Liquid water absorption in wood cladding boards and log sections with and without surface treatment

Vannopptak i kledningsbord og laftestokker med og uten overflatebehandling

Philosophiae Doctor (PhD) Thesis

Mari Sand Sivertsen

Dept. of Ecology and Natural Resource Management
Norwegian University of Life Sciences

Ås 2010

Thesis number 2010:6
ISSN 1503-1667
ISBN 978-82-575-0918-7

Supervisors:

Professor Birger Eikenes
Norwegian University of Life Sciences
Department of Ecology and Natural Resource Management

Professor Halvor Solheim
Norwegian Forest and Landscape Institute /
Norwegian University of Life Sciences
Department of Ecology and Natural Resource Management

Preface

This thesis is submitted as one of the requirements for the degree of Philosophiae Doctor at the Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management. The work has been carried out as part of the project “Protection of wood in exterior cladding and timber walls”, which has been funded by the Norwegian Research Council. These two institutions are gratefully acknowledged for contributing to making the work presented in this thesis possible.

Prof. Birger Eikenes and Prof. Halvor Solheim have been my supervisors, and they have offered valuable comments and discussions during the writing process. Prof. Knut Einar Larsen was an inspiring supervisor in the initial phase of the work. Ass. Prof. Olav Høibø and Ass. Prof. Geir Vestøl have provided valuable help during the planning and execution of the experiments, and have been enthusiastic guides in the worlds of wood physics and statistics. Without them this thesis would never have seen the light of day. Dr. Per Otto Flæte, Treteknisk, has been a valuable discussion partner and co-author. Engineer Bjørn Slette has provided practical solutions to all the obstacles on the way from idea to experiment. Dr. Gry Alfredsen and Dr. Lone Ross Gobakken have been valuable discussion partners, sources of inspiration and shining examples, making me believe that crossing the finish line was actually possible.

I would like to thank Mycoteam AS for providing a haven for me when my funding threatened to run out, and showing me the real world of biological damages on wood and other construction materials in service. I would also like to thank the Norwegian Forest and Landscape Institute for hosting me while the Sørhellinga building was renovated. I am grateful to good colleagues at the Norwegian University of Life Sciences, Mycoteam AS, and the Norwegian Forest and Landscape Institute, for inspiration and support – and a lot of good laughs on the way. I am also grateful to the board, administration and members of the Norwegian Women in Forestry for support and inspiration.

I wish to thank Maia and Amund for being the most wonderful children, and the rest of my family and friends for always being there. Special thanks are due to my father for reading and commenting on the thesis manuscript.

Thank you, Torstein, for holding the life in our family together during these last months. You’re my knight in shining armour.

Ås, January 2010

Mari Sand Sivertsen

Summary

Water absorption in wood in service is of great importance both because of the resulting dimensional changes of the wood and because of the risk of deterioration by microorganisms at wood moisture content levels above 20 %. Due to the strong position of wood as a constructional material in Norway, wood–water relationships are of major commercial importance. The effects of different surface treatments on water absorption in wood have been extensively studied, but the effects of wood with different properties in combination with different coatings are not as well documented. The main objective of this study was to investigate the effects of surface treatments and wood properties on liquid water absorption in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst). Scots pine log sections and cladding boards of both species have been subjected to study, as well as small decay test specimens in Scots pine and *Robinia pseodoaccacia*. In the process, different methods for analysis have been evaluated and the mechanisms behind water absorption, particularly in Norway spruce wood, have been studied.

A procedure in accordance with a European standard but with substantially prolonged exposure times was used for liquid water exposure of cladding specimens, while a spraying rig was used for cyclic wetting and drying of log sections. An unforeseen fungal attack on several of the Scots pine log sections posed some challenges in the design of the log section experiment and interpretation of the results. On the other hand, it gave the opportunity to study the effect of incipient decay on liquid water uptake compared to effects of coatings and crack orientation. It also facilitated a test of an ultrasonic measurement apparatus for dynamic modulus of elasticity (MOE) on detection of incipient decay in specimens of large dimensions.

The weight of the specimens was recorded regularly during the experiments, and modelling of the resulting curves was done in order to describe the moisture absorption and/or desorption in each specimen. The emphasis was on finding models that both gave close fits to the data and generated parameters that were few in number and easy to interpret. The development of water absorption in Scots pine log sections during cyclic wetting and drying was studied using a mechanistic growth model. The model did not fit perfectly to the data, both due to the way the measurements were done and to the nature of water uptake in partly uncoated wood. Two parameters derived from the model were useful in evaluating the effect of surface coatings, incipient decay and crack directions. Liquid water absorption in uncoated Norway spruce cladding specimens was modelled in two distinct phases, one governed by both diffusion and capillary flow and one governed by capillary flow alone. This was shown to describe the absorption in uncoated Norway spruce specimens satisfactorily. The parameters derived from the models (apparent diffusion coefficient and rate of void filling degree) were found useful in evaluating the effects of wood properties.

If the relative performance of combinations of surface treatments and wood substrates with different properties are of interest, rather than analytical evaluation of the physical processes involved in water absorption, analyses of single measurements of the amount of absorbed water were shown to give sufficient information. The resulting moisture content was shown to give valuable information regarding the performance of the different wood types. The European standard procedure evaluated in this part of the study can be used to evaluate the combined effect of wood substrates and coatings, provided that the exposure time is prolonged.

The permeability to water was higher in waterborne than in solvent-borne coating during wetting of cladding specimens. Regarding Scots pine log specimens, wood tar caused less accumulation of water than film-forming coatings did. Upwards-facing cracks caused faster absorption than downwards-facing cracks, but surface treatment had a larger effect than crack orientation. Incipient decay caused substantially increased water absorption, overriding both surface treatments and crack orientation. Ultrasonic dynamic MOE measurements were found to give valuable information regarding early decay detection, both in log section specimens and in small decay test specimens. Moisture conditions and temperature have to be taken into consideration in experimental planning if this measurement method is to be used. Transversal measurements on Scots pine log sections were not successful, possibly because of the mode of action of the decay fungus in question.

Wood properties were shown to affect liquid water absorption both in coated and in uncoated cladding specimens. In coated specimens, the effect of differences between slow-grown and fast-grown Norway spruce was not statistically significant after short-term exposure (72 hours) but was very important after long-term exposure (4 weeks or more). Coated cladding specimens of slow-grown spruce absorbed larger amounts of water than those of fast-grown spruce, but this did not cause correspondingly larger moisture contents. When Scots pine heartwood was included the effect of wood type could be seen already after 72 hours. In uncoated Norway spruce larger effects of wood properties were found on capillary flow than on apparent diffusion, and heartwood proportion had larger effect than density. No effect from annual ring width was found, but origin (growth site) had significant effect when wood properties were accounted for. Thus, the good reputation slow-grown Norway spruce has as a cladding material is probably more due to large heartwood content than to high density or narrow annual rings.

Sammendrag

Forståelse av vannopptak i tre i brukssituasjoner er svært viktig, både fordi vannopptak forårsaker dimensjonsforandringer og på grunn av risikoen for mikrobiell nedbrytning ved fuktinnhold i veden på over 20 %. Tre har en sterk posisjon som konstruksjonsmateriale i Norge, og problemstillinger knyttet til vann i ved er dermed kommersielt viktige. Effekter av ulike overflatebehandlinger på vannopptak i kledningsvirke har vært gjenstand for omfattende undersøkelser, men effekter av ulike virkesegenskaper i kombinasjon med ulike overflatebehandlinger er ikke like godt dokumentert. Hovedproblemstillingen i denne studien har vært å undersøke effekter av ulike overflatebehandlinger og virkesegenskaper på vannopptak i furu (*Pinus sylvestris* L.) og gran (*Picea abies* (L.) Karst). Materialet har bestått av prøver av kledningsbord i gran og kjerneved av furu, samt seksjoner av laftestokker i furu og små prøver fra en råtesopptest i furu og *Robinia pseudoaccacia*.

En framgangsmåte for testing av opptak av flytende vann i henhold til en europeisk standard ble brukt på kledningsprøvene, men med sterkt forlenget eksponeringstid. Laftestokkseksjonene ble utsatt for syklisk oppfukting og nedtørking ved hjelp av flyttbare stativer og et dysearrangement. Et uforutsett råtesoppangrep på flere av laftestokkseksjonene bød på enkelte utfordringer i utformingen av forsøket og tolkningen av resultatene. På den annen side ga det muligheten til å undersøke effekten av et begynnende råtesoppangrep på vannopptaket, sammenlignet med effektene av overflatebehandling og sprekkretning. Det ga også anledning til å teste et ultralydapparat for måling av dynamisk elastisitetsmodul (E-modul) i detektering av begynnende råte på treprøver med store dimensjoner.

Vekten av prøvene ble målt regelmessig i løpet av hvert eksperiment, og det ble laget kurver som beskrev fuktopptaket i hver prøve. Modelltilpasning til disse kurvene ble gjort for å kunne beskrive fuktopptaket ved hjelp av få, lett tolkbare parametre. Fuktutviklingen i laftestokkseksjoner av furu under syklisk oppfukting og nedtørking ble studert ved hjelp av en mekanistisk vekstmodell. Modellen ga ikke perfekte tilpasninger til dataene, både på grunn av måten målingene ble gjort på og på grunn av mekanismene bak vannopptak i delvis ubehandlet tre. To parametre utvunnet fra modellen var nyttige i evalueringen av effektene av overflatebehandling, sprekkretning og et begynnende råtesoppangrep. Opptak av flytende vann i ubehandlete kledningsprøver av gran ble modellert i to separate faser, én styrt av både diffusjon og kapillærstrøm og én styrt kun av kapillærstrøm. Dette ble vist å beskrive opptaket i ubehandlete granprøver på en tilfredsstillende måte. Parametrene som ble utvunnet fra modellene (den tilsynelatende diffusjonskoeffisienten og raten til porefyllingsgraden) ble funnet nyttige i evalueringen av effektene av ulike virkesegenskaper.

Analyse av enkeltmålinger ble vist å gi tilstrekkelig informasjon dersom det er den innbyrdes rangeringen av ulike kombinasjoner av overflatebehandling og substrater med ulike virkesegenskaper man ønsker å undersøke, snarere enn å foreta en analytisk evaluering av de fysiske prosessene involvert i vannopptaket. Fuktinnholdet gitt av vannopptaket i den enkelte prøve ble vist å gi verdifull informasjon om oppførselen til ulike virkestyper. Med forlenget eksponeringstid kan den europeiske standardprosedyren som ble vurdert i denne delen av studien med fordel benyttes til å evaluere den kombinerte effekten av overflatebehandling og virkesegenskaper.

Vannløst maling hadde høyere permeabilitet for flytende vann enn løsemiddelløst maling under oppfukting av kledningsprøver. Tretjære ga mindre akkumulering av vann enn filmdannende maling under syklisk oppfukting og nedtørking av laftestokkseksjoner. En stor sprekk orientert oppover ga raskere vannopptak enn én stor sprekk orientert nedover, men overflatebehandling hadde større effekt enn sprekkretning. Et begynnende råtesoppangrep ga svært mye større vannopptak, og overstyrte både overflatebehandling og sprekkretning. Måling av dynamisk E-modul med ultralydapparat ble vist å kunne detektere begynnende råtesoppangrep, både på laftestokkseksjoner og på små prøver til råtetesting. Fuktinnhold og temperatur må tas med i betraktningen ved bruk av denne målemetoden. E-modulmåling i tverretning på laftestokkseksjonene fungerte ikke, muligens på grunn av hvordan den aktuelle råtesoppen bryter ned trevirket.

Virkesegenskaper ble vist å ha effekt på vannopptak både i overflatebehandlete og ubehandlete kledningsprøver. Effekten av forskjeller mellom hurtigvokst og seinvokst gran var ikke statistisk signifikant i overflatebehandlete prøver etter kort eksponering (72 timer), men var svært viktig etter lengre eksponering (fire uker eller mer). Overflatebehandlete prøver av seinvokst gran tok opp større mengder vann enn prøver av hurtigvokst gran, men fuktinnholdet ble allikevel høyest i hurtigvokst gran. Når prøver av furukjerneved ble tatt med i betraktningen, kunne effekten av virkestype sees allerede etter 72 timer. I ubehandlet gran ble det funnet større effekt av virkesegenskaper i fasen med ren kapillærstrøm enn i fasen med ”tilsynelatende diffusjon”, og kjernevedinnhold var viktigere for vannopptaket enn densitet. Det ble ikke funnet noen effekt av årringbredde, men opphav (voksested) hadde signifikant effekt selv om det var tatt høyde for virkesegenskaper. Dermed kan kjernevedinnhold være viktigere for det gode omdømmet til seinvokst gran som kledningsmateriale enn høy densitet eller smale årringer.

List of papers

I. Sivertsen, M. S., Høibø, O. H. and Eikenes, B. (2009): Water sorption in coated Scots pine (*Pinus sylvestris* L.) logs and influence from incipient decay. Wood Material Science and Engineering, 4:3, 167–179

II. Sivertsen, M. S., Alfredsen, G. and Westin, M. (2009): Ultrasound – a feasible tool for decay detection? *In* Proceedings of the 5th meeting of the Nordic-Baltic Network in Wood Material Science and Engineering (WSE). Copenhagen, Denmark, October 1–2.

III. Sivertsen, M. S. and Flæte, P. O. (2009): Water uptake in coated wood. Part 1: Analysis of different evaluation approaches. Submitted to Holz als Roh- und Werkstoff.

IV. Sivertsen, M. S. and Flæte, P. O. (2009): Water uptake in coated wood. Part 2: Influence of different wood types and coatings. Submitted to Holz als Roh- und Werkstoff.

V. Sivertsen, M. S. and Vestøl, G. (2009): Liquid water absorption in uncoated Norway spruce claddings as affected by origin and wood properties. Submitted to Wood Material Science and Engineering.

Contents

1. Introduction

Wood is a remarkable material. Despite the fact that it is a tissue developed by evolution to provide support and conduction systems in a living organism, it has proven useful to humans in countless utilisations. Wood has numerous advantages for use in constructions; it has a high strength-to-mass ratio, it is easily shaped and adjusted at the building site, it provides more insulation than concrete, bricks, or metal (Panshin and De Zeeuw 1980), and it is environmentally friendly compared to alternative materials (Petersen and Solberg 2005). However, its biological origin causes disadvantages as well.

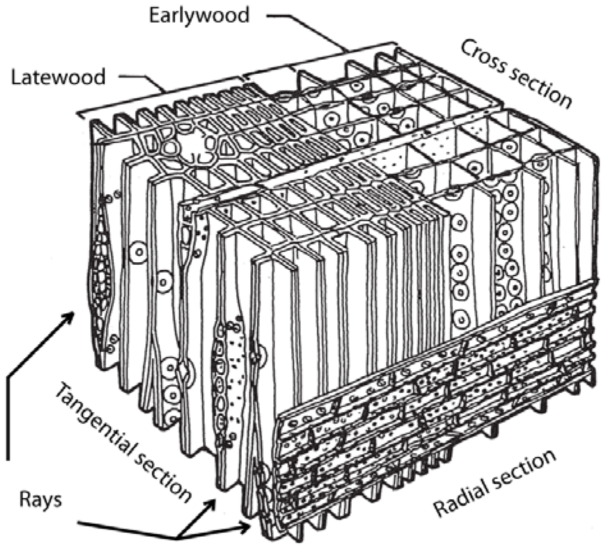

Figure 1. The microscopic structure of Norway spruce wood, showing early- and latewood tracheids, bordered pits between tracheids, and rays. The foremost ray features ray tracheids with bordered pits in its upper and bottom row. Reproduced from Stemsrud (1989).

Wood tissue is constituted by numerous longitudinally oriented cells. Coniferous wood consists almost exclusively of tracheids (Kollmann and Cöté 1968); long cells in which the lumens are encircled by walls composed of microfibrils, which are bundles of micelles (crystalline matrices of cellulose strings). The microfibrils are mainly oriented at a small angle to the longitudinal axis of the tracheid, and are surrounded by an amorphous lignin and hemicellulose matrix. This structure makes the mechanical and physical properties of wood fibres differ greatly in the longitudinal and transversal directions. Trees grow by adding new external tissue layers each growing season, making the cross section of a tree stem consist of concentric rings (annual rings in temperate zones). The tracheids generated in the beginning of the growing season (earlywood tracheids) have thinner walls and larger lumens than latewood tracheids, which are generated near the end of the growing season (Figure 1). Pits in the cell walls facilitate transport of liquids from cell to cell, and the pits between tracheids are of the bordered pit type. Bordered pits consist of a pit chamber and a membrane consisting of cellulose strands, which in many coniferous species has a central thickening called the torus (Figure 2). In the sapwood of the living tree, the torus is in a mid-position and liquid can pass easily through the margo. If gas enters one cell, for instance during drying of the wood, the retreating water menisci force the torus to the wet side of the pit chamber and the torus seals the pit shut. This process is called aspiration.

In order to facilitate radial transport the tree stem has bands of cells oriented perpendicularly to the longitudinal cells in the radial direction, i.e. rays (Figure 1). This causes differences in properties between the tangential and radial directions as well. As a result of the structure of wood any divergence in grain angle, i.e. the angle of the tracheids relative to the longitudinal axis of the tree stem, causes large divergences regarding mechanical strength, moisture conductivity and other properties.

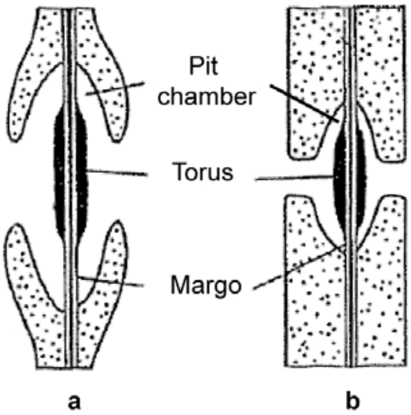

Figure 2. Bordered pits between tracheids in coniferous trees. A bordered pit between two earlywood tracheids is shown in a and one between two latewood tracheids in b. Adapted from Wagenführ (1999).

Wood is hygroscopic, which combined with the construction principle of the fibres causes it to shrink and swell with variations in moisture conditions. During water absorption, water molecules are sorbed to hydroxyl groups in amorphous regions of the cellulose micelles and in submicroscopic spaces in the cell wall, forcing the micelles further apart (Figure 3). As a result of the anisotropy of wood the dimensional variations occur almost exclusively in transversal directions, and more in the tangential than in the radial direction. If given the chance wood will also absorb water and other liquids by capillary action of the cell lumens, as the tissue of the wood stem is essentially a sap conduction system.

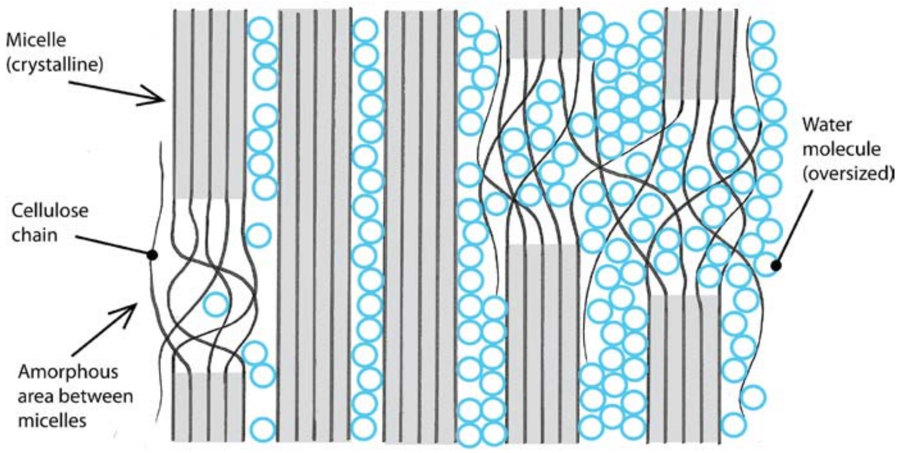

Figure 3. Schematic illustration of water sorption (wetting from right to left) between micelles and within amorphous regions between micelles in a microfibril, disregarding other wood constituents. The micelles are forced further apart when water molecules are absorbed between them.

If the moisture conditions become favourable to microorganisms, wood is susceptible to deterioration. If the wood is seen as a part of an ecosystem this is an advantageous feature, but with respect to wood as forming part of a construction it is not as advantageous. Water serves wood-degrading fungi as a reactant in hydrolysis, as a diffusion medium for enzymes and solubilised substrate molecules, as a solvent or medium for life systems and as a wood-capillary swelling agent for entry into the wood cell walls (Zabel and Morrell 1992). Decay fungi are dependent on free water within the wood structure for effective growth, while mould fungi can grow on wood superficially wetted by high relative humidity. The other main requirements for survival and growth are oxygen and favourable temperature (Zabel and Morrell 1992) (Figure 4).

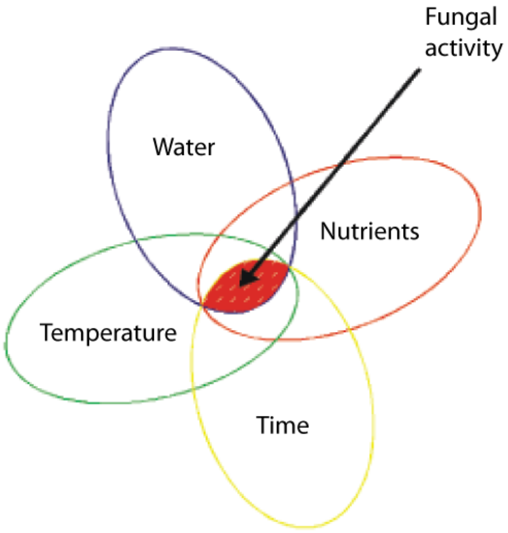

Figure 4. Illustration of the main ecological requirements of fungi. Provided that temperature and moisture conditions are favourable during a long enough period of time, the available nutrients can be utilised by fungi. Illustration by Johan Mattsson (Mycoteam AS), reproduced with permission.

Because of the importance of water content for wood properties and microbial degradation wood–water relations have been given extensive study. The textbooks “Transport processes in wood” (Siau 1984) and “Wood and cellulose science” (Stamm 1964) give a good introduction to the subject.

1.1 Wood as a construction material

Wood has traditionally been the dominating construction material in Norway, and its position is still very strong. Wooden houses constitute a larger part of the building stock in Norway than in any other country besides USA and Canada, and in residential areas houses built from other materials are few. In 1997, 98 % of new smaller-sized domestic houses in Norway had load-carrying constructions of wood (Edvardsen et al. 1997). In addition industrial and office buildings less than three storeys high are often built from wood, and houses with other constructional materials are often given wooden cladding. As long as the demands regarding fire resistance are met there are no restrictions on the use of wooden claddings on multi-storey buildings in Norway (KRD/MD 1997).

Norway spruce (Picea abies (L.) Karst) wood is the most common exterior cladding material on Norwegian domestic houses (Øvrum 2002). Although Norway spruce is classified as “less durable” according to the European standard EN 350-2 (CEN 1994), wooden houses more than 150 years old made from spruce wood exist in Norway (Raknes 1996). Of the annually harvested wood volume in Norway, spruce constitutes the largest and Scots pine (Pinus sylvestris L.) the second largest portion (Vennesland et al. 2006). As pine heartwood is in a higher durability class than spruce it could be expected to be the preferred cladding material. Pine sapwood, however, is much more permeable to liquid water than spruce (Siau 1984) and even more easily degradable (CEN 1994). As the sawing patterns used in most Norwegian sawmills tend to produce boards with a mixture of heartwood and sapwood (Flæte and Høibø 2009), pure Scots pine heartwood is not readily available. Combined with its good performance as exterior cladding this makes spruce the preferred material.

The log house was the most common construction type in central parts of Norway from the medieval age until other, less wood-consuming construction techniques took over during the 19th century (Drange et al. 2000). The tradition has been kept active and the technique has had a renaissance since the middle of the 1990s, mainly for cabins but also for domestic houses. A log house is constructed by placing logs horizontally on top of each other and joining them in the corners by carving notches (Figure 5). The performance of the walls regarding insulation and draught is to a large extent determined by the quality of the joining and the fitting of each log to the one underneath it (Edvardsen et al. 1997). In this type of construction the logs both carry the loads and form the outer shell of the building. Compared to the wooden framework with inorganic insulation and sealing materials normally used in modern Norwegian residential houses, log houses have been shown to have some advantages regarding environmental impact (Fossdal and Edvardsen 1995). If exposed to prevailing heavy precipitation, massive logs can be susceptible to decay. The norm developed by the

Norwegian log house builders' association states that log houses should not be built where the exposure to heavy rain is "unacceptably large" (NorskLaft and Treteknisk 2009). Log houses are often left untreated, but some are given an exterior coating. This has been found to give undesired consequences regarding moisture uptake and accumulation in a number of cases (Kolbjørn Mohn Jenssen, pers. comm.).

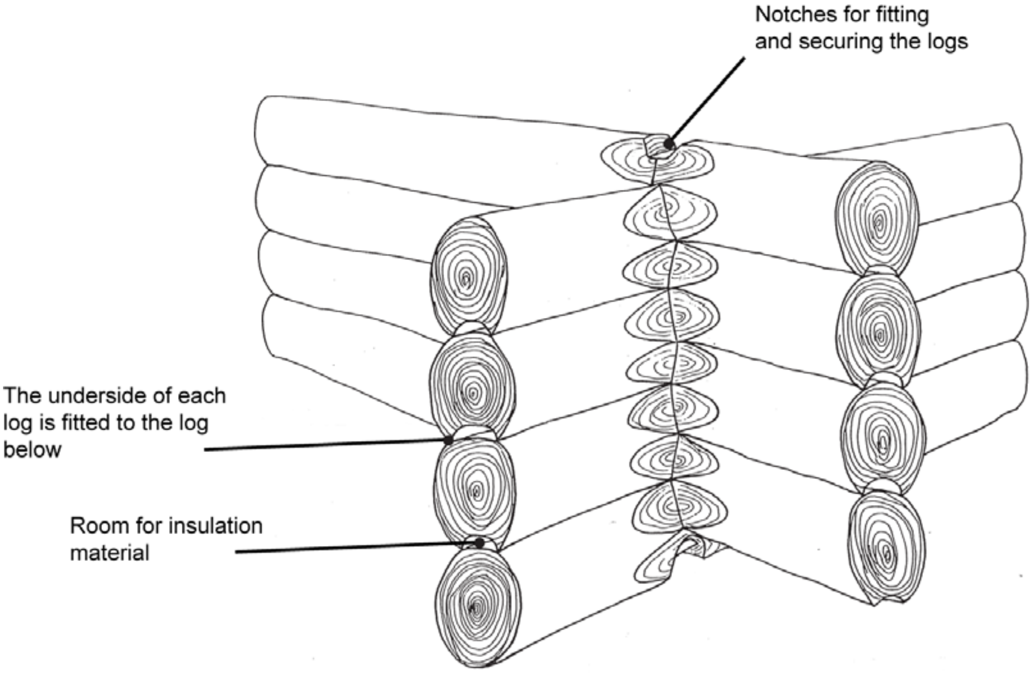

Figure 5. Illustration of the main construction principle in a log house. Round logs are joined in the corners by means of notches on the upper side and underside of each log. Adapted from Hauge (1994).

