in the following, we present selected target applications, in which bioincising could be considered as a pretreatment. Table 1 gives an overview of these applications, including the target of improvement and the required individual penetration depth in the tangential and radial orientations.

Preservative treatment. Treatment of wood with preservatives for protection against wood-destroying microorganisms is regulated or described by national standards (DIN 1990; CSA 1997; EN 2006; EN 2007; AWPA 2008). The standards define a minimum penetration depth for sapwood and/or heartwood depending on the natural durability of the species, its specific susceptibility to preservative treatment, and the conditions in which the wood will be used (use class). However, in practice, complete penetration cannot always be achieved either because of reduced uptake by refractory wood species or for reasons of economy. Commercial processes for effective preservative treatments have been developed. Most methods permit high penetration depths with homogenous distribution of the

Table 1. *Wood preservation and wood modification treatments according to the required penetration depth of the applied substance in tangential and radial orientation.*

Targeted effect	Desired penetration depth	Recommended application method
Wood preservation	Complete penetration or at least border zone following certain standards (eg EN_335_1; EN_351_2)	Impregnation
Dimension stability	Complete penetration or at least border zone	Impregnation
Flame resistance with foam-forming systems	Surface layer and subsurface area	Brushing, dipping
Flame resistance salt solutions	Subsurface area to border zone	Dipping, Impregnation
Hardness	Subsurface area to border zone	Dipping, Impregnation
UV protection	Surface layer and subsurface area	Brushing, dipping
Hydrophobation: liquid water	Surface layer and subsurface area	Brushing, dipping
Hydrophobation: water vapor	Complete penetration or at least border zone	Impregnation

preservative but require expensive industrial facilities and high energy input.

Among these methods, vacuum and pressure impregnation techniques provide the best results. Nevertheless, mechanical drilling or incising is often required for refractory wood species. Hence, the pretreatment of wood with the bioincising technology could be an interesting alternative in this field to facilitate the impregnation process, to gain higher loading rates, and to obtain deeper penetration in refractory wood species.

Dimension stability. An improvement of thedimensional stability of wood is performed by blocking, reducing, or crosslinking of hydroxyl groups (Hill 2006). For this purpose, a wide range of substances and techniques has been developed, eg furfurylation, acetylation, dimethyloldihydroxyethyleneurea, (methylated) melamine-formaldehyde, and thermal modification. With the exception of thermal modification, the techniques use liquid substances that are impregnated. In untreated zones of the wood, the targeted effects are often irregularly realized, and local swelling and shrinking occur, resulting in internal strains and irregular deformation of the wood. Hence, the aim should be a complete and homogenous penetration of liquid modification substances in the required depth of the wood material.

Fire retardance. Fire protection for wood basically follows two principal systems. On the one hand, foam systems are mostly applied as coatings on the exposed wood surfaces. Under the influence of rising temperatures, these systems undergo a sequence of film softening, expansion, and setting of a rigid foam, which ideally traps inert gases and develops good adhesion to the surface. The temperature rise in wood is reduced and the time to ignition is prolonged as well as the depth of charring. For this type of treatment, no or only slight penetration of the substance into the wood surface is necessary. Consequently, these substances can be applied by brushing, dipping, or spraying.

On the other hand, fire-retardant salt solutions are applied by impregnation deeper into the wood. While surface coatings lose their efficiency when the protection layer has been physically destroyed, deep impregnation systems continue to control charring rate and flame formation over an extended period of severe fire impact. Similar to wood preservatives, the effect depends strongly on a deep and homogenous penetration of the flame retardants into the wood.

Although wood is a highly combustible material, the low thermal conductivity and insulating effect of the generated char provide the material with good properties for exposure to fire. The dimensional losses resulting from charring are taken into consideration for the design of wood elements in buildings to guarantee a certain time of service under the impact of fire. In contrast to wood protection or dimension stability, complete penetration of wooden construction units with fire retardants may not be required.

Hardness. For the improvement of surface hardness, full penetration is apparently not necessary. Gindl et al (2004) performed a melamine–formaldehyde (MF) resin treatment of Norway spruce wood and found that a penetration of 2 – 4 mm suffices for an optimal increase in surface hardness. However, satisfactory penetration was achieved only after a 3-da solvent-exchange immersion in liquid MF solution for diffusion of the substance into the wood cell walls. Vacuum treatment was not useful because of pit aspiration. Because a penetration of only a few millimeters is sufficient for a significant improvement of hardness, a full impregnation process does not appear to be necessary. However, species with a lower density will require a deeper penetration of hardness-improving substances than species with a higher density.

UV and visible light protection. The depth of light penetration into the wood surface and, with it, the region of possible photodegradation depends on the density of the specific wood species and on wavelength of the light. Denser wood is penetrated less by UV radiation. Moreover, light with shorter wavelengths penetrates wood less deeply. For UV light, penetration depths of 75 μm have been reported, whereas visible light reaches depths of 200 μm (Rowell 2005). If the impact of weathering effects such as humidity and temperature changes are considered, the maximum depth of photodegradation is approximately 750 – 900 μm. Therefore, the application of UV-protection substances by brushing or dipping into the surface layer and subsurface area might be sufficient for efficient protection against photodegradation.

Hydrophobation. The reduction of surface wettability is a central issue in weathering stabilization for wood in exterior uses. Hydrophobation of the surface can be performed by treatment of the wood surface with paraffins, waxes, oils, silane, siloxane, or silicone polymers. Capillarity is reduced by blocking penetration pathways such as tracheids, ray cells, and pits. Such treatments result in an increase in the contact angle for water (a change in surface tension), inducing a phenomenon also known as the Lotus effect (Donath et al 2006). Unfortunately, these surface treatments do not reduce the EMC, because no chemical modification of the cell wall is achieved (Mai et al 2007).

As in the case of UV and visible light protection, the improvement of permeability in the surface layer and subsurface area should be sufficient to improve the placement and distribution of hydrophobation substances for liquid water. The possible formation of cracks during weathering and the resulting opening of the protected wood surface to liquid water might indicate the need for deeper penetration.

Protection against water vapor and consequently long-term changes in EMC are much more difficult if film-forming finishes are not applied. As in the case of dimension stability, a full or at least a border zone penetration with hydrophobation substances would then be necessary.

CONCLUSIONS AND OUTLOOK

In the present article, we briefly summarize anatomical mechanisms responsible for the liquid flow in softwoods and review techniques for an improvement of permeability in refractory softwood species. A recent approach is aimed at a selective permeability improvement of Norway spruce by means of fungal pretreatment (bioincising). By applying bioincising under controlled conditions, liquid permeability of refractory wood species might be improved at defined depths. The examples given for current wood property improvement technologies showed different requirements of substance penetration into the wood at specific levels of depth.

Within the fields of application discussed, bioincising could be a method to promote the efficiency of the desired property improvement.

The adaptation of the new process to these requirements would help to reduce the technological efforts for the subsequent treatment with modification substances. However, at present, the bioincising process is still in the process of optimization and not yet adapted to industrial applications. We are aware that an application of bioincising at the industrial scale will not be feasible until the biotechnological control of fungal activity permits a homogenous and controlled permeability improvement in the wood substrate. Especially for heartwood, fungal activity has to be intensified and more homogeneous. Undesired side effects of fungal growth must be minimized and a feasible way for the technical application developed.

The aspects presented demonstrate the potential of bioincising, but do not yet represent the latest state of development, because the optimization of the bioincising process is still in progress. Hence, additional work in this field must be carried out. A better understanding of wood–fungal interactions and of the resulting effects of bioincising on wood permeability will ultimately help improve the treatability of refractory wood species.

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