Wood decay has been recognised as a problem at least since Roman times, when various treatments were used to prevent it (Plinius Secundus ~A.D. 77). During the 1980s extensive decay damages occurred on coated wooden claddings. This heightened the awareness of the public and the coating and wood industries with respect to the topic of microbial deterioration of coated claddings and log house walls. In the wake of these damages the link between surface treatment and water transport into and within wood was studied by numerous authors (eg Ekstedt 1992; Hjort 1989; Jenssen 1989). The fact that dry wood does not rot is common knowledge, but the use of wood in exterior applications inevitably entails occasional exposure to high relative humidity and liquid water. Moisture content is one of the main factors affecting the service life of wood (Brischke et al. 2006), and it is crucial for the germination and growth of decay fungi (Viitanen and Ritschkoff 1991a).

1.2 Water transport in wood exposed to liquid water.

In a living tree the wood contains free water, as every living plant cell must be continually bathed in sap. The transport of water from the root to the leaves in even the tallest of trees is a great achievement made possible by their vascular system, without which the leaves "... could not possibly carry on their marvellous chemical synthesis in manufacturing sugar from the defunct CO2 atoms [sic] and H2O, giving back the O and restoring its pristine potential energy by the separation of the C from the O so that animal life can become possible by uniting these again in the breath of life" (Tiemann 1944). In trees the water conducting ability of the vascular system is pushed to its limits, and it is of vital importance to the tree to keep the water columns from the root tissue to the leaves intact. In order to achieve this, coniferous trees have developed a safety valve system; the ability of the bordered pits to aspirate and prevent movement of gas from one tracheid to another (Choat et al. 2008). As the tree increases in diameter it no longer requires the entire cross section to participate in the transport. The inner parts are retired from service and turned from sapwood (conducting wood) into heartwood. Parenchyma cells die, earlywood bordered pits are aspirated, and the wood is often encrusted by extractives, effectively closing off the remaining open pits (Taylor et al. 2002). Thus, in coniferous trees the heartwood is a lot drier than the sapwood.

Water in wood occurs in three forms; water molecules bound to sorption sites in the cell wall (bound water), water vapour in the cell lumens, and liquid water within the cell lumens (free water). In wood exposed to air with stable relative humidity (RH) the RH in the air inside the wood will eventually become the same as in the air surrounding the wood due to water vapour diffusion. Water molecules in the air will be adsorbed to available sorption sites, while bound water molecules will be desorbed into the air. After a period of time the adsorption and desorption will reach a balance point where they are of the same magnitude, and the moisture content (the difference between the weight of the wood and the absolute dry weight, usually expressed in percentages) in the wood becomes stable. This moisture content is designated the equilibrium moisture content (EMC) with the relative humidity in question (Siau 1984). In wood containing free water, the mechanical properties and dimensions of the wood are stable. As the wood dries free water is removed from the lumens, leaving only the bound water in the cell walls. As bound water starts to leave the cell walls, the dimensions and mechanical properties start changing. The theoretical point where all free water is removed but the cell walls are still saturated was designated the fibre saturation point (FSP) by Tiemann (1906), and thus the FSP is a measure of how much water the cell walls in a piece of wood can potentially absorb. During desorption some bound water is lost at moisture contents above the FSP as well (Almeida and Hernández 2007), and the FSP will never be reached simultaneously in an entire piece of wood. The true FSP can only be found by extrapolation on curves for mechanical properties or shrinkage (Kelsey 1956).

When the moisture content in wood is below the FSP, the water transport is a process of diffusion of bound water in the cell walls and water vapour in the lumens (Siau 1984). Diffusion as a physical phenomenon is defined as flow of molecules under the influence of a concentration gradient, and it is governed by Fick's second law (Siau 1984). Studies regarding sorption in wood under hygroscopic conditions have been based upon two assumptions; that the moisture transfer is governed by Fick's law and that the bound water in the wood is at all times in equilibrium with the water vapour in the wood, making the moisture content a unique function of the corresponding relative humidity as given by the sorption isotherm (Krabbenhoft and Damkilde 2004). Moisture sorption in wood has been shown to differ from such true Fickian behaviour, especially when the relative humidity is high (Wadsö 1994). Nonetheless, formulas derived from Fick's second law have proven useful in analytical studies of water sorption in wood below FSP (Comstock 1963; Ekstedt 2002; Simpson and Liu 1991) and as a constituent in numerical studies of water transport both above and below FSP (de Meijer and Militz 2000; Elkouali and Vergnaud 1991; Hukka 1999). The so-called "inverse method", where computerised optimisation of a function is used to obtain diffusion coefficients, has been shown to yield good fits to observed data (Eriksson et al. 2006; Koc et al. 2003; Olek et al. 2005). A non-equilibrium Fickian model has been proposed, where the equilibrium assumption is abandoned and sorption of bound water and water vapour are considered separately (Krabbenhoft and Damkilde 2004). The model showed promising results when tested on the data from the work by Wadsö (1994), and gives a plausible answer to the problem of non-Fickian diffusion behaviour of wood. The model was further developed by Frandsen et al. (2007).

In wood above FSP the free water present in the cell lumens is transported from cell to cell in a flow process driven by capillary pressure. The transport is in theory governed by Darcy's law for liquid flow (Siau 1984). Formulas derived from this law are widely used in studies of permeability of wood (eg Banks and Levy 1980; Comstock and Cöté 1968; Puritch 1971). The approach based on the assumption that Darcy's law holds has some limitations, as reviewed by Kumar (1981); influence of slip flow is often significant in less permeable species, while turbulent flow can occur in highly permeable wood. Entrapment of air in the wood will affect permeability to liquids under an applied pressure gradient (Kelso et al. 1963), and for the results from studies regarding permeability of wood to be directly comparable the liquid has to be deareated for the results to be valid (Booker and Kininmonth 1978). A recently presented percolation approach to modelling liquid flow in wood has shown promising results (Salin 2006a, b), and was used with success to explain some unexpected results in an experiment regarding liquid water uptake in pine sapwood (Segerholm and Claesson 2008). This method operates on a single-fibre level and requires a large computer capacity.

In wood below FSP exposed to liquid water both diffusion and capillary flow will be present. Each process governs a portion of the transport, depending on temperature and moisture content (Voigt et al. 1940). Studies of water transport in wood have often focused on two practical appliances: Firstly, the mechanisms governing wood drying, where diffusion is of large importance but capillary flow is a factor above FSP (Danvind and Ekevad 2006; Hukka 1999; Rosenkilde and Arfvidsson 1997; Salin 2006a; Wiberg and Moren 1999); and secondly, the impregnation of wood, which is mainly governed by capillary flow (eg Larnoy et al. 2005; Siau 1972; Tesoro et al. 1966; Unligil 1972). Analytical considerations of diffusion in combination with capillary flow during absorption of water in conifer wood are, to this author’s knowledge, only given in a few studies (de Meijer and Militz 2000; Derbyshire and Robson 1999; Elkouali and Vergnaud 1991; Fakhouri et al. 1993; Salin 2008).

1.3 Coating affecting water uptake in wood.

Wood used as exterior cladding is usually given a surface coating, both for aesthetical purposes and because the coating inhibits water uptake (Tiemann 1944). The in-service performance of a coating depends on numerous factors. Both inherent properties of the coating and the microclimate (the critical in-situ conditions) of each construction detail are of importance (Gobakken et al. 2009). The presence of moisture is one of the most important stressing factors controlling the performance of a coating on wood in outdoor exposure (de Meijer 2001).

The development of coatings has been heavily influenced by environmental and workplace-related demands, which has made the manufacturers turn from traditional solvent-borne coatings towards coatings with reduced solvent content or with water as the coating solute (Weiss 1997). The environmental impact of the coating as such should be balanced against its performance in service, as the environmental impact from a piece of coated wooden joinery has been shown to depend on its maintenance demands (Häkkinen et al., cited in de Meijer 2001).

The water uptake in wood can be reduced by a number of measures. The most common measure on exterior cladding is coating, which also gives almost infinite options regarding the aesthetical appearance of the wall. No coating is absolutely vapour-tight. Given the hygroscopic nature of wood, the ultimate amount of water absorbed by the wood if continually exposed to water or moist air will in theory be the same no matter how the wood is coated (Tiemann 1944). In practice, the FSP seems to be the maximum possible moisture content in wood with an intact impermeable coating (Derbyshire and Miller 1997). The task of the coating is primarily to delay the uptake, causing less dimensional change and lessening the risk of microbial deterioration.

Coated wood has been described as a three-component system consisting of wood, coating and the wood-coating interface (Rijckaert et al. 2001). The moisture permeability of the coating film is important for the performance of the system as long as it is intact. Failure of the wood-coating interface often involves blistering and peeling of the paint film (Williams et al. 1990), which in turn leads to exposure of the wood surface. This will cause the moisture dynamics of the wood substrate to increase in importance.

In uncoated wood and wood with a coating that allows the entry of liquid water, both diffusion and capillary flow will contribute to the water uptake (de Meijer and Militz 2000; Virta 2005). This will result in steep moisture gradients in the wood, as the wood close to the exposed surface will reach high moisture contents quickly. In early stages of subsequent drying, water penetration will continue further into the wood (Derbyshire and Robson 1999; Elkouali and Vergnaud 1991). Drying is dependent on water transport to and evaporation from the surface, and the transport through a coating has to happen mainly by diffusion. Thus, drying is a slower process than the combined capillary flow and diffusion process involved in water uptake. The slower drying than wetting of uncoated wood will cause the interior of the wood to remain moist for a prolonged period of time (Derbyshire and Robson 1999), and in a climate with regular wetting periods it could result in retention of water in the wood.

In order to effectively protect wood from high moisture contents a coating should be impermeable to liquid water but highly open to water vapour diffusion. However, some coatings have been shown to be more open to penetration by liquid water than to water vapour. This has been argued to result in a risk of accumulation of water over time when the painted wood is exposed to periodic rainy and dry weather (Holbrow et al. 1972). Cracks in an impermeable film as a result of weathering will cause water uptake to proceed much faster than drying (Ahola 1991). The same can be expected to be the case if a coating of low permeability is applied on wood with the large cracks that usually will be present in log house walls.

Tests of the performance of exterior wood coatings are often done according to the European standard series EN 927. Liquid water uptake according to the standard EN 927-5 is assessed after 72 hours (CEN 2006). Short-term liquid water exposure has not shown differences between wood substrates (Ahola et al. 1999; Virta et al. 2006). In the future, interaction with and adaption to wood substrates should be taken into consideration in the development of coatings (Gobakken 2009; Greystone and Ekstedt 2004). This will require methods that can assess the performance of different combinations of coatings and wood substrates.

1.4 Wood properties that affect water uptake.

Wood properties are important for the performance of wood used on or in exterior walls (Williams et al. 2000; Øvrum 2002). The different mechanisms involved in water uptake in wood are affected by different wood properties. Orientation and width of annual rings, density, heartwood content and grain angle are properties that can be expected to be of significance. Variations in wood properties within the same species are mainly governed by growth conditions (Klem 1934; Nylinder and Hägglund 1954; Wilhelmsson et al. 2002), but genetic variations and spatial position within the tree are of importance as well (Hylen 1997; Molteberg and Høibø 2007). In species with visible heartwood, such as Scots pine, the differences between heartwood and sapwood have long been known to be of great importance, and recent investigations have shown differences regarding water uptake between heartwood and sapwood of Norway spruce as well (Bergström and Blom 2007; Sandberg 2002). This confirms earlier experience with wood chips (Wurz and Swoboda 1947).

Diffusion in wood under hygroscopic conditions is dependent both on the resistance of the cell wall material to bound water sorption and on the resistance in the wood matrix to water vapour diffusion. The principal resistance to moisture diffusion through wood in the transverse direction is offered by the cell wall, as the conductivity of the lumens to water vapour diffusion is much larger than the conductivity of the cell walls to bound water diffusion (Siau 1984) (Figure 6). In the longitudinal direction, the lumens are more important and the only bound sorption paths of importance are walls that have to be crossed in the tapered ends of the tracheids (Siau 1984). As a consequence, density can be expected to have a larger effect on transversal than on longitudinal diffusion in wood. Due to the faster water vapour diffusion compared to diffusion of bound water, longitudinal diffusivity is substantially larger than transversal diffusivity (Krabbenhoft and Damkilde 2004; Siau 1984). Because of this, the grain angle in wood specimens has a large effect on measured diffusion rates (Wengert and Skaar 1978).

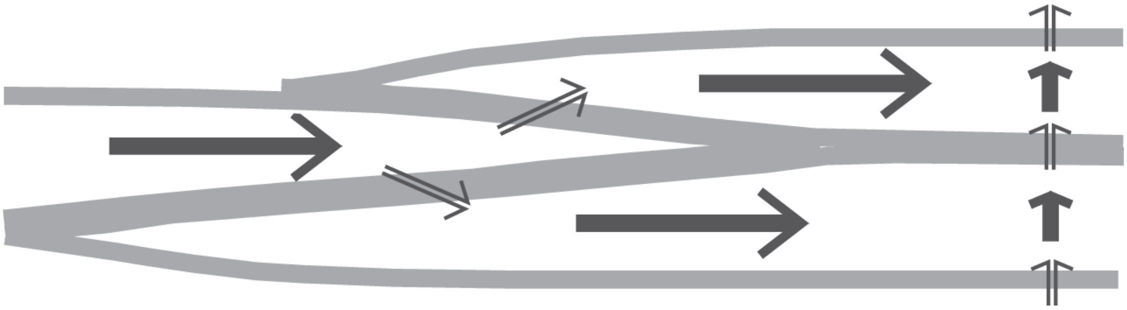

Figure 6. Schematic illustration of the primary paths for diffusion of water vapour (filled arrows) and bound water (outlined arrows) in conifer tracheids. Longitudinal transport paths are shown with long arrows, transversal transport paths with short arrows.

Norway spruce is known to be refractory to impregnation in dry condition. The pore structure between cells in the wood has been shown to be of large importance to capillary transport, both in hardwoods (Almeida and Hernández 2007) and softwoods (Liese and Bauch 1967b). Bordered pits between most softwood tracheids are aspirated when the wood is dried from its original green condition. In the latewood pits have thicker strands, tighter margo texture, smaller diameters, a higher degree of lignification and a denser configuration of the pit chamber than in earlywood. Together with the thicker cell walls giving the torus a greater distance to move in order to aspirate, this causes less aspiration in latewood (Lehringer et al. 2009). Ray tracheid bordered pits in spruce and pine have even smaller pit chambers, and are not aspirated at all (Liese and Bauch 1967a). Relative to Scots pine, which is more easily impregnated, there are fewer unaspirated bordered pits in latewood and fewer ray tracheids in Norway spruce. In addition to rays, bordered pits in the tangential walls of tracheids close to the earlywood–latewood border participate in radial transport in living conifer trees (Kitin et al. 2009). Such pits are studied to a lesser extent than bordered pits in radial walls, but they are reported in Abies alba (Liese and Bauch 1967b) and Cryptomeria japonica (Kitin et al. 2009). The smaller size of and lack of torus-margo structure in these pits entail that they will not aspirate during drying (P. Kitin, pers. comm.). For these reasons, these pits can be expected to participate in radial liquid water transport in sapwood of spruce.

Ray tracheids in latewood are shorter than the ones in earlywood, and series of ray tracheids tend to be interrupted by a ray parenchyma cell at the annual ring boundary (Liese and Bauch 1967a). Thus, a larger number of pits have to be penetrated in latewood than in earlywood, and the flow through series of ray tracheids is interrupted more often (within the same distance) with an increasing number of annual rings. Based on this, a large number of annual rings per transport path length could be expected to have a negative influence on the transport rate regarding radial capillary transport in Norway spruce wood. The effect of annual ring width on longitudinal capillary transport in Norway spruce wood is not straightforward. The permeability is higher in latewood due to the lower proportion of aspirated bordered pits. On the other hand, Salin (2008) stated that the water absorption in Norway spruce and Scots pine will be larger in earlywood although the absorption in latewood is faster, probably due to the larger cell lumens in earlywood.

The effect of extractives in durable heartwood has been argued to consist of a combination of toxicity and influence on moisture dynamics (Brischke et al. 2006; Salin 2008). The heartwood of Norway spruce is not visible in dry condition, and in the standard EN 350-2, “Durability of wood and wood-based materials” (CEN 1994), no distinction between heartwood and sapwood of spruce is made. As the heartwood of spruce does not contain toxic extractives the durability in ground contact is not likely to be very different from sapwood. In out-of-ground applications the exposure does not involve the stable favourable growth conditions for microorganisms provided in ground contact, and the moisture dynamics in the wood are of greater importance. No differences regarding diffusivity have been found between Norway spruce heartwood and sapwood (Bergström and Blom 2007; Tong 1989; Wadsö 1993). Liquid water uptake in heartwood of spruce has been shown to be smaller than in sapwood (Bergström and Blom 2007), especially regarding longitudinal transport (Sandberg 2002). Liese and Bauch (1967a) found that bordered pits in the ray tracheids were heavily encrustated in Norway spruce heartwood, making it even more refractory than the sapwood. No reports have been found regarding whether the encrustation of pits in Norway spruce heartwood also applies to bordered pits in tangential cell walls.

Norwegian forestry practice during the last decades has led to increased increments in Norwegian forests, and large volumes of fast-grown spruce ready for harvesting in coming decades. Slow-grown spruce is often said to be a better cladding material than fast-grown spruce. If true, this would have large implications for the suitability of large spruce volumes as cladding material, and the validity of the notion that slow-grown spruce is superior should be investigated thoroughly.

1.5 Moisture in wood as prerequisite for and consequence of fungal growth

All fungi living on or in wood need sufficient moisture to germinate and grow. Mould fungi are dependent on the moisture on the wood surface and in the ambient air, rather than the moisture content within the wood. As a general rule relative humidity above 85 % gives a high risk of germination and growth of mould on building materials (Mattsson 2004), although slow growth has been found at 80 % RH when temperatures were favourable (Viitanen and Ritschkoff 1991b). Decay fungi grow inside the wood and are dependent on free water within the wood structure, which implies that the wood should be safe from fungal decay at moisture contents below the FSP. In Scots pine heartwood the expected values for the FSP are between 26 and 28 %, while Norway spruce and Scots pine sapwood can be expected to have an FSP from 30 to 34 % (Kollmann and Cötè 1968). FSP of 27 % has been reported for Norway spruce wood, however (Rijsdijk and Laming 1994). In practice wood will often be exposed to varying moisture conditions, which will result in moisture gradients within the wood. Consequently, although the average moisture content in a piece of wood is below the FSP portions of the piece may be above this level. Hence, a prudent limit of 20 % average MC is often used as the value below which the wood is safe from fungal decay (Zabel and Morrell 1992).

Moisture content variation in wood below its fibre saturation point causes dimensional changes. In wood frequently exposed to wetting by liquid water followed by drying, the steep resulting moisture gradients will cause cracks in the surface layers (Panshin and De Zeeuw 1980; Virta 2005), which can be points of entry for microorganisms. In round timber dried from green condition the anisotropic nature of wood will cause cracking along the grain. In logs used in log house walls experience has shown that decay often starts in the vicinity of large cracks (Bøhlerengen and Mattsson 1995).

An attack by mould or decay fungi can affect the way in which wood reacts to water exposure. A number of mould and blue stain fungi have the ability to degrade cellulose but not lignin, and can thus remove the pit tori which mainly consist of cellulose and pectins (Eaton and Hale 1993). Decay fungi are able to penetrate cell walls, but during colonisation they will initially utilise pits as these are easier to penetrate. In the process the membranes in aspirated bordered pits will be degraded by the fungus (Lehringer et al. 2009), opening the pits to water as well as other microorganisms. Thus the permeability of the wood will be heavily affected at an incipient stage where mechanical properties are only slightly affected. In addition to affecting the permeability of wood, some decay fungi are able to wet the wood by releasing metabolic water (Zabel and Morrell 1992). The enlarged permeability and the retaining of water in the wood by the fungi can be expected to accelerate fungal decay. The ability to detect decay in wood in constructions at an early stage would therefore be of great value when it comes to the maintenance of buildings. Such a method would have to be non-destructive to be of use. It should also facilitate measurements transversally on the wood, as the end-grain is often inaccessible in wood in constructions.

1.6 Objectives of the study

Increased frequency of intense precipitation is one of the main consequences of the expected climatic changes in coming decades (IPCC 2007). The uptake of liquid water in wood in service causes dimensional changes and exposes the wood to degradation by microorganisms. If the wood is allowed to dry quickly, biological activity will be prevented or hampered. Although wood–water relationships have been subject to extensive investigation through several decades, there are still questions left unanswered due to the complexity of the wood and the processes involved in absorption and desorption. The main objective of this study has been to investigate the effects surface treatments, wood properties, and defects have on liquid water absorption in wood.

The objectives of the individual studies presented in paper I–V were as follows:

To study the effects of wood properties on liquid water uptake in coated and uncoated wood (Paper I, III, IV and V).

To study the effect of coating types on liquid water absorption and accumulation, and the effect of interaction with wood with different properties on liquid water absorption (Paper I, III and IV).

To study the performance of specimens with water collecting cracks vs. water draining cracks and the effect of incipient decay regarding liquid water absorption in wood (Paper I).

To investigate whether a method designed for evaluating the liquid water permeability of coatings could be modified for use in the evaluation of wood properties and coatings in interaction (Paper III).

To test a method for non-destructive early decay detection on laboratory specimens during decay testing and on large-dimension construction wood (Paper II).

Figure 7 shows how the different papers are related to each other.

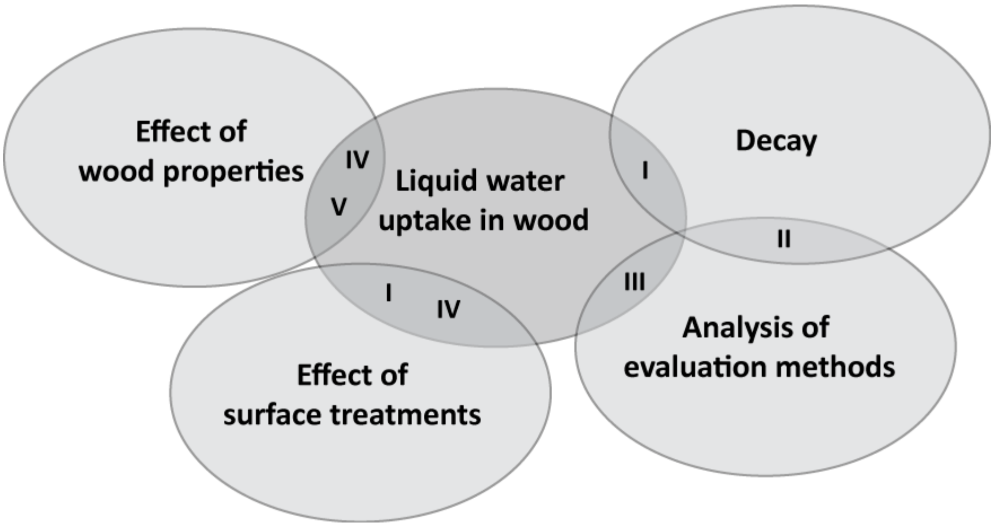

Figure 7. Overview of the relations between the different papers, denoted by their Roman numerals.

2. Material and methods

The work presented in this thesis is based mainly on Norway spruce and Scots pine material, predominantly harvested at different locations in Norway (Table 1). Reference specimens of Robinia heartwood were included in the TMC experiment in Paper II.

The sealant used in all the experiments was Pyrotect 2K (Rütgers Organics), a two-component solvent-borne epoxy-type lacquer intended as a steel topcoat. Used on wood, this lacquer has been shown to prevent water from entering wood even under pressure impregnation (Larnøy 2006).

Table 1. Overview of the material used in the individual studies. Species, type (heartwood or sapwood), origin, test specimen dimensions and measured properties (annual ring width (ARW), density at 12 % moisture content (D12), heartwood content (HW) and/or fungal stain (Staining)) are listed.

Paper	**Species**	**Heartwood/ sapwood**	**Origin**	**Dimensions of test sp.**	**Measured properties**
I, II	Scots pine	Mixed	Flesberg, Norway (one stand)	Log sections, 50 cm	ARW Staining
II	Scots pine	Sapwood	Småland, Sweden	100 x 10 x 5 mm	-
II	Scots pine	Sapwood	Finland (Procured by FinnForest according to their production procedures)	100 x 10 x 5 mm	
II	*Robinia pseudoaccacia*	Heartwood	Hungary	100 x 10 x 5 mm	-
III, IV	Norway spruce	Mixed	Northern Norway	150 x 50 x 20 mm	ARW D12
III, IV	Norway spruce	Mixed	South-eastern Norway	150 x 50 x 20 mm	ARW D12
IV	Scots pine	Heartwood	South-western Norway	150 x 50 x 20 mm	ARW D12
V	Norway spruce	Mixed	Toten, Norway	70 x 100 x 19 mm	ARW D12 HW
V	Norway spruce	Mixed	Larvik, Norway	70 x 100 x 19 mm	ARW D12 HW

2.1 Preparation of specimens and exposure to liquid water

2.1.1 Pine log specimens (Paper I and II)

Preparation of specimens

Scots pine trees from a single stand in Flesberg in Southern Norway were sampled as described in paper I. The variation between and within trees was minimised in the sampling. The logs were pre-cut in order to provoke two distinct cracks during drying, debarked and dried naturally outdoors under cover for 12 months before they were cut into 0.5 m specimens (Figure 8).

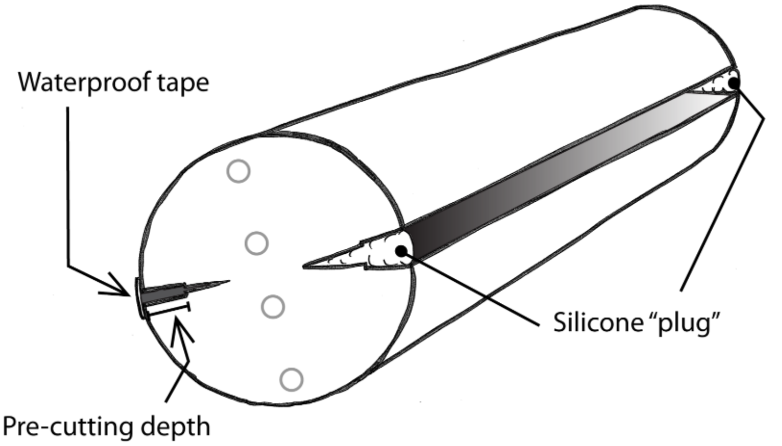

Figure 8. Illustration showing the preparation of pine log specimens for Paper I and II. Two longitudinal ridges were cut in each log in order to provoke two distinct cracks (Pre-cutting). The largest crack was placed facing the nozzles, and silicone was used to seal the ends of the crack. The smallest crack was protected in its whole length by a waterproof tape. The grey circles show the approximate locations of ultrasound measurements for Paper II.

Due to unfavourable weather conditions during drying two of the five logs were attacked by the white rot fungus *Phlebiopsis gigantea*, causing brown-coloured discolouration of the wood in a majority of the specimens taken from these logs. The brown-stained areas were regarded as subject to incipient decay. In addition, all logs sustained attack by blue stain fungi to varying extents (Table 2).

Table 2. Distribution of specimens on treatments (SB = solvent-borne coating; WB = waterborne coating; T = wood tar; U = untreated; D = crack oriented downwards; Up = crack oriented upwards), specimens with brown stain shown with bold numbers. Annual ring width (ARW), area of brown stain (Brown A) and area of blue stain (Blue A). Means for each log, n = 9 specimens for each log. Standard deviation for ARW and minimum (Min) and maximum (Max) values for blue stain and brown stain are listed.

Log	**SB**		**WB**		**T**		**U**		**ARW (mm)**		**Brown A (%)**			**Blue A (%)**		
no.	D	Up	D	Up	D	Up	D	Up	**Mean**	**St.Dev.**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
I	1	1	1	1	1	2	0	2	1.3	0.03	0	0	0	2	0.1	6
II	**1**	**2**+1	**1**	0	0	**1**	**1**+1	1	1.4	0.03	3	0	8	5	0.4	16
III	**2**	**1**	**1**	**2**	**1**	0	0	**2**	1.5	0.13	10	0*	35	6	0.3	20
IV	1	1	2	2	1	0	2	0	1.4	0.04	0	0	0	2	0.8	6
V	1	0	1	1	2	2	1	1	1.3	0.03	0	0	0	2	0.9	6
Sum	6	6	6	6	5	5	5	6								
Sum no brown	3	3	4	4	4	4	4	4								

*One specimen showed brown stain only in the top end, and none on the slice taken from the butt end.

The fungal attack was unplanned for and necessitated a rearrangement of the experiment design. On the one hand it was unfortunate, as it made drawing of clear conclusions more difficult. On the other hand it gave the opportunity to study the effect of incipient decay on liquid water uptake compared to effects of coatings and crack orientation. It also facilitated a test of a non-destructive dynamic modulus of elasticity (MOE) apparatus on specimens of large dimensions.

After 6 months of conditioning in 20 °C and 65 % relative humidity a 2 cm slice was cut from the butt end of each specimen. Annual ring width and moisture content (oven-dry method) were determined from the slices. In addition, the amount of brown stain and blue stain was determined by visual inspection using a magnifying glass after superficial wetting of the slices. The brown stain had a watery appearance when wetted and was easily distinguishable from areas with blue stain. The attacked specimens had amounts of brown stain ranging from 0.3 % to 35 % of slice area. All specimens from log III had brown stain, while three of the specimens from log II had no brown stain. Blue stain was found in all specimens, ranging from 0,1 % to 20 % of the slice area. The distribution of treatments (surface treatments and crack orientation) on specimens with and without brown stain is shown in Table 2.

The end surfaces of each specimen were sealed using two layers of Pyrotect 2K. The surface treatments on T, WB and SB specimens were applied as follows:

Wood tar (T), industrially produced from Scots pine wood, intended for application in room temperature or warmer. One coat was applied; as much tar as the surface would absorb plus an exterior layer as thick as possible without dripping.

White waterborne top coat with light brown solvent-borne primer (WB): One layer of primer and two layers of top coat were applied.

White solvent-borne top coat with light brown solvent-borne primer (SB): One layer of primer and two layers of top coat were applied.

All coatings were applied by brush. The wood in the cracks was coated as far in as the brush would go; approximately 1–2 cm. Sealing and coating of the specimens was done in the conditioned chamber.

All surface treatment products were commercially available and intended for use by homeowners as treatments to be applied on wood in claddings or massive wood walls. Spreading rates and drying times were as specified by the manufacturers.

The largest crack in each specimen was placed facing the spraying nozzles at a 45° angle on the horizontal plane, either upwards or downwards. The upwards-facing cracks were sealed in each end of the specimen to prevent water from running out of the crack. The smaller cracks faced away from the nozzles, and were sealed with waterproof tape (Figure 8).

The spraying nozzles were fastened to a wall, and the specimens were placed on rigs in front of the nozzles (Figure 9). This arrangement yielded approximately 50 l/m2/h of liquid water applied on the specimen surfaces facing the nozzles. The specimens were put through 6 wetting/drying cycles; 68 hours of spraying, 4 hours of draining and 96 hours in a chamber conditioned to 20 °C and 65 % RH. At the end of the experiment the specimens were dried to almost stable weight in 20 °C and 65 % RH. The specimens were weighed after each wetting and each drying, and regularly throughout the final drying.

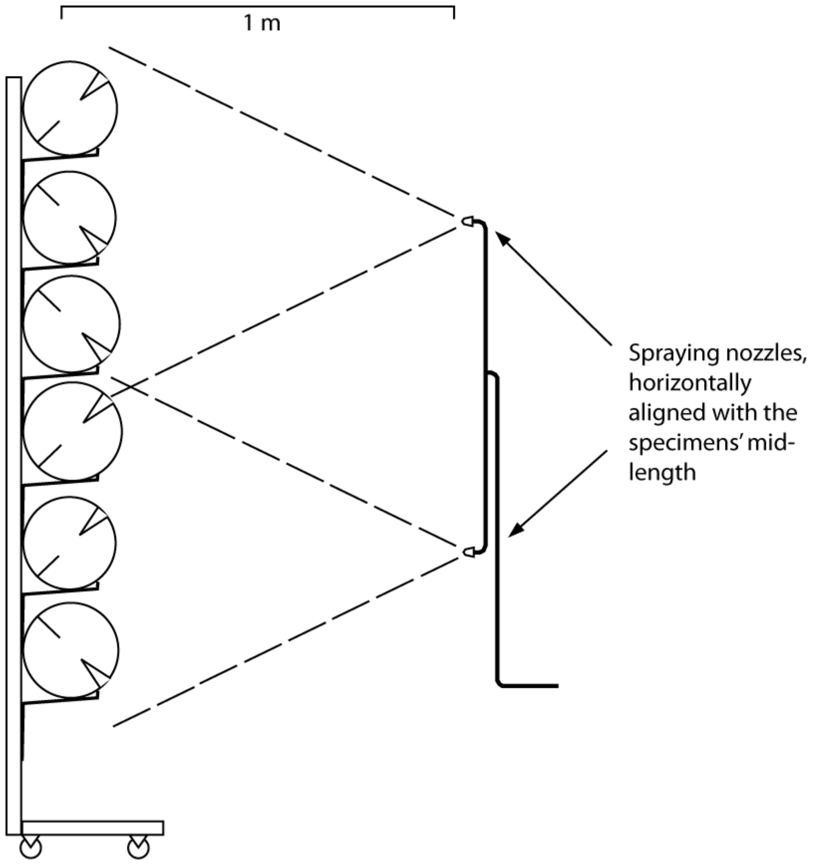

Figure 9. Schematic illustration of the pine log specimens placed in rigs in front of the spraying nozzles. 22 or 23 specimens were sprayed at a time, by eight nozzles. The logs were rearranged systematically in the rigs prior to each spraying cycle in order to avoid systematic differences in water exposure. The rigs had wheels to facilitate movement from the spraying chamber to the conditioned chamber.

2.1.2 Cladding specimens (Paper III, IV and V)

Paper III and IV, material and preparation of specimens

Norway spruce material was sampled from air-dried boards sawn from butt logs in mature trees as described in paper III. The trees were harvested in a low-productivity area in Northern Norway and a high-productivity area in Southern Norway. This yielded specimens with very narrow and very wide annual rings. Scots pine heartwood material was sampled from mature pine trees as described in paper IV. The dimensions of he test specimens were 150 x 50 x 20 mm (l x b x h). Annual ring width and density at 12 % RH were measured on small reference specimens cut adjacent to each test specimen (Table 3).

Table 3. Annual ring width (ARW) and density at 12 % MC (D12) of the specimens in paper III and IV. SL = spruce with wide annual rings; SH = spruce with narrow annual rings; PH = pine heartwood. SB = solvent-borne coating; WB = waterborne coating; PW = waterborne coating with solvent-borne primer; U = uncoated. Mean and standard deviation for each combination is listed. The combinations presented in both papers are indicated by grey row marking.

Wood type	**Coating**	**N**	**D12 (g/cm^3)**		**ARW (mm)**	
			Mean	St.dev.	Mean	St.dev.
SL	SB	6	0.364	0.007	4.4	0.9
SL	WB	6	0.361	0.011	5.0	0.7
SL	PW	6	0.369	0.012	4.5	0.8
SL	U	5	0.357	0.007	5.2	0.6
SH	SB	6	0.522	0.031	1.3	0.4
SH	WB	6	0.518	0.032	1.3	0.4
SH	PW	6	0.522	0.031	1.3	0.3
SH	U	5	0.513	0.019	1.1	0.2
PH	SB	6	0.480	0.080	2.0	0.6
PH	WB	6	0.463	0.045	1.9	0.7
PH	PW	6	0.485	0.078	1.7	0.7
PH	U	5	0.476	0.044	2.0	1.0

All specimens were sealed on ends, side edges and back face with two layers of Pyrotect 2K. The SB, WB and PW specimens were coated as follows:

White solvent-borne top coat (SB): Two layers were applied. The specimens were allowed to dry for 24 hours between the layers, and for several weeks before exposure to liquid water.

White waterborne top coat (WB): Two layers were applied. The specimens were allowed to dry for 4 hours between the layers, and for several weeks before exposure to liquid water.

White waterborne top coat with light brown primer (PW): One layer of primer and two layers of top coat were applied. The specimens were allowed to dry for 24 hours between priming and coating; otherwise the application was done as for WB specimens.

The coatings were commercially available and intended for use by homeowners as treatments to be applied on exterior wood claddings. Spreading rates and drying times were as specified by the manufacturers. All coatings were applied by brush. Sealing and coating of the specimens was done in the conditioned chamber.

Paper V, material and preparation of specimens

Spruce trees from four stands in two geographical origins in Southern Norway (Larvik and Toten) were sampled as described in paper V. The origins were chosen in order to obtain trees with wide annual rings from one and narrow annual rings from the other, which should lead to accordingly high and low density and large and smaller heartwood content. Trees in two diameter intervals were selected, from which the butt logs or the second logs respectively had diameters suitable for sawing into 150 mm wide planks. A width of 100 mm was chosen for the planks produced, however, to give room for the rather unusual sawing pattern needed. Specimens of dimensions 70 x 100 x 19 mm (l x b x h) were produced from inner and outer boards in the butt log and the second log of each tree, as well as from edge-grained boards in a smaller selection of logs (Figure 10). A reference specimen for measuring annual ring width and density at 12 % RH was produced adjacent to each test specimen. In addition, two more test specimens were produced from each board for use in separate experiments which will be presented in the future.

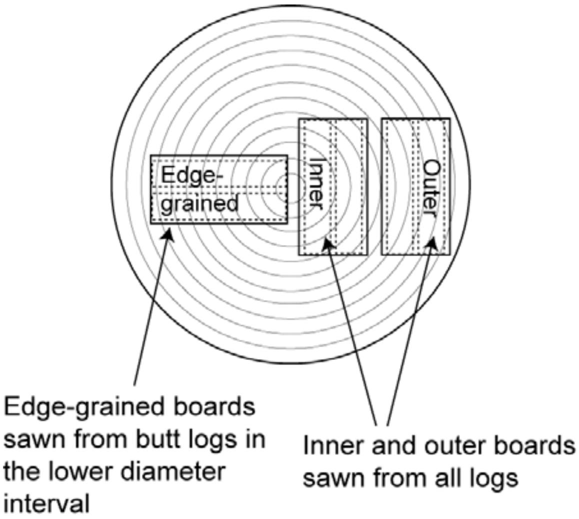

Figure 10. Illustration of sawing pattern for paper V. Inner and outer boards were sawn from all logs, while edge-grained boards were sawn from a smaller selection of logs.

Despite the large difference in annual ring width between the two origins, density differences were not correspondingly large (Table 4). The largest density differences were seen between inner and outer boards in the Larvik material. Heartwood content was different between origins, and between boards within origins.

Table 4. Properties of the specimens in Paper V. Number of specimens (N); annual ring width (ARW); density at 12 % MC (D12); and heartwood proportion (HW). HW was not measured in edge-grained boards. The differing number of specimens between the ARW/D12 and HW columns was due to the loss of some of the small specimens for measuring ARW and D12 and two of the CT scans from which HW was measured.

		ARW (mm)			**D12 (g/cm^3)**			**HW (%)**		
Origin	**Board**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**
Larvik	Inner	38	4.7	1.4	38	0.418	0.041	39	100	1
	Outer	37	2.8	0.8	37	0.481	0.061	37	46	34
	Edge-grained	10	3.0	0.9	10	0.449	0.048	0	.	.
Toten	Inner	36	1.6	0.6	36	0.456	0.030	36	100	2
	Outer	34	1.2	0.4	34	0.458	0.038	34	82	27
	Edge-grained	9	1.1	0.4	9	0.465	0.036	0	.	.

Liquid water exposure of cladding specimens

All cladding specimens used to test liquid water uptake were sealed on ends, side edges and back face with two layers of Pyrotect 2K.

The specimens were exposed to water following the procedure described in EN 927-5 (Figure 11). The exposure time was substantially prolonged relative to the 72 hours specified in the standard, and the specimens were weighed at numerous intervals rather than once. An example of the resulting sorption curves is shown in Figure 12.

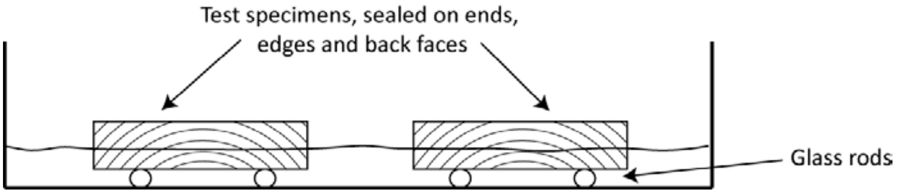

Figure 11. Outline of the experimental setup with respect to liquid water exposure of cladding specimens. The specimens were placed on glass rods, test face down in water. Specimen orientation shown as in Paper V; in Paper III and IV the specimens were oriented with the grain perpendicular to the glass rods.

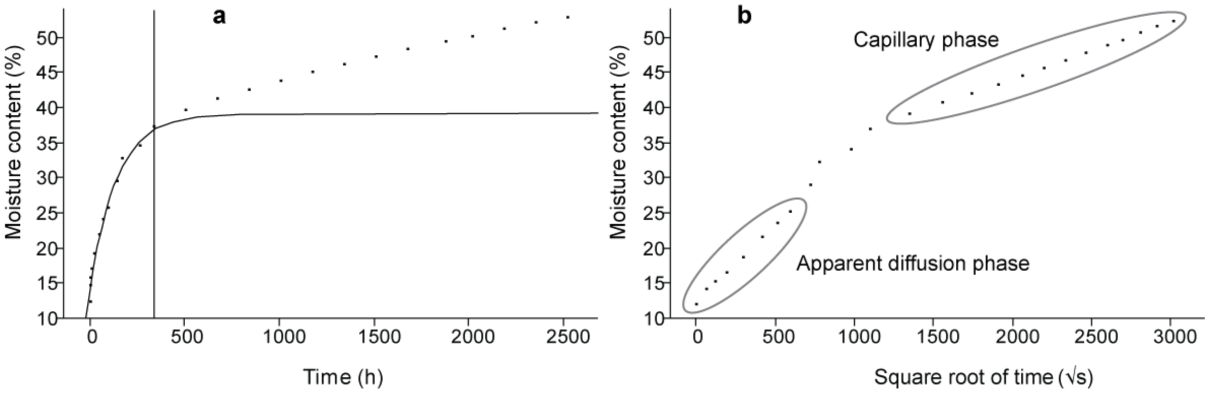

Figure 12. Water absorption in an uncoated Norway spruce cladding specimen exposed to liquid water as reported in paper V. Determination of EMCa by fitting a mechanistic growth model to the water absorption plotted by time is illustrated in a, while the two linear phases of the absorption plotted by the square root of time is shown in b.

2.2 Assessment of incipient decay using dynamic MOE testing (paper II)

The log sections described in Chapter 2.1.1 were included in this experiment as well. In addition, material from a TMC (terrestrial microcosms) experiment was used. The treatments included in this part of the experiment are presented in Table 5. Pine sapwood specimens with four wood modifications plus an untreated control were produced, as well as untreated robinia heartwood and copper chromium salt impregnated reference specimens. The dimensions were 100 x 10 x 5 mm (l x b x h) as specified in ENV 807 (CEN 2001). Pre-leaching and exposure to terrestrial microcosms was performed as described in paper II.

Table 5. Wood treatments in the terrestrial microcosms (TMC) experiment.

	Treatment	**Treatment levels**
Wood modifications:	*Furfurylation*	25 weight percent gain
	Thermal modification	212 °C
	Acetylation	23 weight percent gain
	Linseed oil*	150 kg/m³ retention
References:	*Copper chromium based*	10 kg/m^3 retention
	Semi-durable hardwood	*Robinia pseudoaccacia* heartwood
Control:		*Pinus sylvestris* sapwood

* according to the manufacturer the oil contained a compound to induce grafting of the oil to the wood, hence this could be regarded as wood modification.

Dynamic MOE (MOE_{dyn}) was measured using Pundit Plus, an ultrasonic pulse excitation device (Figure 13). The transducers used had resonant frequencies of 200 kHz. The MOE_{dyn} was calculated from the measured transit times using the following formula:

$$MOE_{dyn} = (l \, / t \,)2 \cdot m \, / v \tag{1}$$

Where l = length of specimen (mm), t = measured transit time (µs), m = mass at measurement moisture level (kg) and v = volume at measurement moisture level (m3). In the TMC experiment the calculation of MOE_{dyn} gave implausible results. Therefore, transit time was used for analyses in this part of the experiment.

Figure 13. Pundit Plus, the ultrasound excitation device used in the experiments presented in Paper II. The transducers are pressed against the ends of the wood piece to be measured, and ultrasound waves are transmitted from one transducer and received by the other. The output from the device is transit time from one transducer to the other in µs.

The coated pine log specimens were tested for $\mathrm{MOE}_{\mathrm{dyn}}$ at approximately 13 % moisture content, prior to the water uptake experiment. The ENV 807 specimens were tested for ultrasound transit time at 4 intervals during the TMC experiment. Measurements of mass loss were done on half of the TMC specimens after 24 weeks, and on the remaining specimens at the end of the experiment (40 weeks).

2.3 Statistical analysis

2.3.1 Modelling of water absorption profiles

Modelling of the curves resulting from the measurements during the experiments was done in order to describe the moisture development in each specimen with a small number of parameters. The emphasis was on finding models that gave close fits to the data and generated easily interpretable parameters. This approach allowed us to use analysis of variance (ANOVA) and analysis of covariance (ANCOVA) methods in descriptive statistical analyses of variables affecting the water absorption.

Description of weight development during cyclic water exposure and final drying (Paper I)

During the cyclic water exposure and subsequent drying described in paper I the development in water absorption and desorption was measured by weighing the specimens after each part of the cycles. This resulted in weight gain diagrams as shown in Figure 14. In Figure 14 a the upper dots show measurements after wetting and the lower dots measurements after drying in each cycle. In Figure 14 b only the measurements after drying are shown. Figure 14 c shows measurements during final drying. In order to describe different aspects of the uptake, a mechanistic growth model was fitted to absorption, accumulation and desorption curves as shown in the figure. This is a model used in modelling biological growth processes (Draper and Smith 1981). The formula for this model, which increases steadily from a point $\theta1(1 - \theta2)$ at $t = 0$ to the limiting value of $\theta1$, is given in Paper I. The model fitting yielded three parameters for each specimen, of which two ($\theta1$, maximum/minimum moisture level and $\theta3$, growth/decrease rate) were used for statistical analysis.

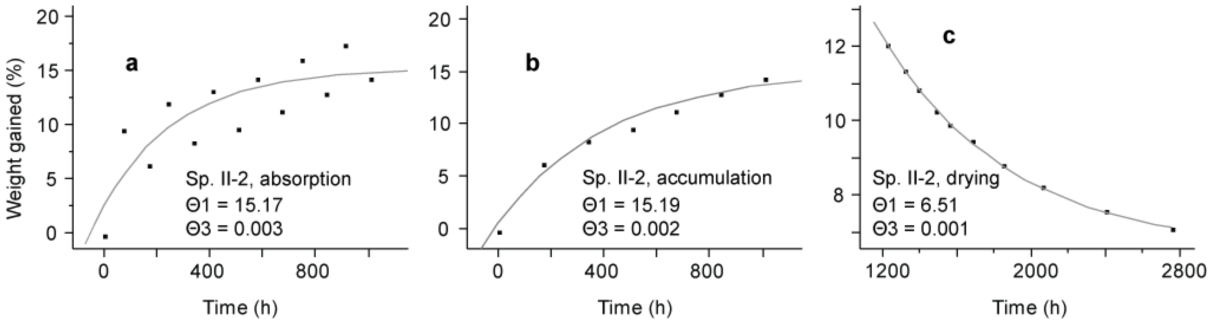

Figure 14. Absorption (a), accumulation (b), and desorption (c) represented by weight gain relative to initial weight for one specimen (log II, sp. 2). The grey lines represent the mechanistic growth model fitted to each curve. Note the differing scale of the y-axis in c. In the chosen software it was not possible to force the absorption models through origo, as can be seen in a and b.

Description of uptake during long-term water exposure

The long-term water exposure of coated specimens described in paper III and IV resulted in water absorption curves as shown in Figure 15 a. These curves all had one linear phase when plotted as a function of the square root of the exposure time, but regression to this part of the curve did not yield a better description of the differences in water uptake caused by different combinations of coatings and wood types than the analysis of mass of absorbed water per area (MWA) after 6 weeks did. Sorption curves in uncoated specimens showed signs of two linear phases like those described in paper V, but the absorption was ended too soon for the second linear phase to show clearly in the plots (Paper III). MWA (Figure 15 a) and moisture content gain (Figure 15 b) at certain points of time were used in statistical analysis of differences between coatings, wood types and combinations of coatings and wood types.

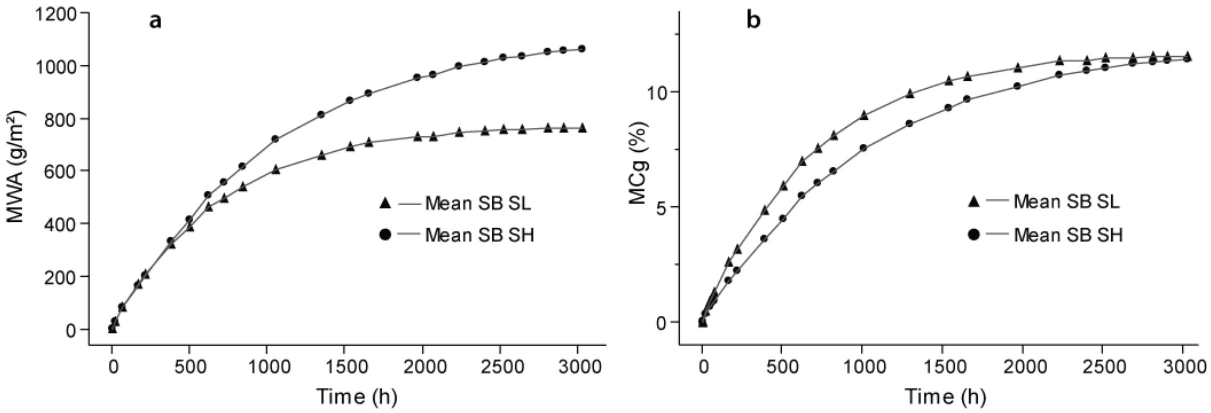

Figure 15. Water absorption expressed as a: mass of absorbed water by area (MWA) and b: moisture content gain (MCg) plotted by time for coated spruce specimens as reported in Paper III.

The long-term water exposure of uncoated spruce specimens described in paper V resulted in water absorption curves as shown in Figure 12. The water absorption was calculated as apparent diffusion and capillary flow, using the formulas adapted from those given in Siau (1984) by de Meijer and Militz (2000). Further description of the calculations is given in paper V. The apparent diffusion coefficient (IDa) and rate of the void filling degree (VFR) calculated from the two phases were used in statistical analysis.

2.3.2 Statistical analysis on result variables

Statistical tests were performed as analysis of variance (ANOVA) between groups of specimens, or as analysis of covariance (ANCOVA) when wood properties were included as covariates in the models. The residuals were assumed to have normal distribution. Effects with probability of type 1 error larger than 0.05 were considered non-significant and removed before re-estimating the final models.

The statistical software used for data analysis and generation of plots was JMP, ©SAS Institute Inc.

3. Results and discussion

3.1 Liquid water absorption in wood

3.1.1 Methods for analysis of the absorption

Using a mechanistic growth model to study the development of water absorption and drying in a cyclic wetting and drying scheme proved useful, and the derivation of parameters from individual specimen model fitting made statistical analysis of the differences between treatments easily interpretable (Paper I). The fits were not perfect, as the models tended to level out before the water uptake did. Liquid water uptake in partly uncoated wood can be expected to keep rising until the wood is fully saturated (Stamm 1964), probably in a way resembling the development shown in Figure 12 b. Thus the mechanistic growth model, which rises towards an asymptote, cannot be expected to yield a perfect fit. Another complication with respect to describing the water uptake in this experiment is that only single measurements after each part of the cycles were performed, rather than numerous measurements of the moisture content during the cycles. In order to describe the sorption in wood during cyclic wetting and drying in a way that allows analysis of physical processes in the wood, continuous monitoring of moisture content (or preferably moisture profiles) by weighing, CT scanning or other measures would be necessary.

The test procedure specified in the European standard EN 927-5, with certain modifications, was shown to be useful in a study regarding the relative performances of different combinations of wood types and coatings. The main modification was prolongation of the exposure time. If relative performance of the combinations is of interest, rather than analytical evaluation of the physical processes involved in water absorption, analysis of single measurements of the amount of absorbed water was shown to be sufficient (Paper III and IV). Information about the resulting moisture content was shown to be valuable in the discussion of the performances of the different wood types.

The parameters IDa (apparent diffusion coefficient) and VFR (rate of void filling degree) were found to describe water absorption in uncoated spruce specimens during long-term exposure to liquid water in a satisfactory way. The values for IDa found were of the same order of magnitude as those found in studies of pure water vapour absorption (Paper V). The mechanistic growth model was found useful for the determination of an apparent EMC for use in calculation of the IDa.

3.1.2 Liquid water absorption in uncoated wood (Paper III–V)

Mechanisms during uptake

The similarity of the mean IDa found in Paper V to values found regarding water vapour absorption indicates that the initial phase in liquid water uptake in uncoated spruce wood is to a large extent governed by diffusion. Spruce is a refractory species due to its small proportion of unaspirated bordered pits (Liese and Bauch 1967b). The initial dominance by diffusion is to be expected as ray tracheids, of which spruce has substantially fewer than pine (Liese and Bauch 1967a), are probably the only path for capillary transport (de Meijer et al. 1998). The driving force for diffusion is the moisture concentration gradient, and this process will come to an end when both the wood substance and the air in the cell lumens have reached saturation. After this point the absorption will be ruled by capillary flow (Voigt et al. 1940). Capillary transport alone is a slower process than diffusion and capillary transport combined. Nonetheless, the effects of origins and wood properties in paper V were substantially larger in the pure capillary transport phase than in the apparent diffusion phase.

Effect of origins and wood properties

The higher level of liquid water absorption in fast-grown relative to slow-grown uncoated spruce found in Paper III indicated a negative density effect on the absorption. As the references found in the literature were less than unanimous on this point, but clear effects of heartwood proportion have been reported, there was a need for a more extensive study on the effects of wood properties in spruce on liquid water absorption in uncoated cladding. This initiated the study reported in Paper V.

In paper V in this work, origin (Larvik or Toten) and horizontal orientation (inner/outer board) were found to have significant effect on both apparent diffusion coefficients (IDa) and rates of void filling degree (VFR), while no effects from size group or vertical orientation (butt log/second log) were found. The lack of effect of tree size and vertical orientation were explained by the fact that there were only small differences between the groups in the sample. The effect of the difference between inner and outer boards was fully explained by heartwood proportion and density, while some effects of origin remained when these properties were accounted for.

Density had negative effects on both parts of the sorption. The negative effect of density on IDa is in accordance with existing knowledge; diffusion within the cell wall material is slower than in air (Burr and Stamm 1947; Siau 1984; Stamm 1948; Wadsö 1994), and more cell wall material (i.e. higher density) will cause slower diffusion (Comstock 1963). The link between density and capillary flow is less clear. The larger cell lumens in the earlywood cause larger water uptake in each cell, while the transport between cells is faster in latewood because of a larger proportion of unaspirated pits (Salin 2008). The effect of density was minor compared to the effect of heartwood proportion for both parameters. The effect of density on VFR was not significant at a 99 % level of confidence and had a low F ratio compared to heartwood content, indicating that heartwood content was of larger importance than density regarding capillary flow.

Heartwood proportion had a negative effect on VFR and a positive effect on IDa. A possible explanation for the effect on IDa, which was unexpected since no difference in diffusivity between spruce heart- and sapwood has previously been found (Bergström and Blom 2007; Tong 1989; Wadsö 1993), is the effect of fibre angle. Longitudinal diffusion is much quicker than transversal diffusion in wood (Siau 1984), and there is thus a strong relation between diffusion and grain angle (Wengert and Skaar 1978). Tong (1989) suggested that much of the variation in reported moisture diffusion coefficients could be due to differing grain angle. The grain angle in spruce increases through the first 4–8 annual rings from the pith, and then decreases slowly until the 50th annual ring (Säll 2002), which means that in the annual rings close to the pith some end-grain will be exposed on radial surfaces. Inner boards had relatively more radial surface exposed on the test faces compared to outer boards, due to the curvature of annual rings. This implies that the larger heartwood content in these boards may be confounded with more end-grain exposed on the test faces. The combined effect of grain angle and heartwood content on water uptake in uncoated wood should be further investigated.

The negative effect of heartwood on VFR is easily explained by changes in bordered pits during heartwood formation (Liese and Bauch 1967a), and supports the hypothesis that spruce heartwood is considerably less permeable to liquid water absorption than spruce sapwood (Bergström and Blom 2007; Sandberg 2002). A modest increase in rotation periods for productive spruce forest has been shown to potentially increase CO_2-binding (Nilsen et al. 2008). As the amount of heartwood is correlated with tree age (Longuetaud et al. 2006), increased rotation periods for Norway spruce might also benefit the performance of claddings.

3.1.3 Liquid water absorption in coated wood (Paper I, III and IV)

Effects of wood types and properties (Paper III and IV)

The results from Paper III indicated that short-term water uptake in coated wood is not significantly affected by wood properties. For the difference between slow-grown (SH) and fast-grown (SL) spruce to emerge, the specimens had to be exposed to water for 4 weeks or more (Paper III). When pine heartwood was introduced as well as fast-grown and slow-grown spruce, the wood substrate had a larger effect than coating (Paper IV). After 72 hours, the mass of absorbed water per area (MWA) was significantly lower in pine heartwood (PH) specimens than in spruce specimens. After 672 hours (4 weeks), SH specimens ranged significantly higher in MWA while no difference between SL and PH specimens was found (Table 6). Regarding moisture content gain (MCg), SL specimens ranged higher than the other wood types throughout the experiment. The development in moisture content in the wood was mainly governed by density.

Table 6. Mean scores in mass of absorbed water per area (MWA) and moisture content gain (MCg) after four weeks for coated and uncoated cladding specimens in Paper III and IV. Tukey HSD test results (Ty) are shown; groups that do not share the same letter are significantly different. Results for coated specimens are shown in capital letters, those for uncoated specimens in minuscule letters. SH = high-density Norway spruce; SL = low-density Norway spruce; PH = Scots pine heartwood.

Treatment	Wood type	Mean MWA (g/m^2)	Ty	Mean MCg (%)	Ty
Coated	SH	570	A	6.1	B
	SL	492	B	7.6	A
	PH	482	B	5.7	B
Uncoated	SH	1706	b	18.0	c
	SL	2135	a	33.3	a
	PH	2016	a	24.4	b

Coated SH specimens absorbed more water than coated SL specimens, while the opposite was the case for uncoated specimens (Paper III, Table 6). The apparently greater water protection efficiency of the coating on SL specimens may be due to larger penetration of the wood coating due to higher proportion of earlywood (de Meijer et al. 1998; Williams et al. 1987), as penetration of a water-repellent resin has been found to have a damping effect on swelling in wood saturated with water (Smulski and Cote 1984).

Additionally, this behaviour can be explained by the fact that the water flux through a coating into the wood is dependent on the diffusion coefficient of the coating and the concentration gradient between the surroundings and the wood-coating interface (Derbyshire and Miller 1996). If the diffusion coefficient for any particular coating is assumed to be constant during continuous water exposure, the water flux through the coating will depend entirely on the concentration gradient. Thus, the water flux will be constant as long as the rate of absorption into the wood is greater than the transmission rate through the coating. If the density of the wood is low, the point where the water flux starts to decrease due to higher moisture concentration at the wood-coating interface will be reached earlier than if the wood has higher density. Thus, the total amount of water absorbed in coated wood can be expected to be higher in high-density wood. If this consideration is true, lower diffusivity in the wood substrate will cause less water flux, explaining the lower degree of water uptake in pine heartwood specimens after 72 hours. The observation that the maximum moisture content in coated wood seems to be the fibre saturation point (Derbyshire and Miller 1997) supports this consideration. Whereas uncoated wood exposed to water-saturated air will continue to take up water through capillary condensation until the wood is fully saturated (Stamm 1964), a surface coating will pose a hindrance to additional water uptake beyond the fibre saturation point. When the cell wall substance is saturated the moisture concentration gradient over the coating film will be non-existent, and the water flux will cease.

Effects of coatings (Paper I and IV)

Without primer, the waterborne coating used was shown to give higher water uptake in cladding boards during long-term water exposure than the solvent-borne coating without primer. With a solvent-borne primer, the performance of the waterborne coating was not significantly different from the performance of the solvent-borne coating (Paper V). The higher liquid water permeability of waterborne compared to solvent-borne coatings is shown in numerous studies (eg de Meijer 2002; Derbyshire and Miller 1997; Roux et al. 1988). Both coatings, used with a solvent-borne primer, initially slowed the water uptake in pine log specimens. However, it was shown that during prolonged cyclic wetting and drying more accumulation of water could be expected in specimens with film-forming coatings than in specimens coated with wood tar. The accumulating effect was strongest in the specimens with a solvent-borne coating. Wood tar performed better in the long term than film-forming coatings or no treatment at all, probably because it repels water during wetting and is open to diffusion during drying (Hauer 2007). The wood tar used in Paper I was not hardened or weathered. Further investigations regarding the effect on water sorption of wood tar hardened by UV radiation and in different stages of deterioration due to weathering should be considered.

Effects of defects (cracks and incipient decay; Paper I)

The results in Paper I showed that one large crack oriented 45° upwards caused higher moisture increase rates than one large crack oriented 45° downwards. The effect of cracks was smaller than the effect of surface treatment. This was surprising, as the upwards-oriented cracks were observed to collect water (Paper I). The orientation of the large crack can be expected to have a large influence on the distribution of water in the cross section of the log, and a steep moisture gradient in the vicinity of upwards-oriented cracks can be expected. This should be investigated further.

The degree of incipient decay, observed as the amount of brown stain caused by an attack by the white rot fungus *Phlebiopsis gigantea*, affected the water uptake heavily. This effect is probably caused by the fungus destroying the tori in the aspirated bordered pits during its colonisation of the wood (Zabel and Morrell 1992). The amount of blue stain was influential in interaction with brown stain, but not by itself. Blue stain fungi are known to be able to cause larger permeability in wood (eg Blew 1952; Lindgren 1952; Panshin and De Zeeuw 1980; Zabel and Morrell 1992).

3.2 Evaluation of incipient decay

Regarding the TMC experiment described in Paper II, the evaluation of strength loss measured as ultrasound transit time gave the same general trends between treatments as mass loss for all soil types. Interestingly, the soil dominated by brown rot fungi gave the most extensive strength loss, while the soil with highest level of microbial activity gave the most extensive mass loss. This is most likely due to differences in species composition of deteriorating fungi in the different soil types. Brown rot fungi are known to cause more rapid strength loss at lower levels of mass loss than other rot fungi (Zabel and Morrell 1992). The soil dominated by white rot had the lowest level of microbial activity and generally gave the least mass loss and the least strength loss. However, for the furfurylated specimens strength loss was most extensive in this soil. Indications that exposure to white rot fungi may pose challenges to the performance of furfurylated wood have been found (Alfredsen and Westin 2009; Pilgård and Alfredsen 2009; Venås 2008). The ultrasound measurements illustrate the influence of different deteriorating organisms, and provide information that supplements mass loss measurements and visual evaluation.

Regarding the coated log sections both degree of incipient decay, measured as amount of brown stain, and log number (between-tree effect) had a significant effect on MOE_{dyn}. Incipient decay had a negative effect on MOE_{dyn}, while the sign of the tree effect varied between logs (Paper II). If transit time was analysed directly, incipient decay was the only significant effect ($p<0.0001$, estimate positive). The correlation between MOE_{dyn} and incipient decay was less clear in samples with very small areas with incipient decay. This could be because the MOE_{dyn} was measured in one point at a time, and the small areas with incipient decay in these specimens may have been missed entirely.

The lack of a significant tree effect on the measured transit time in the coated logs indicates that the tree effect on MOE_{dyn} was caused by the relationship between mass and volume of the samples. On this background the implausible results from calculated MOE_{dyn} regarding the TMC specimens may have been caused by the influence of mass loss (Paper II).

Transversal measurements on the pine log specimens gave substantially lower MOE_{dyn} values than longitudinal measurements. There was a statistically significant correlation between longitudinal and transversal measurements ($p = 0.0362$), but no effect from brown stain on MOE_{dyn} measured transversally. The longer transversal than longitudinal transit time can be explained by the fact that the ultrasound must cross more cell walls in the transversal direction. The significant correlation between longitudinal and transversal measurements indicates that transversal decay detection should be possible, and the lack of success from transversal measurements might be explained by the brown stain being caused by a white rot fungus, which leaves the cellulose fibres more intact than brown rot fungi. This should be given further study, which should include wood in different stages of decay and the influence of brown rot relative to that of white rot.

4. Conclusions and final remarks

4.1 Conclusions

Water absorption is a major factor in the service life of exterior wood, as it affects both dimensional changes and the conditions for microbial degradation. If wetted, wood should be allowed to dry as quickly as possible when the wetting ceases. Impermeable coatings can prevent wetting in a satisfactory way, but only as long as the coating film is intact. If the coating film is degraded through erosion, cracking, or flaking, the water uptake will partly be through an uncoated wood surface, and capillary water transport can be expected to cause a large water uptake. This will make the permeability of the surface treatment to diffusion during drying crucial for the performance of the wood. In wood with or without surface treatment exposed to long-term liquid water exposure, wood properties have a substantial effect on the behaviour of claddings.

The conclusions from the papers presented in this thesis can be summarised as follows:

Wood properties were shown to affect liquid water absorption both in coated and in uncoated wood. The effect of wood properties of Norway spruce was non-existent after short-term exposure, while wood properties were very important with respect to long-term exposure (Paper III). When pine heartwood was included, the effect of wood type could be seen already after 72 hours (Paper IV). Prolongation of the exposure time from 72 hours to 4 weeks in the test method specified in the European standard EN 927-5 was found useful in a study of liquid water uptake in different combinations of wood types and coating types (Paper III and IV).

In spruce specimens subjected to long-term liquid water exposure two phases were displayed; one mainly governed by diffusion (apparent diffusion) and one solely governed by capillary flow. Larger effects of wood properties were found regarding capillary flow than regarding apparent diffusion. Heartwood proportion was more important for liquid water uptake in uncoated spruce than density or annual ring width (Paper V). Thus, the good reputation of slow-grown spruce as a cladding material is probably more due to large heartwood content than to high density or narrow annual rings. The heartwood proportion in Norway spruce is correlated with tree age, and increased rotation periods might thus benefit the performance of Norway spruce cladding boards.

Solvent-borne coating protected cladding specimens better from liquid water absorption than waterborne coating. Used with a solvent-borne primer, the waterborne coating performed almost equally to the solvent-borne coating without primer (Paper III and IV). During cyclic wetting and drying of pine log specimens, wood tar was found to cause less accumulation of water than both solvent-borne and waterborne coatings. Upwards-facing cracks caused faster water absorption than downwards-facing cracks, but the effect of surface treatments was larger than the effect of crack orientation (Paper I).

The presence of incipient decay in pine log specimens caused substantially larger water uptake, overruling the effect of surface treatment. Blue stain had a significant influence only if it occurred together with the incipient decay (Paper I).

Ultrasonic dynamic MOE measurements were found to give information that supplemented the mass loss measurements and visual evaluation regarding early decay detection. Moisture conditions and temperature have to be taken into consideration in experimental planning if this method is to be used. Transversal measurements on log sections were unsuccessful, possibly because of the mode of action of the decay fungus in question (Paper II).

4. 2 Topics for future research

In the present study moisture absorption quantities were obtained by weighing whole specimens, yielding average values for each specimen. In future studies the effects on moisture gradients from wood properties, coating systems, and faults within the wood should be investigated. In particular, further studies should be carried out regarding the probable positive effect from grain angle on diffusion in Norway spruce wood, as well as the interaction with heartwood.

Further studies should also be carried out regarding the performance of wood tar relative to less film-forming surface treatments such as stains and distemper paints, as well as the performance of tar subjected to different degrees of weathering. The performance of wood tar relative to other surface treatments on cladding material as well as massive wood should be investigated. Further investigations on log house material should include differences in wood quality in combination with surface treatments.

The performance of wood-coating combinations regarding liquid water uptake should be compared to the performance of the same combinations in studies regarding fungal deterioration. Both surface growth (mould and staining fungi) and decay should be considered as well as the moisture conditions in the wood, preferably at different depths beneath the coating film.

References

Ahola, P. 1991. Moisture transport in wood coated with joinery paints. Holz Als Roh-Und Werkstoff 49(11):428-432.

Ahola, P., H. Derbyshire, G. Hora, and M.d. Meijer. 1999. Water protection of wooden window joinery painted with low organic solvent content paints with known composition. Part 1. Results of inter-laboratory tests. Holz Als Roh-Und Werkstoff 57(1):45-50.

Alfredsen, G., and M. Westin. 2009. Durability of modified wood - laboratory vs. field performance. in 4th European Conference on Wood Modification. SP Trätek, Stockholm, Sweden.

Almeida, G., and R.E. Hernández. 2007. Influence of the pore structure of wood on moisture desorption at high relative humidities. Wood Material Science and Engineering 2(1):33-44.

Banks, W.B., and J.F. Levy. 1980. The effect of cell wall swelling on the permeability of grand fir wood. Wood Science and Technology 14(1):49-62.

Bergström, M., and A. Blom. 2007. Differences in properties between Norway spruce (Picea abies) heartwood and sapwood. Part 2. Vapour and Liquid permeability. *in* Proceedings of the Wood Protection Conference. Forest Products Society, New Orleans, Lousiana, USA, March 21-32, 2006.

Blew, J.O. 1952. Treatability of southern yellow pine as influenced by fungus infection. Journal of Forest Products Research Society 2(85):85-86.

Booker, R.E., and J.A. Kininmonth. 1978. Variation in longitudinal permeability of green Radiata pine wood. New Zealand Journal of Forestry Science 8(2):295-308.

Brischke, C., R. Bayerbach, and A.O. Rapp. 2006. Decay-influencing factors: A basis for service life prediction of wood and wood-based products. Wood Material Science and Engineering 1(3):91 - 107.

Burr, H.K., and A.J. Stamm. 1947. Diffusion in wood. Journal of Physical and Colloid Chemistry 51(1):240-261.

Bøhlerengen, T., and J. Mattsson. 1995. Tilstandsanalyse av utvendig treverk. Billedkatalog, symptomliste og typiske skadesteder (in Norwegian). Byggforskserien 720.116. SINTEF Byggforsk, Oslo.

CEN. 1994. EN 350-2. Durability of wood and wood-based products - Natural durability of solid wood - Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe. European Committee for Standardisation, Brussels, Belgium.

CEN. 2001. ENV 807. Wood preservatives - determination of the toxic effectiveness against soft rotting microfungi and other soil inhabiting microorganisms. European Committee for Standardisation, Brussels, Belgium.

CEN. 2006. EN 927-5. Paints and varnishes - Coating materials and coating systems for exterior wood - Part 5: Assessment of the liquid water permeability. European Committee for Standardisation, Brussels, Belgium.

Choat, B., A.R. Cobb, and S. Jansen. 2008. Structure and function of bordered pits: new discoveries and impacts on whole-plant hydraulic function. New Phytologist 177(3):608-625.

Comstock, G.L. 1963. Moisture diffusion coefficients in wood as calculated from adsorption, desorption and steady state data. Forest Products Journal 13:97-103.

Comstock, G.L., and W.A. Cöté. 1968. Factors affecting permeability and pit aspiration in coniferous sapwood. Wood Science and Technology 2(4):279-291.

Danvind, J., and M. Ekevad. 2006. Local water vapor diffusion coefficient when drying Norway spruce sapwood. Journal of Wood Science 52(3):195-201.

de Meijer, M. 2001. Review on the durability of exterior wood coatings with reduced VOC-content. Progress in Organic Coatings 43(4):217-225.

de Meijer, M. 2002. Comparison between laboratory water permeability tests and wood moisture content of full-scale window frames. Surface Coatings International Part B-Coatings Transactions 85(2):131-137.

de Meijer, M., and H. Militz. 2000. Moisture transport in coated wood. Part 1: Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz Als Roh-Und Werkstoff 58(5):354-362.

de Meijer, M., K. Thurich, and H. Militz. 1998. Comparative study on penetration characteristics of modern wood coatings. Wood Science and Technology 32(5):347-365.

Derbyshire, H., and E.R. Miller. 1996. Moisture conditions in coated exterior wood. Part 1: An investigation of the moisture transmission characteristics of exterior wood coatings and the effect of coating on moisture permeability. Journal of the Institute of Wood Science 14(1):40-47.

Derbyshire, H., and E.R. Miller. 1997. Moisture conditions in coated exterior wood. Part 2: The relation between coating permeability and timber moisture content. Journal of the Institute of Wood Science 14(4):162-168.

Derbyshire, H., and D.J. Robson. 1999. Moisture conditions in coated exterior wood - Part 4: Theoretical basis for observed behaviour. A computer modelling study. Holz Als Roh-Und Werkstoff 57(2):105-113.

Drange, T., H.O. Aanensen, and J. Brænne. 2000. Gamle trehus: Historikk, reparasjon og vedlikehold (in Norwegian). Landbruksforlaget, Oslo. 455 p.

Draper, N.A., and H. Smith. 1981. Applied Regression Analysis. John Wiley & Sons, New York.

Eaton, R.A., and M.D.C. Hale. 1993. Wood. Decay, pests and protection. Chapman&Hall, London, Glasgow, New York, Tokyo, Melbourne, Madras. 469 p.

Edvardsen, K.I., L. Torjussen, and E. Vercoe (eds.). 1997. Trehus (in Norwegian). Norges byggforskningsinstitutt, Oslo. 295 p.

Ekstedt, J. 1992. Fuktfördelning i ytbehandlad utomhuspanel (in Swedish). Trätek. Report no. I 9204027.

Ekstedt, J. 2002. Influence of coating additives on water vapour absorption and desorption in Norway spruce. Holzforschung 56(6):663-668.

Elkouali, M., and J.M. Vergnaud. 1991. Modeling the process of absorption and desorption of water above and below the fiber saturation point. Wood Science and Technology 25(5):327-339.

Eriksson, J., H. Johansson, and J. Danvind. 2006. Numerical determination of diffusion coefficients in wood using data from CT-scanning. Wood and Fiber Science 38(2):334-344.

Fakhouri, B., H. Mounji, and J.M. Vergnaud. 1993. Comparison of the absorption and desorption of water between Scots pine and spruce after submersion in water. Holzforschung 47(4):271-277.

Flæte, P.O., and O.A. Høibø. 2009. Models for predicting vertical profiles of heartwood diameter in mature Scots pine. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 39(3):527-536.

Fossdal, S., and K.I. Edvardsen. 1995. Energy consumption and environmental impact of buildings: case study of traditional and modern wooden buildings. Norwegian Building Research Institute, Oslo. 17 p.

Frandsen, H.L., L. Damkilde, and S. Svensson. 2007. A revised multi-Fickian moisture transport model to describe non-Fickian effects in wood. Holzforschung 61(5):563-572.

Gobakken, L.R. 2009. Surface mould growth on painted and unpainted wood; Influencing factors, modelling and aesthetic service life. Thesis for the degree of Philosophiae Doctor (Ph.d), Norwegian University of Life Sciences, Ås. 29 p.

Gobakken, L.R., O.A. Høibø, and H. Solheim. 2009. Factors influencing surface mould growth on wooden claddings exposed outdoors. *In*: Gobakken, L.R. 2009. Surface mould growth on painted and unpainted wood; Influencing factors, modelling and aesthetic service life. Thesis for the degree of Philosophiae Doctor (Ph.d), Norwegian University of Life Sciences, Ås. Paper IV, 19 pp.

Greystone, J., and J. Ekstedt. 2004. Current views on the role of water in the behaviour of coated wood substrates. *in* COST E18, High Performance Wood Coating. Final seminar, Paris, 26. - 27. April.

Hauer, D. 2007. Bruk av ikkepigmentert overflatebehandling med konservering av trebygninger, med vekt på steinkulltjære og steinkulltjærederivater. En sammenlignende studie av forholdet mellom overflatebehandlinger og fuktdynamikk (in Norwegian). Master thesis, University of Oslo, Oslo. 128 p.

Hauge, T. 1994. Littlemannen og skoftungen. Faguttrykk om trehus og tømring. TI-forlaget, Oslo. 210 p.

Hjort, S. 1989. Rötskadade träfasader i en klimatiskt utsatt miljö: En utredning av rötskador med speciell inriktning mot småhusområdet Torpet, Lysekil (in Swedish). Chalmers Tekniska Högskola. Report no. P-89:4.

Holbrow, G.L., A.F. Sherwood, M.C. Gibson, D. Gardiner, D. Dasgupta, and M.J. Haines. 1972. Wood protection. Journal of the Oil & Colour Chemists Association 55(1):35-51.

Hukka, A. 1999. The effective diffusion coefficient and mass transfer coefficient of Nordic softwoods as calculated from direct drying experiments. Holzforschung 53(5):534-540.

Hylen, G. 1997. Genetic variation of wood density and its relationship with growth traits in young Norway spruce. Silvae Genetica 46(1):55-&.

IPCC. 2007. Summary for policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report for the Intergovernmental Panel on Climate Change. Solomon, S., D. Quin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, United Kingdom and New York, NY, USA.

Jenssen, K.M. 1989. Decay of external woodwork caused by *Dacromyces stillatus*. A case study. P. 11-14 *in* Degradation of Painted Wood by Fungi: Proceedings of the International Minisymposium., Gatenholm, P. (ed.). Nordic Institute for Coatings Research, Copenhagen, Denmark.

Kelsey, K.E. 1956. The shrinkage intersection point - its significance and the method of its determination. Forest Products Journal 6:411-416.

Kelso, W.C., R.O. Gertjejansen, and R.L. Hossfeld. 1963. The effect of air blockage upon the permeability of wood to liquids. University of Minnesota Agricultural Experiment Station, Technical Bulletin 242:40.

Kitin, P., T. Fujii, H. Abe, and K. Takata. 2009. Anatomical features that facilitate radial flow across growth rings and from xylem to cambium in Cryptomeria japonica. Annals of Botany:1145-1157.

Klem, G.G. 1934. Undersøkelser av granvirkets kvalitet (in Norwegian). Meddelelser fra Det Norske Skogforsøksvesen 17(2):201-348.

Koc, P., M. Houska, and B. Stok. 2003. Computer aided identification of the moisture transport parameters in spruce wood. Holzforschung 57(5):533-538.

Kollmann, F.F.P., and W.A. Cöté. 1968. Principles of wood science and technology. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. 551 p.

Krabbenhoft, K., and L. Damkilde. 2004. A model for non-Fickian moisture transfer in wood. Materials and Structures 37(273):615-622.

KRD/MD. 1997. Forskrift om krav til byggverk og produkter til byggverk (TEK). Forskrift til plan- og bygningsloven (in Norwegian).

Kumar, S. 1981. Some aspects of fluid flow through wood. 1. Mechanism of flow. Holzforschung Und Holzverwertung 33(2):28-33.

Larnoy, E., M. Eikenes, and H. Militz. 2005. Uptake of chitosan based impregnation solutions with varying viscosities in four different European wood species. Holz Als Roh-Und Werkstoff 63(6):456-462.

Larnøy, E. 2006. The use of chitosan as a wood protecting agent. Thesis for the degree of Philosophiae doctor (Ph.d.), Georg-August-Universität, Göttingen. 44 p.

Lehringer, C., K. Richter, F. Schwarze, and H. Militz. 2009. A review on promising approaches for liquid permeability improvement in softwoods. Wood and Fiber Science 41(4):373-385.

Liese, W., and J. Bauch. 1967a. On anatomical causes of the refractory behaviour of spruce and douglas fir. Journal of the Institute of Wood Science 19:3-14.

Liese, W., and J. Bauch. 1967b. On the closure of bordered pits in conifers. Wood Science and Technology 1:1-13.

Lindgren, R.M. 1952. Permeability of southern pine as affected by mold and other fungus infection. P. 158-168 *in* AWPA Proceedings. American Wood Preservers Associaton, New York City.

Longuetaud, F., F. Mothe, J.M. Leban, and A. Makela. 2006. Picea abies sapwood width: variations within and between trees. Scandinavian Journal of Forest Research 21(1):41-53.

Mattsson, J. 2004. Muggsopp i bygninger: forekomst, påvisning, vurdering og utbedring (in Norwegian). Mycoteam, Oslo. 94 p.

Molteberg, D., and O.A. Høibø. 2007. Modelling of wood density and fibre dimensions in mature Norway spruce. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 37(8):1373-1389.

Nilsen, P., K. Hobbelstad, and N. Clarke. 2008. Opptak og utslipp av CO_2 i skog: vurdering av omløpstid, hogstmetode og hogstfredning for CO_2-binding i jord og trær. Skog og landskap, Ås. 24 p.

NorskLaft, and Treteknisk. 2009. Bransjenorm for laftebygg (in Norwegian). Kvalitetskontrollen Norsk Laft, Oslo.

Nylinder, P., and E. Hägglund. 1954. Ståndorts- och trädegenskapers inverkan på utbyte och kvalitet vid framställning av sulfitmassa av gran (in Swedish). Meddelanden från Statens Skogforskningsinstitut 44(11):1-184.

Olek, W., P. Perre, and J. Weres. 2005. Inverse analysis of the transient bound water diffusion in wood. Holzforschung 59(1):38-45.

Panshin, A.J., and C. De Zeeuw. 1980. Textbook of wood technology: structure, identification, properties, and uses of the commercial woods of the United States and Canada. McGraw-Hill, New York. 722 p.

Petersen, A.K., and B. Solberg. 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics 7(3):249-259.

Pilgård, A., and G. Alfredsen. 2009. A better understanding of the mode of action of furfurylated wood. P. 13-20 in The Nordic-Baltic Network in Wood Material Science and Engineering, Bergstedt, A. (ed.). University of Copenhagen, Forest & Landscape, Copenhagen, Denmark.

Plinius Secundus, G. ~A.D. 77. Naturalis Historia.

Puritch, G.S. 1971. Water permeability of wood of grand fir (*Abies grandis* (Doug) Lindl) in relation to infestation by balsam woolly apid, *Adelges piceae* (Ratz). Journal of Experimental Botany 22(73):936-&.

Raknes, E. 1996. Fokus på tre nr 2. Vurdering av norske treslag til bruk som fasadematerialer utendørs (in Norwegian). Norsk Treteknisk Institutt, Oslo.

Rijckaert, V., M. Stevens, and J. van Acker. 2001. Effect of some formulation parameters on the penetration and adhesion of water-borne primers into wood. Holz Als Roh-Und Werkstoff 59(5):344-350.

Rijsdijk, J.F., and P.B. Laming. 1994. Physical and related properties of 145 timbers: information for practice. Kluwer Academic Publishers, Dordrecht. VIII, 380 s. p.

Rosenkilde, A., and J. Arfvidsson. 1997. Measurement and evaluation of moisture transport coefficients during drying of wood. Holzforschung 51(4):372-380.

Roux, M.L., E. Wozniak, E.R. Miller, J. Boxall, P. Bottcher, F. Kropf, and J. Sell. 1988. Natural weathering of various surface coatings on five species at four European sites. Holz Als Roh-Und Werkstoff 46(5):165-170.

Salin, J.-G. 2006a. Modelling of the behaviour of free water in sapwood during drying -- Part I. A new percolation approach. Wood Material Science and Engineering 1(1):4-11.

Salin, J.-G. 2006b. Modelling of the behaviour of free water in sapwood during drying -- Part II. Some simulation results. Wood Material Science and Engineering 1(2):45-51.

Salin, J.-G. 2008. Modelling water absorption in wood. Wood Material Science and Engineering 3(3):102 - 108.

Sandberg, K. 2002. Influences of growth site on different wood properties in spruce sap-/heartwood using CT scanner measurements. *in* Workshop 4, Connection Between Forest Resources and

Wood Quality: Modelling Approaches and Simulation Software. IUFRO Working party S5.01-04, Harrison Hot Springs, BC, Canada.

Segerholm, I., and J. Claesson. 2008. Unexpected experimental results for capillary suction in wood: Analysis on the fibre level. Wood Material Science and Engineering 3(3):109-118.

Siau, J.F. 1972. The effects of specimen length and impregnation time upon the retention of oils in wood. Wood Science 4(3):163-170.

Siau, J.F. 1984. Transport processes in wood. Springer, Berlin. 245 p.

Simpson, W.T., and J.Y. Liu. 1991. Dependence of the water vapor diffusion coefficient of aspen (*Populus* spec.) on moisture content. Wood Science and Technology 26:9-21.

Smulski, S., and W.A. Cote. 1984. Penetration of wood by a water-borne alkyd resin. Wood Science and Technology 18(1):59-75.

Stamm, A.J. 1948. The passage of water through the capillary structure of wood. Discussions of the Faraday Society 3:264-273.

Stamm, A.J. 1964. Wood and cellulose science. Ronald Press, New York. 549 p.

Stemsrud, K.D. 1989. Trevirkets oppbygning - vedanatomi (in Norwegian). Landbruksforlaget, Oslo. 119 p.

Säll, H. 2002. Spiral grain in Norway spruce. Thesis for the degree of philosophiae doctor (Ph.d.), Växjö University Press, Växjö. 171 p.

Taylor, A.M., B.L. Gartner, and J.J. Morrell. 2002. Heartwood formation and natural durability - A review. Wood and Fiber Science 34(4):587-611.

Tesoro, F.O., E.T. Choong, and C. Skaar. 1966. Transverse air permeability of wood as an indicator of treatability with creosote. Forest Products Journal 16(3):57-59.

Tiemann, H.D. 1906. Effect of moisture upon the strength and stiffness of wood. U.S. Dept. of Agriculture, Forest Service, Washington, D.C.

Tiemann, H.D. 1944. Wood technology: constitution, properties and uses. Pitman, New York. 328 p.

Tong, L. 1989. Moisture diffusivities and sorption isotherms of Swedish spruce and pine. TRITA-BYMA 1989:8. Dep. of Building Materials, The Royal Institute of Technology, Sweden. 60p.

Unligil, H.H. 1972. Penetrability and strength of white spruce after ponding. Forest Products Journal 22(9):92-100.

Vennesland, B., K. Hobbelstad, T. Bolkesjø, S. Baardsen, J. Lileng, and J. Rolstad. 2006. Skogressursene i Norge 2006: Muligheter og aktuelle strategier for økt avvirkning (in Norwegian). Norsk institutt for skog og landskap.

Venås, T.M. 2008. An assessment of the fungal decay protection rendered by furfurylation to Scots pine sapwood (*Pinus sylvestris L.*) by the use of laboratory-based test methods. *In*: A study of mechanisms related to the fungal decay protection rendered by wood furfurylation. Thesis for the degree of Philosophiae doctor (Ph.d), University of Copenhagen, Copenhagen. Paper II, 16 p.

Viitanen, H., and A.-C. Ritschkoff. 1991a. Brown rot decay in wooden constructions. Effect of temperature, humidity and moisture. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Report no. 222.

Viitanen, H., and A.-C. Ritschkoff. 1991b. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Sveriges Lantbruksuniversitet, Institutionen för virkeslära. Report no 221.

Virta, J. 2005. Cupping of wooden cladding boards in cyclic conditions--A study of heat-treated and non-heat-treated boards. Building and Environment 40(10):1395-1399.

Virta, J., S. Koponen, and I. Absetz. 2006. Modelling moisture distribution in wooden cladding board as a result of short-term single-sided water soaking. Building and Environment 41(11):1593-1599.

Voigt, H., O. Kirscher, and H. Schauss. 1940. Die Feuchtigkeitsbewegung bei der Verdunstungstrocknung von Holz (in German). Holz Als Roh-Und Werkstoff 3(10):305-321.

Wadsö, L. 1993. Measurements of water-wapor sorption in wood. 2. Results. Wood Science and Technology 28(1):59-65.

Wadsö, L. 1994. Unsteady-state water vapor adsorption in wood: an experimental study. Wood and Fiber Science 26(1):36-50.

Wagenführ, R. 1999. Anatomie des Holzes. DRW-Verlag, Leinfelden-Echterdingen. 188 p.

Weiss, K.D. 1997. Paint and coatings: A mature industry in transition. Progress in Polymer Science 22(2):203-245.

Wengert, E.M., and C. Skaar. 1978. Additional consideration in measuring transverse moisture conductivity in wood. Wood Science 11(2):102-104.

Wiberg, P., and T.J. Moren. 1999. Moisture flux determination in wood during drying above fibre saturation point using CT-scanning and digital image processing. Holz Als Roh-Und Werkstoff 57(2):137-144.

Wilhelmsson, L., J. Arlinger, K. Spångberg, S.-O. Lundqvist, T. Grahn, Ö. Hedenberg, and L. Olsson. 2002. Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. Scandinavian Journal of Forest Research 17(4):330-350.

Williams, R.S., C. Jourdain, G.I. Daisey, and R.E. Springate. 2000. Wood properties affecting finish service life. Journal of Coatings Technology 72(902):35-42.

Williams, R.S., P.L. Plantinga, and W.C. Feist. 1990. Photodegradation of wood affects paint adhesion. Forest Products Journal 40(1):45-49.

Williams, R.S., J.E. Winandy, and W.C. Feist. 1987. Paint adhesion to weathered wood. Journal of Coatings Technology 59(749):43-49.

Wurz, O., and O. Swoboda. 1947. Saugfähigkeit von Sulfitzellstoffen (in German). Svensk Papperstidning 50(2):26-27.

Zabel, R.A., and J.J. Morrell. 1992. Wood microbiology: decay and its prevention. Academic Press, San Diego, Calif. 476 p.

Øvrum, A. 2002. Fokus på tre nr 22. Utvendig kledning. 2. reviderte utgave (in Norwegian). Norsk Treteknisk Institutt, Oslo.

Wood Material Science and Engineering, 2009; 3–4: 167–179

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

Water sorption in coated Scots pine (*Pinus sylvestris* L.) logs and influence of incipient decay

MARI SAND SIVERTSEN, OLAV A. HØIBØ & BIRGER EIKENES

Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Abstract

Scots pine log specimens were given three different surface treatments and two different orientations of large cracks, and subjected to cyclic wetting and drying. Individual fitting of a mechanistic growth model was used to study the shape of absorption and accumulation curves and the final drying curve. Two parameters from this model (increase/decrease rate and maximum/minimum weight gain) were used for statistical analysis. The results indicate that wood tar results in less accumulated moisture over time than solvent-borne or water-borne coating or no treatment at all. An incipient attack by a white-rot fungus on parts of the material during storage affected water uptake greatly, often overriding surface treatment.

Keywords: *Cyclic wetting, incipient rot, log building, mechanistic growth model, Scots pine, water absorption, white rot wood tar.*

Introduction

The log house is a traditional and still widely used building type in Norway, especially in the central, heavily forested parts of the country. Modern log buildings are mostly cabins for recreational use, but the log-building technique has had a certain renaissance in houses for permanent habitation as well. New log-built cabins and houses are rarely cladded. The most commonly used species for log house buildings in Norway is Scots pine.

One of the challenges facing a timber structure is water. Rain and snow will moisten the wood, thus exposing it to a risk of biological deterioration given sufficient temperatures.

Water transport in wood is governed by two different processes. In wood below the fibre saturation point (FSP) bound water in the cell walls is transported by diffusion driven by a concentration gradient. In wood above FSP free water in the cell lumens is transported by liquid flow driven by capillary pressure (Siau, 1984). In uncoated wood exposed to liquid water both processes govern a share of the water transport until FSP is reached, the size of each share depending on moisture content (Voigt *et al.*, 1940). It can be expected that coating will strongly reduce the rate of liquid flow into the wood (de Meijer & Militz, 2000), making absorption of water through a coated surface mainly a diffusion process. Drying is dependent on transportation to and evaporation from the surface (Wadsö, 1993). Water transport in wood and through coating is dependent on internal properties, while evaporation depends on external properties. In partly coated wood accumulation of water can be expected during a series of wetting and drying periods.

Experience has shown that rot fungi tend to attack the wood in the vicinity of large cracks (Bøhlerengen & Mattsson, 1995). A natural explanation for this phenomenon is that upward-facing cracks collect water, providing favourable conditions for deteriorating fungi.

Cracking will almost always occur in logs, and in coated logs water that enters the uncoated wood in the cracks must be allowed to exit through the coating. Several cases of major rot damage on wood in outdoor applications in the 1980s and 1990s have been attributed to the use of coatings that did not let moisture through, thus sealing it

Correspondence: M. S. Sivertsen, Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, PO Box 5003, NO-1432 Ås, Norway. E-mail: mari.sivertsen@umb.no

(Received 25 June 2009; accepted 19 October 2009)

ISSN 1748-0272 print/ISSN 1748-0280 online
DOI: 10.1080/17480270903427591

inside the wood (Hjort, 1989; Jenssen, 1989). It is reasonable to expect that the type of coating used on logs will influence both water uptake in moist periods and drying in dry periods.

Wood tar is the traditional wood coating for wooden heritage buildings in Norway. According to Norwegian medieval law, farmers were responsible for the tarring of the stave church in their local parish (Egenberg, 2003). The fact that a number of medieval stave churches remain intact is strong evidence for the virtues of tar as a coating for wooden walls, even though there has been some replacement of exposed building parts. In a Norwegian study, Mattsson (personal communication) found that the inhibiting effect of wood tar on staining and rot fungi was weak compared with modern coatings. The conclusion was that other properties, such as water repellence, are probably more important for the efficiency of wood tar as a wood-protecting agent (Egenberg, 2004). A study on tar products for preservation of wooden heritage buildings found wood tar to be repellent to liquid water but open to diffusion of water vapour (Hauer, 2007).

The aim of this study was to quantify the performance of wood tar used on log surfaces exposed to liquid water compared with that of two types of film-forming coatings, when it comes to both water uptake during moist periods and drying during dry periods. In addition, the influence on water uptake by incipient decay was studied.

Materials and methods

Logs from five Scots pine (*Pinus sylvestris* L.) trees from a single stratus in a single stand in the central part of southern Norway were used. Site index was F 14 (dominant height at age 40 years at breast height) (Tveite & Braastad, 1981). The trees were sampled to minimize between- and within-tree variation. The experiment specimens were taken from the second log of each tree, between 5 and 10 m from the tree stump. Using a chainsaw, a ridge with a depth of approximately one-quarter of the log's diameter was cut along two sides of each log. This gave two distinct cracks during drying (Figure 1). The logs were debarked manually and dried naturally outdoors under cover for 12 months. Each log was cut into nine pieces of 0.5 m in length.

During drying two logs (logs II and III) were attacked by a rot fungus (determined by microscope analysis on material from log III to *Phlebiopsis gigantea*). The attack caused brown discoloration of the wood (brown stain) in all specimens from log III and a number of the specimens from log II (Figure 1). The attack did not seem to extend to the root end of log III, as the specimen taken from the butt end (III-1) showed brown stain only in its top end.

After 6 months of conditioning in a laboratory climate (20°C, 65% relative humidity) the moisture content 2 cm into the specimens was measured with a electrical resistance moisture meter to range from approximately 14% near the ends to 15% at mid-length. A slice was cut from the bottom end of each specimen. Annual ring width and moisture content (oven-dry method) were determined from the slices. In addition, the amount of brown stain and bluestain was determined by visual inspection using a magnifying glass. Up to 35% (of slice area) in specimens from log III and up to 8% in specimens from log II had brown stain. Bluestain was found in all specimens, ranging from 0.1% to 20% of the slice area (Table I).

The end surfaces of the specimens were sealed using a two-component epoxy sealant. The specimens were placed on racks, with cracks orientated upwards or downwards as shown in Figure 2. They were given four different surface treatments: water-borne acrylic coating (WB), solvent-borne alkyd coating (SB), wood tar (T) or none (U). Combined with the two crack orientations, this resulted in eight different treatments. The treatments were intended to be randomly distributed on eight of the specimens from each log. As nine specimens were produced from each log this would leave five specimens on which five randomly chosen treatments would be distributed. Owing to a misunderstanding during allocation of treatments this did not proceed as planned. Instead, the treatments were distributed randomly within specimens with brown stain and within specimens without brown stain (Table II).

The specimens were put through six wetting/drying cycles: 68 h of spraying, 4 h of draining and 96 h in a laboratory climate. The nozzle arrangement used yielded approximately $50\,\mathrm{l\,m^{-2}\,h^{-1}}$. The specimens were distributed randomly on the racks and moved systematically before each spraying period to eliminate any effect of position relative to the spraying nozzles. All specimens were weighed before and after each spraying period. After the end of the last cycle, the test logs were left in a laboratory climate to dry for 8 weeks. They were weighed twice a week during this time to determine drying behaviour. Absorbed moisture is given as percentage weight gain relative to the start weight, as dry weight was not determined (eq. 1):

$$\text{Weight gain} = ((\text{Weight} - \text{Start weight}) \times 100)/\text{Start weight} \qquad (1)$$

Non-linear regression was used to fit the weight gain data to a mechanistic growth model (MGM).

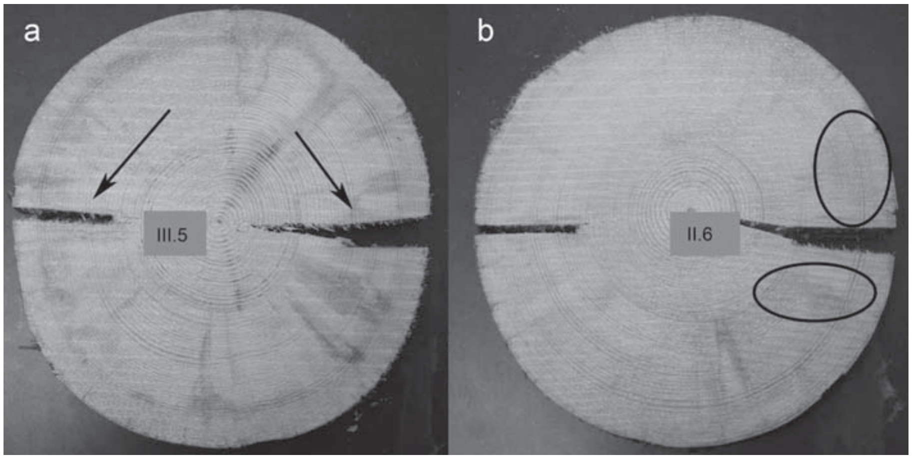

Figure 1. (a) Slice of specimen III-5, one of the specimens with most extensive brown stain. Arrows indicate precut cracks. (b) specimen II-6, one of the specimens with minor brown stain (rings).

The model is given in eq. (2):

$$F(t) = \Theta1(1 - \Theta2 \cdot e^{-\Theta3 \cdot t}) \tag{2}$$

where $t = \text{time}$. $F(t)$ increases steadily from a point $\Theta1(1 - \Theta2)$ (at $t = 0$) to the limiting value of $\Theta1$ (Draper & Smith, 1981).

The specimens were fitted individually, yielding parameters Θ1, Θ2 and Θ3 for each specimen (e.g. Figure 4). Θ1 denotes the asymptote, Θ2 the curvature and Θ3 the growth rate of the curve. Analysis of covariance (ANCOVA) tests were performed on the parameters Θ1 and Θ3 to find effects of treatments, brown stain and bluestain on the curve shape. This approach to analysis of longitudinal data is discussed by Diggle *et al.* (1996).

Three curves were derived from the modelling, each describing one aspect of the specimen's behaviour: an absorption curve (modelled on all weights during wetting/drying cycles), an accumulation curve (weights after each drying period) and a drying curve (weights during final drying). The absorption curve modelled the development in weight gain during prolonged cyclic wetting and drying, and behaved as an interpolation between the "wet" and "dry" moisture data. The accumulation curve described the development in accumulated weight gain (dry moisture data) during the same period.

In addition to the non-linear fitting, ANCOVA tests were performed on the observed weight gain data at selected time intervals to control the accuracy of the models and acquire a better basis for the discussion of the results.

The ANCOVA tests were carried out at the 95% confidence level. A p value lower than 0.05 indicates that mean square error was reduced significantly by introducing the tested effect, and that the null hypothesis (that the effect is not influential on the result variable) can be rejected. To look for differences between surface treatments Tukey–Kramer HSD tests were used within the ANCOVA for comparison of the different treatments.

Results

Figure 3(a) shows absorption data for the whole test material. Brown-stained specimens absorbed more water than specimens with no brown stain. Figure 3(b) shows absorption data for specimens with no brown stain. Untreated specimens ranged high after each wetting, but lower after drying. The

Table I. Initial moisture content, annual ring width, brown stain and bluestain.

	Moisture content (%)		Annual ring width (mm)		Brown stain (% area)		Bluestain (% area)		
Log no.	Mean	SD	Mean	SD	Mean	Max.	Mean	Min.	Max.
I	13.7	0.31	1.3	0.03	0	0	2	0.1	6
II	13.6	0.35	1.4	0.03	3	8	5	0.4	16
III	13.2	0.48	1.5	0.13	10	35	6	0.3	20
IV	13.3	0.33	1.4	0.04	0	0	2	0.8	6
V	13.5	0.39	1.3	0.03	0	0	2	0.9	6

Note: Means for each log, $n = 9$ specimens. Minimum values for bluestain and maximum values for bluestain and brown stain are listed.

Figure 2. Specimens V-9 (42) and III-1 (43) in the rig. The water was sprayed from the left. The largest crack in each specimen was placed at a 45° angle on the horizontal plane, either upwards or downwards (arrows). The other crack was sealed with waterproof tape. Upward-facing cracks were sealed in each end of the specimen to prevent water from running out of the crack (ring).

difference between untreated and other specimens diminished with each cycle.

Modelling

The development in weight gain in a majority of the specimens could be described successfully using the chosen model. Examples are shown in Figure 4(a, b), which also show the model's flexibility. For some, mainly untreated, specimens the modelled absorption curve reached asymptotic values earlier than the actual weight gain curve of the specimens did (Figure 4c). This effect was not as pronounced in the accumulation curve (Figure 4d). The model generated excellent fits to drying data from the same specimens (Figure 4e).

Specimens with large amounts of brown stain yielded very different results from the rest of the material, and for three of these the model did not generate acceptable fits. The drying plot for one of these specimens shows that it had a clearly diverging drying behaviour, and that the generated fit was virtually linear (Figure 4f).

When all specimens with brown stain were excluded, fitting of mean models for all surface treatments was possible. An example of the results for absorption data is shown in Figure 5. Plots showing mean model curves for all surface treatments are shown in Figure 6.

Influence of surface treatment and crack orientation

Surface treatment. When all specimens with brown stain were excluded, surface treatment had the largest effect on the shape of the modelled curves in this study (Table III). Tests on weight gained at selected time intervals confirmed this (Table IV).

A plot of mean absorption curves (mean value for each wetting/drying cycle) for the surface treatments shows that U specimens absorbed most water, followed by WB, T and SB specimens (Figure 6a). By the end of all wetting/drying cycles mean model curves for the T and U samples had almost reached asymptotic values, while the curves for the WB and SB samples were still rising.

The development of the model curves for absorption towards asymptotic values is shown in Figure 7(a). Tar treated specimens had a lower LSMean value for Θ1 compared with the other treatments, but the difference was not significant at the 5% level (Tukey HSD tests, Table Va). Untreated specimens had significantly higher growth rates (Θ3) than all other treatments, and tar-coated specimens (T) ranged significantly higher than SB specimens for Θ3.

The same relationships were found for the accumulation curves (values after each drying period, Figure 6b), but SB and T curves intersected by the end of the experiment. In tests on the model

Table II. Distribution of specimens on treatments.

	SB		T		U		WB	
Log no.	Crack down	Crack up	Crack down	Crack up	Crack down	Crack up	Crack down	Crack up
I	1	1	1	2	0	2	1	1
II	**1**	**2**+1	0	**1**	**1**+1	1	**1**	0
III	**2**	**1**	**1**	0	0	**2**	**1**	**2**
IV	1	1	1	0	2	0	2	2
V	1	0	2	2	1	1	1	1
Sum	6	6	5	5	5	6	6	6
Sum no brown stain	3	3	4	4	4	4	4	4

Note: Specimens with brown stain are shown with bold numbers.
SB = solvent-borne coating; T = tar coating; U = no coating; WB = water-borne coating.

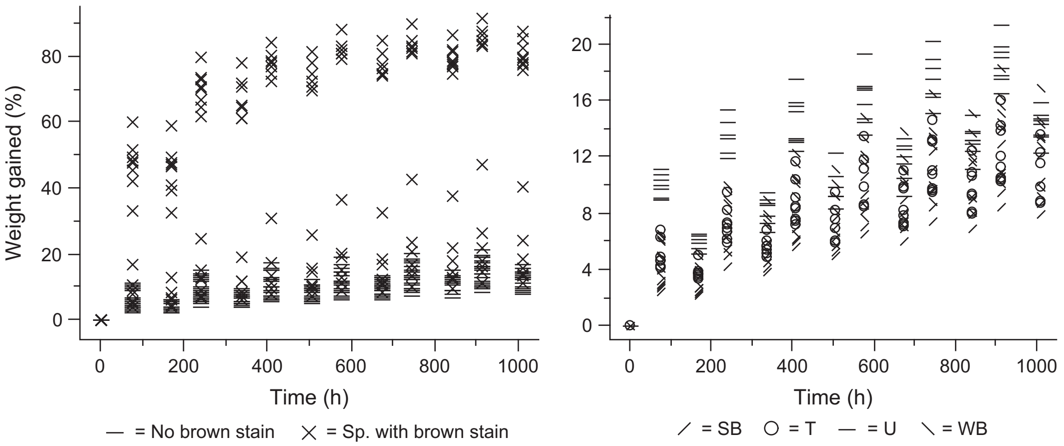

Figure 3. (a) Absorption data for the whole material. Specimens with extensive brown stain ranged high in weight gain. (b) Absorption data for specimens with no brown stain. Note the different *y* axis. Specimens with no coating (U) ranged high after the wetting periods but dried quickly, and differences diminished with each cycle. Specimens with solvent-borne coating (SB) ranged low throughout, and specimens with tar (T) ranged slightly lower with each cycle.

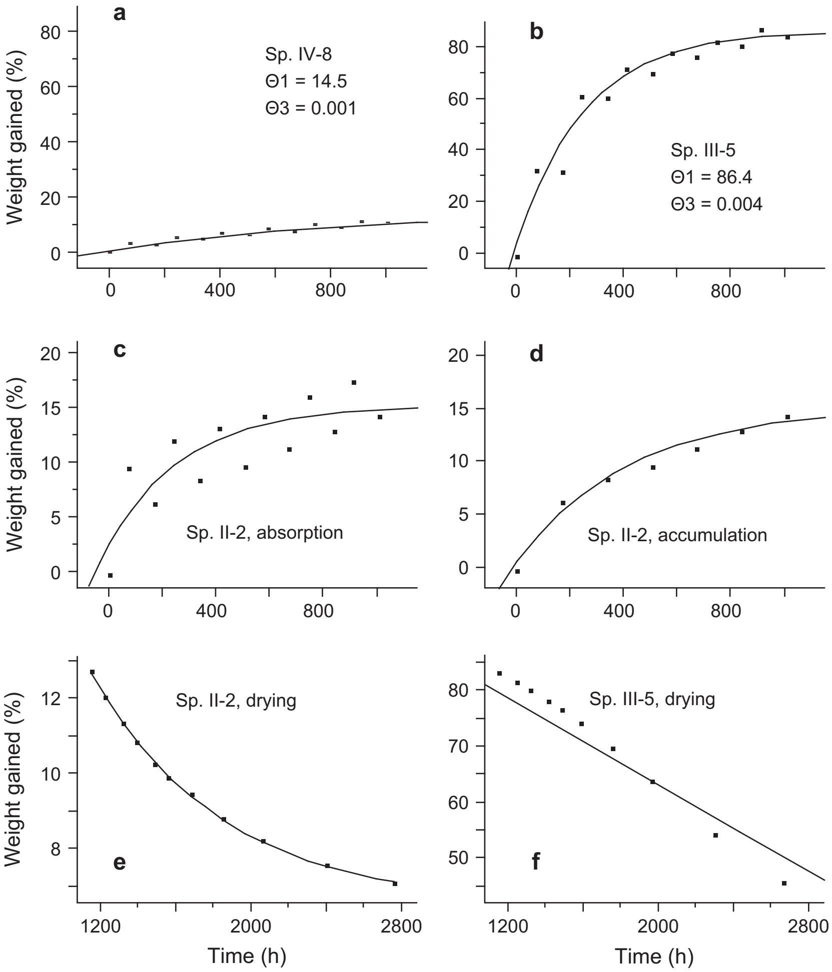

Figure 4. Absorption curves for specimens IV-8 (a) and III-5 (b) illustrate the flexibility of the mechanistic growth model. Absorption (c) and accumulation (d) curves for specimen II-2 indicate that the model fit is better for the accumulation curve than for the absorption curve; in the latter it seems to reach asymptotic values too early. The drying curve for specimen II-2 (e) illustrates that the model generally generated good fits to drying data. Specimen III-5 (f) had extensive brown stain, and the model could not generate a good fit to its drying behaviour.

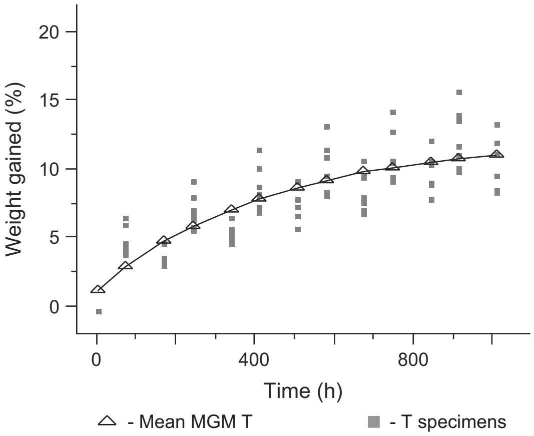

Figure 5. Mean model, absorption curve, shown with observed data from tar-treated specimens. Specimens with brown stain were excluded.

parameters SB specimens had the highest Θ1 value. The difference between SB and T specimens was statistically significant (Table Vb). The growth rate was highest for U specimens and lowest for SB specimens, and differences between three of the treatments were statistically significant (Table Vb).

In the final drying curve Θ1 denotes the minimum retained weight level and Θ3 the decrease rate. T specimens ranged low in retained weight throughout (Figure 6c). U and T specimens dried more quickly than specimens with film-forming coatings (Table Vc), and at the end of the experiment differences between U, WB and SB specimens were indiscernible. In the parameter tests on Θ1 SB and T specimens ranged significantly lower than U and WB specimens (Table Vc). U and T specimens had significantly higher decrease rates than WB and SB specimens.

The accumulation curves had smaller growth rates than the absorption curves (Table Va, b). Large differences in growth rate between the two curves indicate that the specimens dried out a lot during the drying periods, thus slowing down accumulation of water. The largest difference in mean values for Θ3 was found for U specimens, followed by T specimens (Table Vd).

In tests on data observed at selected time intervals untreated specimens maintained the highest level of weight gain throughout the wetting/drying cycles (Table VIa, b). The difference between T and SB specimens was significant only after the first measurements. During final drying T specimens ranged lowest throughout; otherwise the relative levels among surface treatments were the same as during wetting/drying cycles (Table VIc).

Tests on both model parameters and weight gain data from selected time intervals indicated that tar-treated specimens ranged low in moisture gain, and that the moisture gained in these specimens dried out quickly. The two test methods also agree that untreated specimens ranged very high in moisture gain. Contrary to tests on data obtained at selected time intervals, tests on model parameters indicated that untreated specimens would accumulate less water over time than coated specimens.

Plots for extrapolated curves show that SB and T models intersected after approximately 1000 h in both accumulation and absorption curves (Figure 7a, b). After this point, T specimens ranged lowest in moisture gain. In the absorption curve the mean model for SB specimens reached asymptotic values after about 3000 h. In the accumulation curve, the SB model did not reach asymptotic values within the 4000 h shown (Figure 7b). The extrapolated drying curves did not display substantial changes in relative behaviour of the mean model curves (Figure 7c).

Crack orientation. When specimens with brown stain were excluded, the absorption and accumulation curve plots indicated that logs with cracks orientated upwards absorbed slightly more water than those with cracks orientated downwards (Figure 8). The

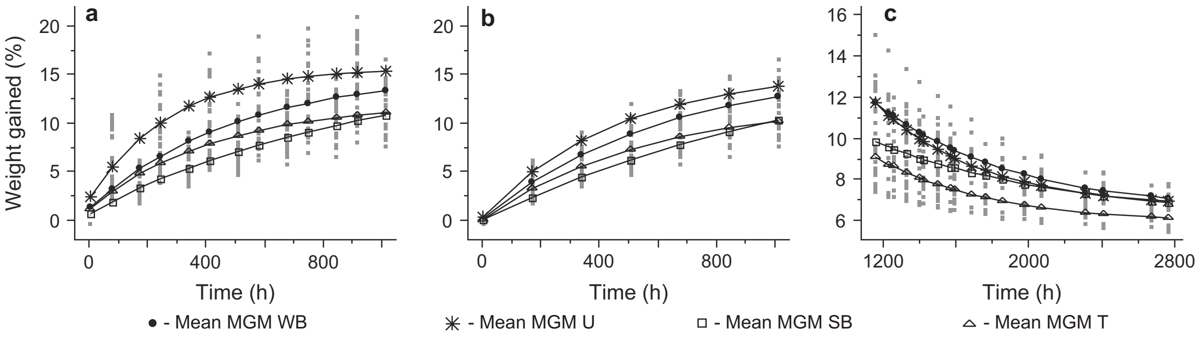

Figure 6. Mean mechanistic growth models (MGMs) fitted to surface treatments: (a) absorption, (b) accumulation, and (c) drying curves. Specimens with brown stain were excluded. By the end of the wetting and drying specimens with tar (T) and solvent-borne coating (SB) were similar in gained moisture; the T sample had almost reached asymptotic values, while the SB sample was still rising steadily. During drying tar-treated specimens were driest throughout.

Table III. Results from tests on parameters from the mechanistic growth model.

Curve	Parameter	Effect	Prob >*F*: whole sample	No specimens with brown stain
(a) Absorption	Θ1	Surface treatment	(0.0597)	0.0550
		Crack orientation	(0.3967)	(0.8794)
		Bluestain	0.0083*[a]	(0.8858)
		Brown stain	<0.0001*[a]	–
	Θ3	Surface treatment	0.0313*	<0.0001*
		Crack orientation	(0.0785)	0.0046*
		Bluestain	(0.0558)	(0.0665)
		Brown stain	<0.0001*	–
(b) Accumulation	Θ1	Surface treatment	(0.0631)	0.0295*
		Crack orientation	(0.4932)	(0.9715)
		Bluestain	0.0188*[a]	(0.7920)
		Brown stain	<0.0001*[a]	–
	Θ3	Surface treatment	(0.0841)	<0.0001*
		Crack orientation	(0.0700)	0.0226*
		Bluestain	0.0191*	(0.1537)
		Brown stain	<0.0001*	–
(c) Final drying	Θ1	Surface treatment	0.0143*	0.0002*
		Crack orientation	(0.3086)	0.2520
		Bluestain	0.9692[a]	(0.9805)
		Brown stain	<0.0001*[a]	–
	Θ3	Surface treatment	<0.0001*	<0.0001*
		Crack orientation	(0.1193)	0.0033*
		Bluestain	0.0172*	(0.3534)
		Brown stain	<0.0001*	–

Note: *Significant at 95% confidence level; [a] significant interaction term. *p* values for non-significant terms are shown in parentheses. These were removed from the final model.

tests on model parameters indicated that this was caused by differences in growth rate and that there was some interaction with surface treatment (Table III). Tests on weight gain data from selected time intervals indicated that crack orientation was most important in the first cycles (Table IV).

Influence of incipient decay and bluestain

Influence of incipient decay

Specimens with heavy attack by *P. gigantea* were already markedly heavier than the others after the first wetting period, as can be seen from the plots (Figure 5a).

When the entire material was included in *F* tests on the model parameters, brown stain had a significant effect on both parameters in all curves. Bluestain was important as well, mostly for maximum moisture level (Θ1) and often in interaction with brown stain (Table III). The results from tests on data obtained at selected time intervals were similar to the results from the parameter tests (Table IV).

Influence of surface treatment and crack orientation on specimens with brown stain

Surface treatment and crack orientation did not affect the model parameters significantly when all specimens were included, with the exception of growth rate (Θ3) in the absorption curve (Table III a). In tests on weight gain at selected time intervals with all specimens included, surface treatment only had a significant effect after the spraying periods (Table IV).

Influence of bluestain

In the parameter tests bluestain had significant effect on both Θ1 and Θ3 when all specimens were included, but not in all curves. Where bluestain had a significant effect, interaction with brown stain mostly had a significant effect as well (Table III). Similar results were found for the effect of bluestain in tests on weight gain at selected time intervals. (Table IVc).

Discussion

Materials, modelling and statistical method

The mistake made during distribution of the treatments on the specimens introduces a minor risk of between-log effects confounding the other effects in this study. As a result of the efforts made to minimize between-tree effects during sampling in the forest the differences between logs were very small, as exemplified by the very small differences in year-ring width (Table I). The material was studied closely to

Table IV. Results from tests on weight gain at selected time intervals.

Phase	Time (h)	Effect	Prob >t: all specimens	No brown stain
(a) After spraying	72	Surface treatment	0.0489*	<0.0001*
	(Cycle 1)	Crack orientation	(0.0684)	0.0002*
		Bluestain	0.0064*	(0.3894)
		Brown stain	<0.0001*	–
	408	Surface treatment	0.0165*	<0.0001*
	(Cycle 3)	Crack orientation	(0.1461)	0.0046*
		Bluestain	0.0007*[a]	(0.8620)
		Brown stain	<0.0001*[a]	–
	912	Surface treatment	0.0065*	<0.0001*
	(Cycle 6)	Crack orientation	(0.2108)	(0.0992)
		Bluestain	0.0014*[a]	(0.6573)
		Brown stain	<0.0001*[a]	–
(b) After drying	168	Surface treatment	(0.3682)	<0.0001*
	(Cycle 1)	Crack orientation	(0.1290)	0.0045*
		Bluestain	0.0033*	(0.4709)
		Brown stain	<0.0001*	–
	504	Surface treatment	(0.1719)	<0.0001*
	(Cycle 3)	Crack orientation	(0.2359)	0.0064*
		Bluestain	0.0003*[a]	(0.6046)
		Brown stain	<0.0001*[a]	–
	1008	Surface treatment	(0.0535)	0.0010*
	(Cycle 6)	Crack orientation	(0.2932)	0.2113
		Bluestain	0.0010*[a]	(0.5286)
		Brown stain	<0.0001*[a]	–
(c) Final drying	1152	Surface treatment	(0.0913)	0.0074*
		Crack orientation	(0.4185)	(0.3436)
		Bluestain	0.0008*[a]	(0.8910)
		Brown stain	<0.0001*[a]	–
	1488	Surface treatment	(0.0851)	0.0150*
		Crack orientation	(0.7048)	(0.5916)
		Bluestain	0.0005*[a]	(0.8268)
		Brown stain	<0.0001*[a]	–
	2700	Surface treatment	(0.0943)	0.0048*
		Crack orientation	(0.5273)	(0.7738)
		Bluestain	0.0001*[a]	(0.9221)
		Brown stain	<0.0001*[a]	–

Note: *Significant at 95% confidence level; [a] significant interaction term. p values for non-significant terms are shown in parentheses. These were removed from the final model.

look for possible effects of differences between logs, but none was found as long as specimens with brown stain were excluded from the analysis.

The study of water transport in wood is often based on formulae derived from Fick's law for diffusion and Darcy's law for liquid flow, with diffusion coefficients and void filling degrees derived from sorption curves for each specimen plotted by the square root of time (Siau, 1984; Derbyshire & Robson, 1999; de Meijer & Militz, 2001). In the present experiment this approach would have required the sorption during each of the wetting and drying cycles to be modelled for each specimen. This would demand continuous monitoring of the weight profiles of the specimens, rather than one measurement after each part of the cycles. In addition, the specimens would have to be oven dried to obtain moisture content values. For the purpose of this study, where comparison of the treatments was the main issue, this was deemed unnecessarily complicated.

During absorption, plotting of the weight gain data by the square root of time yielded fairly linear curves for some specimens. For many specimens with brown stain only small parts of the curves were approximately linear, making the use of the growth rate of these curves to describe the data dubious. A non-linear modelling approach provided a model with the necessary flexibility to allow comparison of specimens with brown stain with the rest of the material.

The method of derivation of parameters from non-linear models and subsequent analysis of variance (ANOVA) are discussed in Diggle *et al.* (1996). According to these authors the most important limitation is that the ANOVA approach fails to exploit the potential gains in efficiency from modelling the covariance among repeated observations. The possibility of

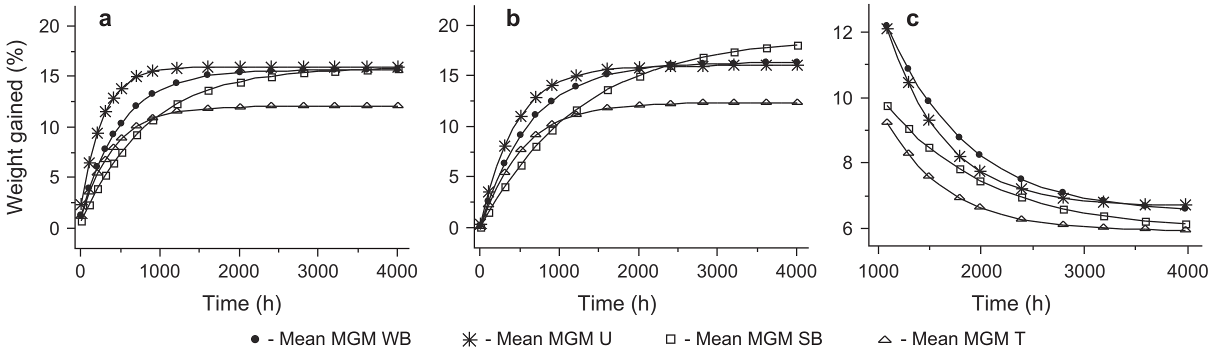

Figure 7. Mean mechanistic growth models (MGMs) for coatings, plotted to 4000 h: (a) absorption, (b) accumulation, and (c) drying curves.

fitting non-linear models to each time sequence, and using parameter estimates from these fits as a natural set of derived variables, is mentioned as an "imaginative way of using derived variables". The argument against this approach is that small-sample behaviour of ordinary least squares estimation in non-linear regression is often poor, making analyses based on it dubious. It also requires complete data sets, and the relevant scientific questions should, if possible, be addressed by a single derived variable. If more variables are of interest, the separate derived variables should address substantially different questions, and each should have a natural interpretation in its own right. If these reservations are taken into consideration, Diggle *et al.* (1996) state that the method can give a simple and easily interpretable analysis. In the present study the data sets are complete and the models deliver rather good fits, with some reservations to be discussed later. The parameters $\Theta 1$ and $\Theta 3$ denote the asymptote and increase rate of the curves, describing different aspects of the moisture development of the test logs. The parameter

Table V. Results from Tukey HSD tests: effect of surface treatments on parameters from the mechanistic growth model.

Curve	Parameter	Level	Tukey	LSMean
(a) Absorption	$\Theta 1$	U	A	16.06
		SB	A	15.98
		WB	A	15.72
		T	A	12.15
	$\Theta 3$	U	A	0.0037
		T	B	0.0024
		WB	BC	0.002
		SB	C	0.0012
(b) Accumulation	$\Theta 1$	SB	A	18.93
		WB	AB	16.42
		U	AB	16.09
		T	B	12.44
	$\Theta 3$	U	A	0.0023
		T	AB	0.0019
		WB	B	0.0016
		SB	C	0.0011
(c) Final drying	$\Theta 1$	U	A	6.69
		WB	A	6.47
		SB	B	5.93
		T	B	5.93
	$\Theta 3$	U	A	0.0018
		T	A	0.0017
		WB	B	0.0013
		SB	B	0.001
(d) Difference between Abs and Acc for $\Theta 3$	$(\Delta(\Theta 3) = (\Theta 3\text{Abs} - \Theta 3\text{Acc}))$	U	A	0.0014
		T	B	0.0005
		WB	B	0.0004
		SB	B	0.0001

Note: All specimens with brown stain excluded. Levels with different letters are significantly different at 95% confidence level. SB = solvent-borne coating; T = tar coating; U = no coating; WB = water-borne coating; Abs = absorption; Acc = accumulation.

Table VI. Results from Tukey HSD tests: effect of surface treatments on weight gain at selected time intervals.

Phase	Time (h)	Level	Tukey	LSMean
(a) After spraying	72	U	A	9.87
		WB	B	5.33
		T	B	5.03
		SB	C	3.02
	408	U	A	14.54
		WB	B	9.78
		T	BC	8.78
		SB	C	6.73
	912	U	A	18.74
		WB	B	14.35
		T	BC	12.12
		SB	C	11.04
(b) After drying	168	U	A	5.81
		WB	B	4.36
		T	B	3.75
		SB	C	2.65
	504	U	A	10.01
		WB	AB	8.67
		T	BC	7.15
		SB	C	6.16
	1008	U	A	14.21
		WB	AB	13.05
		SB	BC	10.47
		T	C	10.42
(c) Final drying	1152	U	A	11.85
		WB	A	11.78
		SB	AB	9.87
		T	B	9.19
	1488	U	A	9.86
		WB	AB	9.5
		SB	AB	8.82
		T	B	7.80
	2712	U	A	7.14
		WB	A	6.99
		SB	AB	6.89
		T	B	6.18

Note: All specimens with brown stain excluded. Levels with different letters are significantly different at 95% confidence level. SB = solvent-borne coating; T = tar coating; U = no coating; WB = water-borne coating.

Θ2 is dependent on both of these variables, and since an interpretation of that parameter could not be performed independently it was omitted from the analyses.

The MGM can be used when modelling biological growth processes (Draper & Smith, 1981). Although it is not a standard method in studies of moisture transport in wood, it proved useful for the purpose of the present work as it provided good, easily interpretable representations of the amount of water absorbed. As shown in Figure 4, model fitting was less successful to untreated logs than to treated logs, especially in the interpolated absorption curve. Fitting the models to an uninterrupted absorption would have been easier and would have allowed the use of physically founded models for water transport in wood, but would not offer the opportunity to study moisture development during cycles of wetting and drying, which is of interest in relation to wood used outdoors. The accumulation curve was not interrupted in the same way, and the model generated better results. The modelling would probably benefit from an experiment with even more cycles, particularly the SB and WB specimens. The drying curve was uninterrupted and had a longer duration, and the models fit these data very well.

As additional moisture above a conditioned starting point was measured, one would expect the asymptote Θ1 to be 0 in the drying curve. As none of the mean models yielded a Θ1 value lower than 5.9% this was not the case. The main reason for this is probably that the model reached its asymptote too soon, thus failing to predict the very slow weight decrease that will occur during the last phases of drying in large wood specimens. In addition, the initial acclimatizing and final drying took place in different laboratory facilities, which might have slightly different climates due to different room sizes and climate unit capacities.

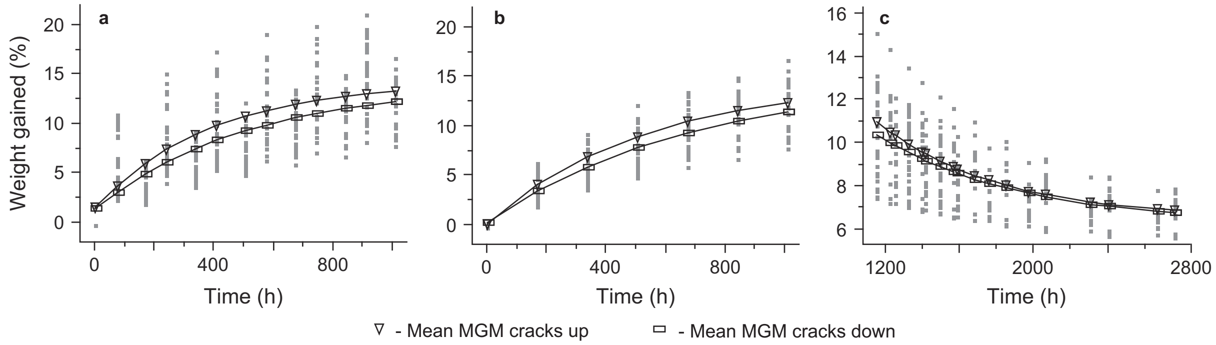

Figure 8. Mean mechanistic growth models (MGMs) fitted to cracks up/down:: (a) absorption, (b) accumulation, and (c) drying curves. All specimens with brown stain were excluded. Models based only on orientation of cracks seem to describe the variation in the data rather poorly.

The results from the modelling are an extrapolation of the relative development of the different treatments during the experiment. It is important to bear in mind when interpreting the results that some of the treatments yielded better model fits than others.

Surface treatment

As shown in the extrapolated curves in Figure 7, there would have to be approximately 2500 h (almost 4 months) of three rainy days followed by four dry days for the specimens with SB coating to accumulate more water than untreated specimens and specimens with WB coating. The spraying nozzles used also yielded more water per area than normal rain. This makes direct transfer of these results to the reality of a timber wall difficult, but the experiment does provide information on the relative performance of different surface treatments.

In uncoated wood water uptake is driven by both diffusion and capillary processes (Voigt *et al.*, 1940; Siau, 1984; de Meijer & Militz, 2000; Virta *et al.*, 2006). Drying is a slower process, dependent on water transport to and evaporation from the surface of the wood. The moisture front developed during wetting will initially move farther into the wood during drying, causing retention of water (Derbyshire & Miller, 1997). A coating film will prevent capillary uptake and inhibit diffusion during both water uptake and drying to a varying degree, depending on the barrier properties of the coating. In the present study the uncoated wood exposed in the cracks speeded up the water uptake and possibly resulted in smaller differences in increase rates between coated and uncoated specimens, but probably did not contribute accordingly to speed up the drying process. This explains why cyclic drying and wetting resulted in accumulation of water in the logs, and more so in specimens with coatings that impede diffusion. However, the models for the uncoated specimens seem to have reached asymptotic values too soon, indicating that these specimens probably should have had greater maximum moisture levels ($\Theta 1$).

SB-coated specimens had the highest $\Theta 1$ of all in the accumulation curve (Table Vb, Figure 7b). This indicates that this coating acted as a diffusion barrier during drying, sealing the moisture inside the wood. The same effect was seen for WB-coated specimens. This coating gave higher absorption rates, which correlates well with results from other studies (Ahola *et al.*, 1999; de Meijer *et al.*, 2001; de Meijer & Militz, 2001). Water repellence and openness to diffusion during drying are probably the reasons for the good performance shown by tar-coated logs in the present study. Wood tar has been shown by Hauer (2007) to repel liquid water, but to be much more open to diffusion than a standard solvent based coating. Another partial explanation for the good performance of wood tar when applied to wood might be the fact that the components of wood tar are very similar to wood resin (Egenberg, 2003), which is the natural protection agent used by living trees. This may give it the ability to penetrate the wood easily and perhaps also bond better with the wood than other non- or semi-film-forming agents. None of the specimens was exposed to sunlight or ultraviolet (UV) radiation before testing, which means that no hardening of the tar had taken place (Egenberg, 2000). If allowed to harden, the tar might have become more film-forming and water repellent (Hauer, 2007). If the test logs had been exposed to sunlight over some time, wood tar would probably deteriorate more rapidly than the coatings, becoming less water repellent.

Crack orientation

Crack orientation was less important than surface treatment in this test. This was unexpected, as water was standing in a number of the upward-orientated cracks after each drying. The most important reason for this apparent discrepancy is probably that the effect of the cracks is more important to the moisture content close to the crack than in the specimen as a whole. If the moisture profiles in the specimens had been measured after each cycle, the cracks would probably have had a larger influence. The moisture content in wood adjacent to a crack will be higher than in the rest of the log, and this can explain the common pattern of deterioration starting in the vicinity of a large crack.

Oxygen, water and wood are readily available to microorganisms in a crack. An attack initiated by conditions due to the treatment of the log will probably start at the point most easily accessible to the fungus. Consequently, upward-orientated cracks may be the chosen points of attack by deteriorating fungi because of the availability of all necessary factors, rather than because the crack causes the piece of wood as a whole to gain more moisture during rain. The cracks in this study were triggered by a chainsaw cut, resulting in a different wood surface in the outer part of the crack than would have been the case if it had formed naturally. This might have caused somewhat different sorption behaviour in these cracks than in a naturally formed crack, but any effect of this was probably very small.

Incipient decay and bluestain

In this study water absorption in log specimens was shown to be very dependent on the level of attack by

Phlebiopsis gigantea. This fungus has been shown to increase cell-wall porosity in wood after 8 weeks of colonization of 2–2.5 m length pine logs (Behrendt & Blanchette, 1997). In the present study, the attack was seen towards the end of 12 months of natural drying of logs twice as long, giving the fungus ample time to increase the porosity of the wood. During conditioning of the 0.5 m specimens, areas with brown stain were moist for a long time after the rest of the specimen seemed dry. Rot fungi of this type have the ability to produce metabolitic water as they deteriorate the wood, and thus attacked wood retains moisture longer than unattacked wood (Eaton & Hale, 1993).

The attack by *P. gigantea* was not planned for, and resulted in reduction of the sample size. However, it presented an opportunity to study the influence on incipient decay on water uptake, and the relative importance of incipient decay and surface treatment. Even specimens with very little brown stain were influential. Relative to results shown in Table III for specimens with no brown staining, inclusion of specimens with 5% brown stain caused substantial changes. No effect by surface treatments was found for $\Theta 1$ in absorption and accumulation curves, while brown stain emerged as an additional significant effect for $\Theta 3$ in the accumulation curve and both parameters in the drying curve. Inclusion of specimens with less than 10% brown stain affected results for both parameters in all curves, for many parameters closely resembling the results obtained from the whole sample. The results from the present study indicate that water uptake in logs is influenced by bluestain, but only in interaction with brown stain. Earlier studies have shown effects of mould or bluestain fungi attacks on the impregnability of wood (Lindgren & Scheffer, 1939; Lindgren, 1952; Schulz, 1956). The degree of bluestain in specimens without brown stain in the present study varied from 0.1% to 6.4% of slice area (not tabulated). This range may be too small to show the effect of the amount of bluestain. All specimens showed some bluestain, so there was no unstained reference material, making it impossible to conclude from this study whether the presence of bluestain is influential on the absorption of water.

Storage rot is prohibited in sawlogs according to Norwegian regulations for timber trade (TMF, 1998). The effect of brown stain found in this study illustrates the importance of this, indicating that a seemingly small rot attack acquired during storage makes the attacked log inappropriate for use in log house walls.

Conclusions

Wood tar had the best long-term effect on pine log specimens subjected to cyclic wetting and drying, probably because it repels water during wetting and is open to diffusion during drying. In the short run film-forming SB and WB coatings prevented water uptake, but in the long run these coatings caused accumulation of water in the wood. This effect was strongest in test logs given an SB coating. Upward-orientated cracks gave higher moisture increase rates than downward-orientated cracks. Brown stain caused by an attack by the white-rot fungus *P. gigantea* was heavily influential on water uptake. Bluestain was influential in interaction with brown stain, but not by itself. Using an MGM to study the development of water absorption and drying in a cyclic wetting and drying scheme proved useful, and the derivation of parameters from individual specimen model fitting made statistical analysis of the differences between treatments easily interpretable.

Further investigations on log house material should include differences in wood quality in combination with surface treatments, as well as the behaviour of wood tar hardened by UV radiation and in different stages of deterioration. Another interesting question is the relations between moisture gain and time given wetting and drying periods of different duration, and moisture profiles in the wood during wetting and drying given different treatments. Such investigations would require a substantially larger material, which should be harvested and conditioned in such a way as to minimize the risk of microbial attack.

Acknowledgements

The authors greatly acknowledge Bjørn Slette (Norwegian University of Life Sciences) for building the experiment rig and contributing much of the work with weighing the test logs, Maria Nunez (Mycoteam as) for performing the microscope analysis and Professor Halvor Solheim for commenting on the manuscript. Guidance in finding a way to model results from cyclic wetting and drying over an extended period from Associate Professor Solve Sæbø (Norwegian University of Life Sciences) is also greatly acknowledged, as is the funding granted by the Norwegian Research Council.

References

Ahola, P., Derbyshire, H., Hora, G. & de Meijer, M. (1999). Water protection of wooden window joinery painted with low organic solvent content paints with known composition. Part 1. Results of inter-laboratory tests. *Holz Als Roh- und Werkstoff*, *57*, 45–50.

Behrendt, C. J. & Blanchette, R. A. (1997). Biological processing of pine logs for pulp and paper production with *Phlebiopsis gigantea*. *Applied and Environmental Microbiology*, *63*, 1995–2000.

Bøhlerengen, T. & Mattsson, J. (1995). Tilstandsanalyse av utvendig treverk. Billedkatalog, symptomliste og typiske skadesteder. *Byggforskserien*, *720*.116. Oslo: SINTEF Byggforsk.

Derbyshire, H. & Miller, E. R. (1997). Moisture conditions in coated exterior wood. Part 2: The relation between coating permeability and timber moisture content. *Journal of the Institute of Wood Science*, *14*, 162–168.

Derbyshire, H. & Robson, D. J. (1999). Moisture conditions in coated exterior wood—Part 4: Theoretical basis for observed behaviour. A computer modelling study. *Holz Als Roh- und Werkstoff*, *57*, 105–113.

Diggle, P. J., Liang, K.-Y. & Zeger, S. L. (1996). *Analysis of longitudinal data*. Oxford: Clarendon Press.

Draper, N. A. & Smith, H. (1981). *Applied regression analysis*. New York: John Wiley & Sons.

Eaton, R. A. & Hale, M. D. C. (1993). *Wood. Decay, pests and protection*. London: Chapman & Hall.

Egenberg, I. M. (2000). *Tjærebreing av stavkirker fra middelalderen*. Norsk institutt for kulturminneforskning, 82-426-1163-7.

Egenberg, I. M. (2003). Tarring maintenance of Norwegian medieval stave churches: Characterisation of pine tar during kiln-production, experimental coating procedures and weathering. *Acta Universitatis Gothoburgensis*, Göteborg.

Egenberg, I. M. (2004). *Milebrent tyritjære: tekniske egenskaper og et historisk korrekt vedlikehold* (pp. 127–136). Oslo: Foreningen til norske fortidsminnesmerkers bevaring.

Hauer, D. (2007). *Bruk av ikkepigmentert overflatebehandling med konservering av trebygninger, med vekt på steinkulltjære og steinkulltjærederivater. En sammenlignende studie av forholdet mellom overflatebehandlinger og fuktdynamikk*. Department of Conservation, University of Oslo.

Hjort, S. (1989). Rötskadade träfasader i en klimatiskt utsatt miljö: En utredning av rötskador med speciell inriktning mot småhusområdet Torpet, Lysekil. *Chalmers Tekniska Högskola*, *P-89*, *4*, 53.

Jenssen, K. M. (1989). Decay of external woodwork caused by *Dacromyces stillatus*. A case study. In P. Gatenholm (Ed.), *Degradation of painted wood by fungi: Proceedings of the International Minisymposium*, Nordic Institute for Coatings Research, Copenhagen, Denmark (pp. 11–14).

Lindgren, R. M. (1952). Permeability of southern pine as affected by mold and other fungus infection. In *AWPA Proceedings*. American Wood Preservers' Association, New York City (pp. 158–168).

Lindgren, R. M., & Scheffer, T. C. (1939). Effect of blue stain on the penetration of liquids into air-dry southern pine wood. In *AWPA Proceedings*. American Wood Preservers' Association, New York City (pp. 325–336).

de Meijer, M. & Militz, H. (2000). Moisture transport in coated wood. Part 1: Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. *Holz Als Roh- und Werkstoff*, *58*, 354–362.

de Meijer, M. & Militz, H. (2001). Moisture transport in coated wood. Part 2: Influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional change. *Holz Als Roh- und Werkstoff*, *58*, 467–475.

de Meijer, M., Creemers, J. & Cobben, W. (2001). Relationships between the performance of low-VOC wood coatings and the dimensional changes of the wooden substrate. *Surface Coatings International Part B: Coatings Transactions*, *84*, 77–85.

Schulz, G. (1956). Exploratory tests to increase preservative penetration in spruce and aspen by mold infection. *Forest Products Journal*, *6*, 77–80.

Siau, J. F. (1984). *Transport processes in wood*. Springer, Berlin.

TMF (1998). FUNT (Ed.). *Målereglement for skogsvirke*. Tømmermålingsrådenes fellesorgan.

Tveite, B. & Braastad, H. (1981). Bonitering for gran, furu og bjørk. *Norsk Skogbruk*, *27*(4), 17–22.

Virta, J., Koponen, S. & Absetz, I. (2006). Modelling moisture distribution in wooden cladding board as a result of short-term single-sided water soaking. *Building and Environment*, *41*, 1593–1599.

Voigt, H., Kirscher, O. & Schauss, H. (1940). Die Feuchtigkeitsbewegung bei der Verdunstungstrocknung von Holz. *Holz Als Roh- und Werkstoff*, *3*, 305–321.

Wadsö, L. (1993). *Studies of water vapour transport and sorption in wood*. Lund University.

ULTRASOUND – A FEASIBLE TOOL FOR DECAY DETECTION?

Mari Sand Sivertsen[1], Gry Alfredsen[2], Mats Westin[3]

ABSTRACT

Mechanical strength properties are the most important feature of wood in constructions. In decaying wood strength loss can precede mass loss. Hence, both in laboratory and outdoor applications non-destructive measurement methods for early decay detection are in demand. The aim of this study was to evaluate the applicability of ultrasonic pulse propagation as a tool for decay detection in different laboratory setups. A dynamic MOE (MOE_{dyn}) strength test device based on measurement of ultrasonic pulse propagation was used for non-destructive strength evaluation in different exposure situations for Scots pine sapwood. Two different test setups were used.

In the first test MOE_{dyn} was measured above fibre saturation. A range of different wood protection treatments were tested according to the terrestrial microcosms (TMC) test, a modified ENV 807. Three different soil types were used: forest soil dominated by white rot, Simlångsdalen test field soil dominated by brown rot and compost soil characterised by a mixture of bacteria and soft rot. Before strength testing the samples were water saturated and MOE_{dyn} was measured above the fibre saturation point at time intervals (0, 8, 16, 24, 32 and 40 weeks) using ultrasound. Comparisons of strength loss were performed between treatments in the different soil types, and strength loss was also compared with mass loss.

In the second test MOE_{dyn} were measured below fibre saturation. Ultrasound measurements were performed on 0.5 m pine logs sampled from five trees from the same stand in central Southern Norway. Logs from two of the trees had varying amounts of discoloration due to an incipient attack by the white rot fungus *Phlebiopsis gigantea* during storage. Amount of visible discoloration had effect on MOE_{dyn} values from measurements on log ends. Transversal measurement of MOE_{dyn} was not successful. In a subsequent water uptake test, logs with discoloration absorbed substantially more water than the rest of the sample.

The conclusion of this study was that the use of ultrasonic MOE is applicable as an evaluation tool in early decay detection.

Key words: ultrasound, early decay detection, dynamic MOE

---

[1] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Tel: +47 64 96 58 00, Fax: +47 64 96 58 01, E-mail: mari.sivertsen@umb.no

[2] Norwegian Forest and Landscape Institute, P.O. Box 115, NO-1431 Ås, Tel: +47 64 94 80 00, Fax: +47 64 94 80 01, E-mail: gry.alfredsen@skogoglandskap.no

[3] SP Technical Research Institute of Sweden, SE-501 15 Borås, Sweden, Tel: +46 10 516 50 00, Fax: +46 33 13 55 02, E-mail: mats.westin@sp.se

INTRODUCTION

Mechanical properties, usually the most important characteristics of wood for use in structural applications, are highly influenced by microbial deterioration. In order to assess the degree of decay in wood in laboratory tests and in use, non-destructive tests are in demand. Modulus of elasticity (MOE) is highly correlated to the ultimate strength in bending (Kollmann & Côté 1968), and a high correlation between static MOE and dynamic MOE has been reported (e.g. Gerhards 1975; Pellerin 1965). The determination of dynamic MOE (MOE_{dyn}) is non-destructive even on decayed wood, and these methods are particularly interesting for evaluation of wood decay. Ultrasound is one of the main methods of determining MOE_{dyn}, and this method has been shown to give satisfactory results (Bauer & Kilbertus 1991; Faraji et al. 2004).

When evaluating ongoing decay tests, drying of the specimens is not feasible because it will affect the biological activity in the wood in a negative manner. All mechanical properties of wood stay more or less constant above the fibre saturation point (e.g. Kelsey 1956; Skaar 1984; Tiemann 1906). This makes it feasible to test wood specimens at moisture contents above the fibre saturation point (FSP). However, earlier studies have reported some problems with ultrasound measurements above FSP (Alfredsen et al. 2006; Larnøy et al. 2006).

The permeability of wood is known to increase in very early stages of decay (Behrendt & Blanchette 1997; Lindgren 1952), paving the ground for further decomposition of the wood. Early detection of decay in wood in outdoor use is therefore of great importance. MOE_{dyn} testing has mainly been done on small dimension specimens prepared for durability tests (e.g. Machek et al. 1998; Alfredsen et al. 2006). Possible utilisation of the method on the larger dimensions used in wooden constructions would be practical in early decay detection on wood in use.

The aim of this study was to evaluate the applicability of ultrasonic pulse propagation as a tool for decay detection in different laboratory setups.

MATERIAL AND METHODS

Terrestrial microcosms (TMC)

The wood modifications, reference treatments and control samples used in this part of the study are given in Table 1. Scots pine sapwood (*Pinus sylvestris* L.) was used for the different wood modifications and preservative treated reference. The specimens had the dimensions specified in ENV 807 (2001), 5 x 10 x 100 mm, and were leached according to EN 84 prior to decay testing. The decay study was a terrestrial microcosms (TMC) test (Edlund 1998), a modified ENV 807 (2001). Three different types of soil were used: soil from Scandinavian coniferous forest, garden compost from Sweden and soil from the Swedish test field in Simlångsdalen. The forest soil is dominated by white rot fungi, Simlångsdalen soil by brown rot and compost soil by soft rot and bacteria. Further soil characteristics are given in Westin and Alfredsen (2007). MOE_{dyn} was measured above the fibre saturation point at time intervals (0, 8, 16, 24, 32 and 40 weeks) using ultrasound. The specimens were water saturated for one hour prior to the strength testing. Twelve replicates of each treatment were tested in each of the three soil types. Six specimens of each treatment were harvested and oven dried after 24 and 40 weeks.

Table 1. Wood treatments in the terrestrial microcosms experiments (TMC).

	Treatment	**Treatment levels (abbreviations)**
Wood modifications:	*Furfurylation*	25 WPG (FA 25)
	Thermal modification	212°C, (TM)
	Acetylation	23 WPG (Ac 23)
	Linseed oil*	150 kg/m^3 ret. (Linseed)
References:	*Copper chromium based*	10 kg/m^3 (CC 10)
	Semi-durable hardwood	*Robinia pseudoacacia* heartwood (Robinia)
Control:		*Pinus sylvestris* sapwood (Control)

* wood modification according to the manufacturer due to grafting compound.

Coated log sections

Five Scots pine trees from a single stratus in a single stand in the central part of southern Norway were sampled in such a way as to minimise between-tree and within-tree variation. The specimens for the experiment were taken from the second log of each tree, between 5 and 10 m from the tree stump. The logs were pre-cut along two sides to obtain two distinct cracks during drying, debarked manually and dried naturally outdoors for 12 months. Each log was cut into nine test specimens of 0.5 m in length.

During drying two logs were attacked by a rot fungus (determined to the white rot fungus *Phlebiopsis gigantea* (Fr.)). The attack caused brown staining of the wood (up to 35 % of the slice area) in all specimens from log III and in some specimens from log II (up to 8% of the slice area) (Figure 1; Table 2). Annual increment and brown stain were determined by visual inspection of slices cut from the butt end of the specimens.

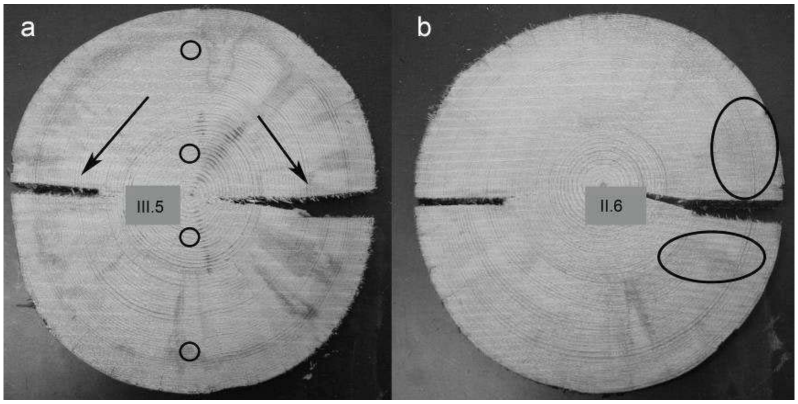

Figure 1. a: Slice from log III showing extensive brown stain. Arrows indicate pre-cut cracks. Measurement points for MOE_{dyn} (3 cm from the pith and outer edge) is indicated with circles. **b:** Slice from log II showing only minor brown stain (rings) and some blue stain.

Table 2. Annual increment width and brown stain. Means for each tree, n = 9 specimens. Max values for area of brown stain due to the white rot fungus *Phlebiopsis gigantea* are listed.

Tree no.	**Annual increm. (mm) Mean**	**StDev**	**Brown stain (% area) Mean**	**Max**
I	1.3	0.03	0	0
II	1.4	0.03	3.06	8.42
III	1.5	0.13	10.30	35.07
IV	1.4	0.04	0	0
V	1.3	0.03	0	0

After 6 months of conditioning in lab climate (20 °C, 65 % relative humidity) the end surfaces of the specimens were sealed using a two-component epoxy sealant. Three different surface coatings (alkyd, acrylic and untreated) and two crack directions (up/down) were used, and the experiment was designed to give two full replicates from the brown stained part of the sample. The test logs were put through 6 wetting and drying cycles, and ultrasonic MOE_{dyn} measurements were done on the specimens prior to the first wetting cycle. Measurement points on the end faces are shown in Figure 1 a. Transversal measurements were done on the midpoint and 10 cm from each end on the same axis as measurements on end faces.

Ultrasound

In both parts of the experiment, dynamic MOE (MOE_{dyn}) was measured using Pundit Plus, an ultrasonic pulse exitation device. The transducers used had resonant frequencies of 200 kHz. The MOE_{dyn} was calculated from the measured transit times using the following formula:

$$MOE_{dyn} = (l \;/ t)2 \cdot m \;/ v \qquad (1)$$

where l = length of specimen (mm), t = measured transit time, m = mass at measurement moisture level (kg) and v = volume at measurement moisture level (m^3). In the TMC experiment calculation of MOE_{dyn} gave illogical results. Therefore, transit time was used for analyses in this part of the experiment.

RESULTS

Terrestrial microcosms (TMC)

In Table 3, percent mass loss and percent strength loss (measured as transit time) compared to initial measured values are shown. The strength evaluation using ultrasound gave the same general trends between treatments as mass loss for all soil types. Interestingly, Simlångsdalen soil gave the highest strength loss, while compost soil gave the highest mass loss. Forest soil generally gave the lowest mass and the lowest strength loss. However, for FA 25 strength loss was highest in forest soil. Mass loss after 40 weeks was equal in compost and forest soil and higher in forest soil than in Simlångsdalen soil. In compost soil several specimens failed (fell apart) from week 32.

Table 3. For the three soil types: percent change in dry weight mass loss (ML) at 24 and 40 weeks and percent change in ultrasound transit time at 8, 16, 24, 32 and 40 weeks.

	Compost soil							Simlångsdalen soil							Forest soil						
	ML		Transit time					ML		Transit time					ML		Transit time				
	24	40	8	16	24	32	40	24	40	8	16	24	32	40	24	40	8	16	24	32	40
FA 25	1	4	3	3	3	1	1	0	3	3	5	4	5	4	0	4	5	6	6	10	10
TM	1	3	4	5	5	5	5	1	2	3	5	5	6	4	1	5	5	5	6	7	8
AC 23	1	1	1	2	1	2	2	0	1	0	0	0	1	1	0	1	3	3	2	3	3
Linseed	11	26	5	5	5	7	5	2	4	6	5	4	9	6	4	9	4	3	2	8	6
CC 10	7	20	0	1	3	6	8	5	7	1	1	1	2	2	3	6	1	1	0	2	2
Robinia	28	45	7	11	12	14	17	5	12	6	7	10	13	14	6	10	7	8	8	10	9
Control	36	74	9	14	19	15*	9*	33	50	20	23	30	50	83	8	27	4	4	4	2	4

* Decrease in ultrasound transit time occurred due to failure of specimens.

Coated log sections

In an ANCOVA test on the whole sample, both amount of brown stain and log number (between-tree effect) had significant effect on MOE_{dyn}. Brown stain had negative effect on MOE_{dyn}, while the sign of the tree effect varied between logs (Table 3). Analysis including only specimens with more than 2.5 % brown stain (n=11) yielded even higher R^2 (0.64) (p brown stain = 0.0171, no tree effect). If transit time was analysed directly, brown stain was the only significant effect (p<0.0001, estimate positive).

Table 4. Results from ANCOVA tests, effect on MOE_{dyn} and transit time.

Sample	Effect	R2	Sign of estimate	p value
All sp., n=35	Log no.	0.79	+(I, III)/-(II, IV, V)	0.0110
	Brown stain		-	<0.0001
All sp., n=35	Brown stain		+	<0.0001

Transversal measurements gave substantially lower MOE_{dyn} than longitudinal measurements. There was a statistically significant correlation between longitudinal and transversal measurements (p = 0.0362). The correlation was clearer in analysis on specimens with no brown stain (p = 0.0084), and disappeared if logs with no brown stain were excluded.

Brown stain had a large influence on water uptake, and effects of coating and crack orientation became important only when brown stained specimens were excluded from the analysis. Detailed description of the results regarding moisture uptake in specimens with different treatments and degrees of brown stain will be reported in an article presently in preparation.

DISCUSSION

The use of ultrasound to measure strength in small soil exposed samples was shown to be useful in detecting early stages of decay. An interesting result was that the highest strength loss was found in Simlångsdalen soil while the highest mass loss was found in compost soil. This is most likely due to differences in species composition of deteriorating fungi in the different soil types. The Simlångsdalen soil is dominated by brown rot. Brown rot is known to cause more rapid strength loss at lower mass losses than white rot fungi. Even though the highest general mass loss was found in compost soil and the highest strength loss was found in Simlångsdalen soil, the furfurylated samples were most affected by the forest soil. The forest soil is dominated by white rot fungi and had the highest water holding capacity and the lowest pH. This result will be of interest for further investigations on the mode of action of furfurylated wood.

The correlation between MOE_{dyn} and brown stain due to *Phlebiopsis gigantea* was less clear in samples with very minor brown stain. MOE_{dyn} was measured in one point at a time, and as the brown stained areas in these specimens were small the MOE_{dyn} measurements may have missed them entirely. The moisture data include the whole log cross sections, including the highly permeable brown stained areas. This might explain why these small areas of brown stain gave little effect on measured MOE_{dyn}, even if they were highly influential on water absorption.

The lack of a significant tree effect on the measured transit time in the coated logs indicates that the tree effect on MOE_{dyn} was caused by the relationship between mass and volume of the samples. On this background the influence by mass loss can be the reason why calculated MOE gave illogical results in the TMC experiment.

The much higher transversal than longitudinal transit time can be explained by the fact that the ultrasound must cross a lot more cell walls in the transversal direction. The significant correlation between longitudinal and transversal transit time indicates that transversal decay detection should be possible. The lack of success in detecting early fungal colonization by transversal transit time might be explained by the fact that the brown stain is caused by *Phlebiopsis gigantea,* a white rot fungus which leaves the cellulose fibres more intact than brown rot. This should be given further study, which should include wood in different stages of decay and brown rot versus white rot.

The conclusion of this study was that the use of ultrasonic MOE is applicable as an evaluation tool in early decay detection, but that it is important to take moisture and temperature into consideration in experimental planning. Ultrasound measurements during decay give supplemental information to mass loss measurements and visual evaluation, illustrating the influence by different deterioration organisms. The direct link to strength properties makes ultrasound a potentially useful tool in technical service life prediction.

REFERENCES

Alfredsen, G., Larnøy, E. & Militz, H. 2006. Dynamic MOE Testing of Wood: The influence of wood protecting agents and moisture content on ultrasonic pulse and resonant vibration. Wood Research 51(1): 10.

Bauer, C. & Kilbertus, G. 1991. Ultrasonic technique for determining the extent of fungus attack of beech and pine wood. Holzforschung 45: 41-46.

Behrendt, C.J. & Blanchette, R.A. 1997. Biological processing of pine logs for pulp and paper production with *Phlebiopsis gigantea*. Applied and Environmental Microbiology 63(5): 1995-2000.

Edlund, M-L. 1998. Durability of untreated wood exposed in terrestrial test fields and microcosms. Material Und Organismen, 32(4): 253-275.

ENV 807 2001. Wood preservatives - Determination of the toxic effectiveness against soft rotting micro-fungi and other soil inhabiting micro-organisms. Brussels, Belgium, European Committee for Standardization (CEN).

Faraji, F., Thèvenon, M.F. & Thibaut, B. 2004. Evaluation of the natural durability and ultrasonic method for decay detection of some European hardwood and softwood species. The International Research Group on Wood Preservation. IRG/WP 04-10537, 12 p.

Gerhards, C.C. 1975. Stress wave speed and MOE of sweetgum ranging from 150 to 15 percent MC. Forest Product Journal 25: 51-57.

Kelsey, K.E. 1956. The shrinkage intersection point - its significance and the method of its determination. Forest Products Journal 6: 411-416.

Kollmann, F.F.P. & Cötë, W.A. 1968. Principles of wood science and technology. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. 551 p.

Larnøy, E., Alfredsen, G. & Militz, H. 2006. Moisture correction for ultrasonic MOE measurements above fibre saturation point in Scots pine sapwood. The International Research Group on Wood Protection. IRG/WP 06-20333, 9 p.

Lindgren, R.M. 1952. Permeability of Southern Pine as affected by mold and other fungus infection. In: AWPA Proceedings, American Wood Preservers Associaton, New York City. p. 158-168.

Machek, L., Militz, H., & Sierra-Alvares, R. 1998. A dynamic approach to assess the modulus of elasticity in wood decay testing. The International Research Group on Wood Preservation. IRG/WP 98-20139

Pellerin, R.F. 1965. A vibrational approach to non destructive testing of structural lumber. Forest Product Journal 15: 93-101.

Skaar, C. 1984. Wood-water relationships. Advances in Chemistry Series (207):127-172.

Tiemann, H.D. 1906. Effect of moisture upon the strength and stiffness of wood. U.S. Dept. of Agriculture, Forest Service, Washington D.C. 144 p.

Westin, M. & Alfredsen, G. 2007. Durability of modified wood in three different soil types (TMCs). In: Proceedings of The Third European Conference on Wood Modification (ECWM3), Cardiff, Wales, UK, p. 309-315.

Water absorption in coated wood.

Part 1: Analysis of different evaluation approaches

Mari Sand Sivertsen[1] and Per Otto Flæte[2]

[1]: Norwegian University of Life Sciences, P.O.box 5003, NO-1432 Ås

[2]: Norsk Treteknisk Institutt, P.O.box 113 Blindern, NO-0314 Oslo

Abstract

Coated and uncoated specimens of fast-grown and slow-grown Norway spruce were subjected to liquid water exposure according to the European standard EN 927-5. The exposure time was prolonged, and different ways of evaluating the amount of absorbed water were analysed. Uncoated specimens of fast-grown spruce absorbed more water and gained more in moisture content at all time intervals. For coated wood specimens a significant effect of wood type was only found after four weeks of exposure or more. Therefore, the flux of water through the surface coating is most likely not influenced by wood properties during the 72 hours of exposure specified in the standard. After four weeks of exposure to liquid water coated slow-grown spruce absorbed larger amounts of water, but the resulting moisture content gain was higher in coated fast-grown spruce. Studying moisture content gain as well as amount of absorbed water was of value in understanding the differences between wood types. Linear regression to sorption curves did not discern better between treatments than amount of absorbed water at selected points of time. The modified EN 927-5 method can be used to evaluate the performance of wood types in combination with coatings regarding liquid water uptake.

Keywords: *liquid water absorption, EN 927-5, Norway spruce,* Picea abies*, coated wood, wood properties*

1. Introduction

The main functions of a wood coating for exterior use are to give the wood a desired aesthetical appearance and to protect the wood from deteriorating agents. Fungal decay is normally the most serious deteriorating agent in exterior wooden structures. Since permanently low moisture content prevents the wood from being decayed by fungi, a major function of coatings should be to protect the wood from water. The standard EN 927-5 (CEN 2000) has been widely used to assess the liquid water permeability of coatings (Ahola et al. 1999; Ekstedt 2003; Ekstedt and Östberg 2001). Better correlation with outdoor tests has been found for laboratory tests of liquid water permeability than for laboratory tests of water vapour permeability (de Meijer 2002).

As the standard EN 927-5 is developed to evaluate coatings rather than differences in wood properties, a uniform test material is specified. The time span for absorption specified in the standard is 72 hours. In tests using the EN 927-5 procedure and other short-term water penetration studies on coated specimens the wood substrate has been shown to be of little importance (Ahola et al. 1999; Virta et al. 2006). In outdoor natural weathering tests of coated wood the wood substrate has been shown to be of importance to water uptake, however (Ahola 1991; Feist 1990; Roux et al. 1988; Williams and Feist 1994), and an effect of substrate has been found on water vapour absorption in coated wood as well (Feist 1985). This indicates that wood properties might affect the water absorption if the time span of the EN 927-5 experiment is extended.

Water uptake according to the standard is reported in terms of grams per test face area and not in terms of increase in moisture content. The effect of the absorbed water on the resulting moisture content of the wood is of large interest, since the activity of deteriorating organisms is dependent on moisture content (Eaton and Hale 1993). The density of the wood substrate will have an effect on moisture content gain, since the same amount of water absorbed will cause larger gain in moisture content in a light specimen than in a heavy one. In an immersion test on coated wood using moisture content gain as response variable, wood species had an effect after 24 hours' exposure. Density values were not reported in this work (Ahola 1991).

Sorption of water in wood where the moisture content is below fibre saturation is described as diffusion (i.e. flow of molecules under the influence of a concentration gradient). Non-steady state diffusion of bound water in wood can be described using equations based on Fick's second law, using sorption isotherms to generate diffusion coefficients (Siau 1984). These equations have been useful in studies on the relative water vapour sorption behaviour of wood with different treatments (de Meijer and Militz 2001; Ekstedt 2002). De Meijer and Militz (2000) showed that the equations in Siau (1984) based on Fick's law for diffusion are applicable to water uptake in coated wood exposed to liquid water. As the diffusion coefficient is determined from plots of dimensionless moisture concentration by the square root of time, the coefficient from regression to a plot of weight or moisture content gain by the square root of time should be applicable as a response variable in water absorption studies. This is a more work-intensive way of reporting water absorption than simply measuring the amount absorbed after a given period of time, but this can be tolerated if better results regarding detection of differences between treatments are generated.

The objectives of this study were 1) to study the effect of prolonging the water exposure time on results from the EN 927-5 liquid water absorption test; 2) to study the effect of reporting results in terms of either mass of water absorbed per area or moisture content gain in the wood specimens; 3) to evaluate how the results are affected by using regression coefficients from linear regression on sorption curves plotted as functions of the square root of time, compared to direct measurements of absorbed water after a given time.

2. Material and methods

2.1 Preparation of test specimens

The material was sampled from air-dried centre boards sawn from butt logs originating from mature Norway spruce (*Picea abies* (L.) Karst), which is the species indicated in the EN 927-5 standard. In order to obtain the desired large differences in wood properties between wood types fast-grown, low-density (SL) Norway spruce trees were sampled in southwestern Norway and slow-grown, high-density (SH) Norway spruce was sampled in northern Norway. A 50 cm section of clear wood was cut from each board, and the board sections were stored in a climate chamber at 20 °C and 65 % RH until they achieved a stable mass.

Each board section was re-sawn to 20 mm x 50 mm dimensions. Sawn rather than planed test surfaces were used, as coating penetration is better on sawn surfaces (Nussbaum et al. 1998). A 150 mm test specimen and an adjacent reference specimen for calculation of mean annual ring width and density were cut from the centre part of the section. Annual ring width and density of the test specimens were calculated according to the procedures described in Kucera (1992), and are given in Table 1. Mean values for density were much lower and mean values for annual year rings much higher in SL specimens than in SH specimens, and there was no overlap in annual ring width or density between the two wood types (Table 1). The reference specimens were also used to calculate initial moisture content and dry weight, as the dry weights of the test specimens were not determined to avoid modification of the wood due to high temperature.

Table 1. Density at 12 % MC (D12) and annual ring width (ARW) of the specimens in the sample groups. SL = Norway spruce with wide annual rings, SH = Norway spruce with narrow annual rings, SB = solvent-borne coating, U = uncoated.

Wood type	**Coating**	**D12 (g/cm^3)**				**ARW (mm)**			
		Mean	St.dev.	Min.	Max.	Mean	St.dev.	Min.	Max.
SL	SB	0.364	0.008	0,354	0,376	4.4	0.9	3,4	6,0
SL	U	0.357	0.007	0,348	0,365	5.2	0.6	4,5	6,1
SH	SB	0.518	0.032	0,468	0,567	1.3	0.4	0,6	1,9
SH	U	0.513	0.019	0,479	0,529	1.1	0.2	0,8	1,3

The test specimens were sealed with two layers of a two component solvent-borne laquer ("Pyrotect Schutslack 2K") on ends, edges and back face. Two layers of a solvent-borne alkyd coating were applied by brush. The test specimens were then conditioned at 20 °C and 65 % RH. In order to leach any water-soluble components the specimens were subjected to three cycles of 72 hours wetting and 96 hours drying prior to the final test, and re-conditioned at 20 °C and 65 % RH to stable mass.

2.2 Water absorption test

During the absorption test the specimens were placed on glass rods, test face down in de-ionised water (Figure 1). The water was maintained at a level where the test face was well into the water (3–4 mm), but the specimens did not float. At intervals during the absorption test the specimens were removed from the water, dried with tissue, weighed and returned to the water. Each specimen was away from the water approximately 5 minutes during this procedure. The coated specimens were exposed to water for 3024 hours (18 weeks), while the uncoated specimens were exposed for 1128 hours (almost 7 weeks). The exposure of the uncoated specimens was stopped earlier than that of the coated specimens due to the development of extensive mould growth on the test face of one of the specimens.

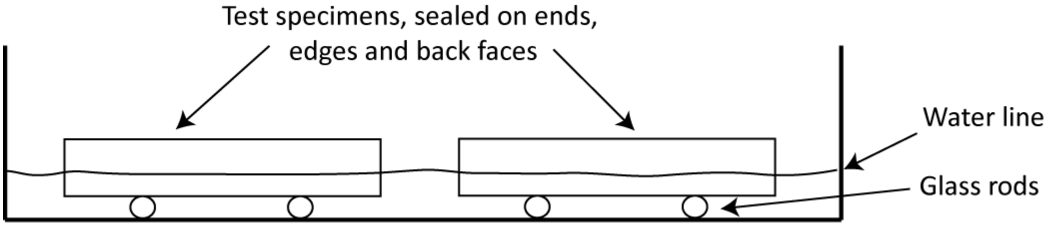

Figure 1. Outline of the experimental setup. The specimens were placed on glass rods, test face down in water.

The water absorbed by each specimen was measured as mass of absorbed water per test face area (MWA, g/m^2) relative to the weight of the conditioned specimen prior to the test, in accordance with EN 927-5 (Equation 1).

$$MWA_1 = (w_0 - w_1)/A \qquad (1)$$

where MWA_1 = mass of absorbed water per area (g/m^2) at time 1; w_0 = weight (g) at time 0; w_1 = weight (g) at time 1; A = area of test face (m^2).

The moisture content gain in each specimen (MCg, %) was calculated according to Equation 2.

$$MCg_1 = ((w_0 - w_1)/w_d) * 100 \qquad (2)$$

where MCg_1 = moisture content gain at time 1(%); w_0 = weight (g) at time 0; w_1 = weight (g) at time 1; w_d = dry weight, untreated (g, calculated based on the MC of the reference specimen).

The MCg was used in order to evaluate the change in moisture content as a result of the absorbed water. This was considered to give more relevant information than the moisture content, which would have to be estimated based on the calculated equilibrium moisture content (EMC) at the outset of the experiment. This calculated EMC value varied between 13.4 and 15.2, and differed significantly between SL and SH specimens.

2.3 Data analysis

Statistical tests were performed as analysis of variance (ANOVA) where only wood type or only continuous variables were studied, and as analysis of covariance (ANCOVA) where wood type was studied together with a continuous variable. Residuals were assumed to be normally distributed. Effects with probability of type 1 error smaller than 0.05 were considered significant. Student's t-tests were performed to test differences between wood types. Tests were performed on MWA and MCg after 72 hours (3 days), 1008 hours (6 weeks) and 3024 hours (18 weeks) of exposure.

MWA was plotted as a function of the square root of time for each of the coated specimens. Regression coefficients of the resulting curves from 0 to 72 hours and 0 to 1008 hours were determined, as well as the regression coefficients of the rectilinear portion of the curves. The regression coefficients were analysed using ANOVA as specified above.

3. Results

3.1 Mass of absorbed water per area (MWA)

Figure 2 a shows the development in mass of absorbed water per area (MWA), presented as mean values for each wood type. SL and SH specimens had the same MWA regardless of wood type until approximately 400 hours. From then on SH specimens absorbed water at a faster rate than SL specimens, and the difference between the wood types became larger as the experiment progressed. At the end of the experiment water absorption in SL specimens seemed to have levelled out. The MWA in SH specimens was still increasing, but at a slowing rate.

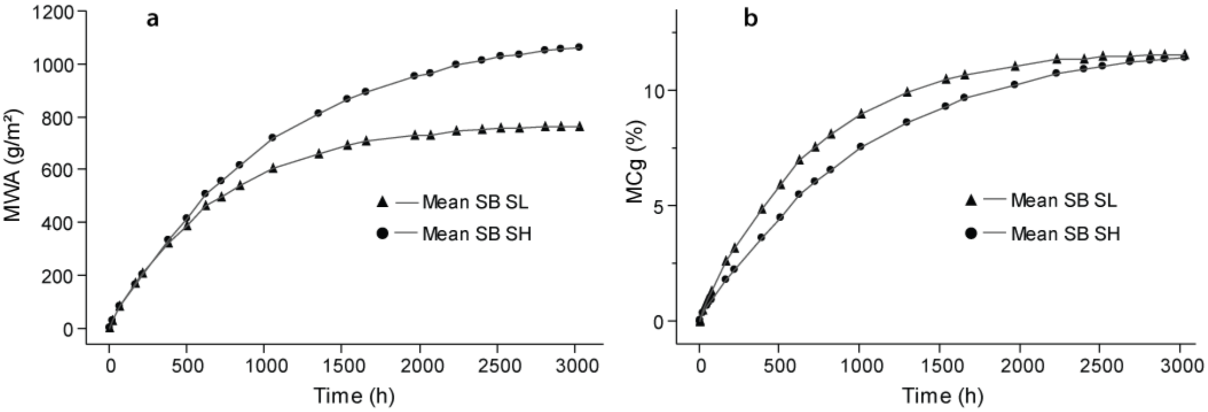

Figure 2. Plots of the development in **a:** mass of absorbed water per area (MWA) and **b:** moisture content gain (MCg) for coated specimens, shown as mean values for each wood type.

The same trend was found in ANOVA tests on MWA. The effect of wood type was tested after 72 hours and every week from then onwards. Results from selected points of time are shown in Table 2. No effect on MWA was found after one, two or three weeks, but after four weeks (672 hours) of exposure the effect from wood type was significant. After that point the importance of wood type kept increasing (Table 2).

Table 2. ANOVA results for wood type vs. mass of absorbed water per area (MWA) and moisture content gain (MCg) in coated specimens at four points of time during the experiment: 72 hours (3 days), 672 hours (4 weeks), 1008 hours (6 weeks) and 3024 hours (18 weeks). Prob >|t| (p-values) lower than 0.05 indicate significant effect of wood type at a 95 % confidence level.

Response	**72 hours**		**672 hours**		**1008 hours**		**3024 hours**	
	R^2	Prob >|t|	R^2	Prob >|t|	R^2	Prob >|t|	R^2	Prob >|t|
MWA	0.0002	0.9687	0.40	0.0271	0.70	0.0004	0.87	<0.0001
MCg	0.70	0.0007	0.78	0.0001	0.74	0.0002	0.02	0.6305

Including both density and wood type in ANCOVA analysis did not yield any significant effects after 72, 672 or 1008 hours, but density had a significant effect on MWA after 3024 hours (p = 0.0070). Wood type did not have any significant effect when density was included. Density analysed alone yielded slightly better fits than wood type (R^2 = 0.004 after 72 h, 0.40 after 672 h, 0.70 after 1008 h and 0.94 after 3024 h) and also had a significant effect after 672, 1008 and 3024 h (p = 0.9270 after 72 h, 0.0234 after 672 h, 0.0002 after 1008 h, and <0.0001 after 3024 h).

3.2 Moisture content gain (MCg)

Figure 2 b shows the development in moisture content gain (MCg), presented as mean values for each wood type. SL specimens ranged high throughout, but the difference between the wood types diminished as the experiment progressed. At the end of the experiment the mean moisture content was 26 % for SH specimens and 27 % for SL specimens. The MCg levelled out from approximately 2500 hours in SL specimens, while in SH specimens it had slowed down and seemed to have almost levelled out at the end of the experiment (Figure 2 b). The same trend was found in ANOVA tests; wood type had a significant effect on MCg at all times until 2300 hours, after which point it had no significant effect. Results from selected points of time are shown in Table 2.

Including both density and wood type in ANCOVA analysis did not yield any significant effects on MCg at any of the times analysed. Density analysed alone yielded identical or slightly better fits than wood type alone (R^2 = 0.75 after 72 h, 0.82 after 672 h, 0.81 after 1008 h and 0.02 after 3024 h) and had significant effect after 72 (p = 0.0003), 672 (p < 0.0001) and 1008 hours (p < 0.0001), but not after 3024 hours (p = 0.6549).

3.3 Linear regression

An example of the linear regressions for one of the specimens is shown in Figure 4. The regressions yielded mean R^2-values of 0.96 for the MWA curve until 72 hours, 0.98 for the MWA curve until 1008 hours and 0.996 for the rectilinear part of the curve. Results from ANOVA on the regression coefficients are shown in Table 3. The effect of wood type on the regression coefficient until 72 h resembled that from ANOVA on MWA until 72 h (Table 2). The results from ANOVA on regression coefficients after 1008 h were slightly poorer and the result from the linear portion of the curve was slightly better than the result from ANOVA on MWA after 1008 h (Tables 2, 3).

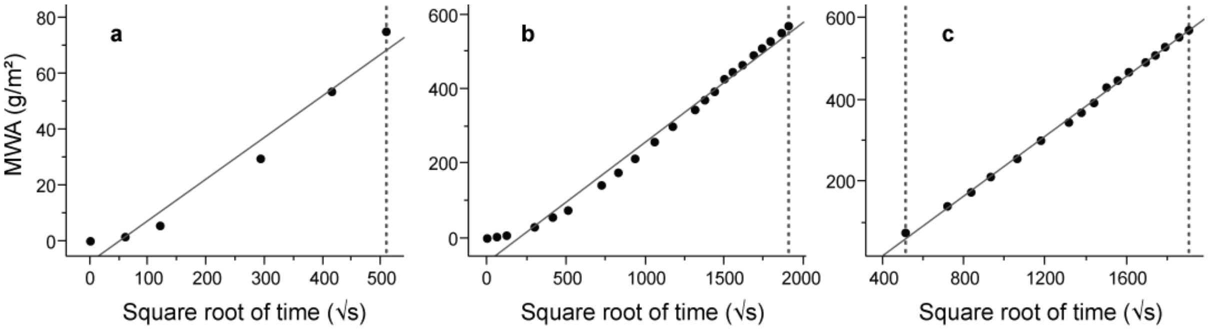

Figure 3. Regressions on the curve of MWA by the square root of time for specimen 85 (SL). **a**: 0–72 hours; **b**: 0–1008 hours; **c**: The rectilinear portion of the curve, 72–1008 hours. Vertical lines indicate the endpoints of the regression. The lowest endpoint is only indicated if different from 0.

Table 3: ANOVA results for wood type vs. magnitude of the parameters from regression to three different time intervals in coated specimens. The first 72 hours (3 days), the first 1008 hours (6 weeks) and the interval from 72 to 1008 hours. p-values lower than 0.05 indicate significant effect of wood type at a 95 % confidence level.

Until 72 h		**Until 1008 h**		**Rectilinear part**	
R^2	Prob >|t|	R^2	Prob >|t|	R^2	Prob >|t|
0.0007	0.9365	0.62	0.0022	0.76	0.0002

3.4 Uncoated control specimens

As opposed to what was found for coated specimens, uncoated SL specimens absorbed more water than uncoated SH specimens (Figure 4 a). The moisture gain was also faster in uncoated SL than in uncoated SH specimens (Figure 4 b). The difference between wood types increased throughout the experiment, but was larger for MCg than for MWA at all times. The much larger absorption in uncoated than in coated specimens can be seen from the different y-axes in Figure 2 and 4, and the shorter time span in Figure 4.

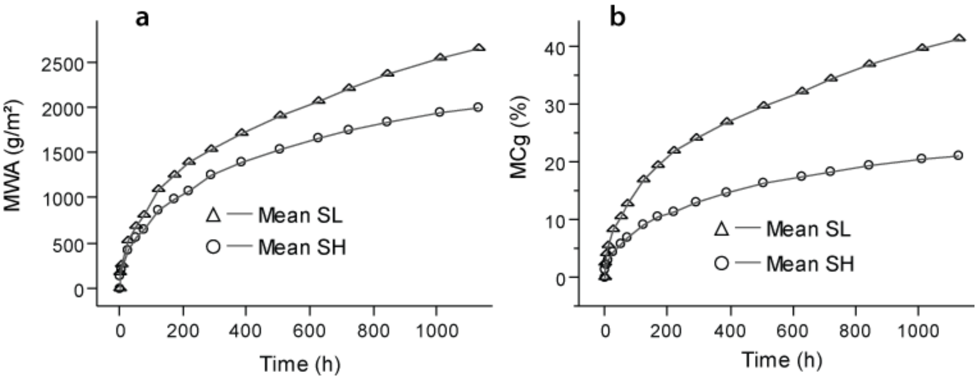

Figure 4. Curves showing development in **a:** moisture content gain (MCg), and **b:** mass of absorbed water per test face area (MWA) for uncoated specimens, mean values for each wood type. Note different axes from Figure 2.

Wood type had significant influence on MWA in uncoated specimens for all the time intervals analysed. Results from selected points of time are shown in Table 4. Adding density to the model and performing ANCOVA yielded almost identical R^2-values, but neither wood type nor density had any significant effect. Inclusion of interaction between density and wood type had no effect after 72 hours. After 672 hours both wood type and interaction were significant ($p = 0.0309$ for wood type, 0.0526 for density and 0.0496 for interaction), and R^2 was 0.85. After 1008 hours wood type was the only significant effect ($p = 0.0292$ for wood type, 0.0571 for density and 0.0585 for interaction), and R^2 was 0.88. Density alone yielded slightly poorer fits than wood type alone ($R^2 = 0.77$ after 72 h, 0.58 after 672 h and 0.66 after 1008 h), but had significant effect on MWA at all times ($p = 0.0020$ after 72 h, 0.0170 after 672 h and 0.0075 after 1008 h).

Wood type had significant effect on MCg at all times (Table 4). Adding density to the model and performing ANCOVA did not affect the R^2-values, but neither wood type nor density had significant effect. Inclusion of interaction between density and wood type had no effect after 72 hours. After 672 and 1008 hours both wood type and interaction were significant ($p = 0.0132$ for wood type, 0.0641 for density and 0.0440 for interaction after 672 h; $p = 0.0107$ for wood type, 0.0619 for density and 0.0455 for interaction after 1008 h), and R^2-values were 0.97 and 0.98, respectively. Density alone yielded slightly poorer fits than wood type alone ($R^2 = 0.95$ after 72 h, 0.89 after 672 h, and 0.90 after 1008 h), but had significant effect on MCg at all times ($p = 0.0001$ after 672 h, $p < 0.0001$ after 72 h and 1008 h).

Table 4: ANOVA results for wood type vs. moisture content gain (MCg) in uncoated specimens at three points of time during the experiment. 72 hours (3 days), 672 hours (4 weeks), and 1008 hours (6 weeks). Prob >\|t\| (p-values) lower than 0.05 indicate significant effect of wood type at a 95 % confidence level.

Response	**72 hours**		**672 hours**		**1008 hours**	
	R^2	Prob >|t|	R^2	Prob >|t|	R^2	Prob >|t|
MWA	0.79	0.0014	0.64	0.0100	0.72	0.0037
MCg	0.97	<0.0001	0.93	<0.0001	0.94	<0.0001

Linear regression was not performed on uncoated specimens, but in plots of mean curves for the wood types vs. the square root of time indications of two linear phases were found (Figure 5).

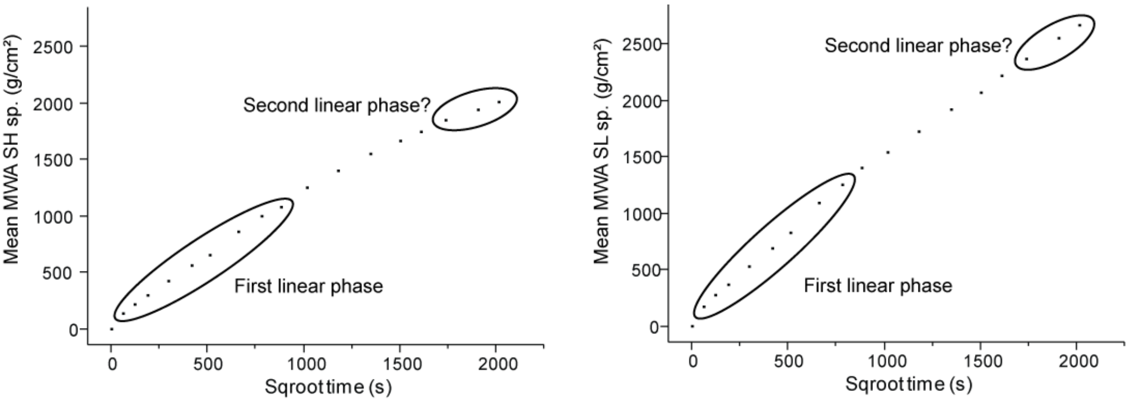

Figure 5. Plots of mean MWA by the square root of time for both wood types. **a**: SH specimens; **b**: SL specimens. There were indications of a second linear phase at longer exposure times, outlined by ellipses in the plots. First linear phases corresponding to those shown for coated specimens in Figure 4 are outlined as well.

4. Discussion and conclusions

4.1 EN 927-5, feasibility for use on combinations wood types/coatings

The standard method described in EN 927-5 (CEN 2000) is developed to evaluate the water permeability of coating films, rather than the water uptake in different wood types. The EN 927-5 method has earlier been shown to discern between the permeability of coatings to a satisfactory degree (Ahola et al. 1999; Ekstedt 2003; Ekstedt and Östberg 2001). In experiments using slightly modified versions of the EN 927-5 procedure on uncoated wood, liquid water permeability has been shown to be different in sapwood and heartwood of Norway spruce (Bergström and Blom 2007), and in thermally modified heartwood and sapwood of Scots pine and Norway spruce specimens (Metsa-Kortelainen et al. 2006). In the revised EN 927-5 (CEN 2006) a consideration is included in Appendix A, indicating that results from this test should be used to evaluate the relative performance of the coating systems tested rather than to predict the performance of a coating in service.

The wood material in the present study was selected in order to obtain large differences in density and annual ring width. Based on the large effect of wood types found on water absorption in uncoated specimens (Figure 2 b) effects on absorption in coated specimens could be expected as well. Still, no significant differences between wood types could be found after 72 hours. Against this background tests according to the standard EN 927-5 should perform well regarding coating performance, unaffected by density or annual ring width variations even beyond the scope specified in the standard. However, as MWA in uncoated specimens was heavily affected by wood type from the onset of the test, it should be kept in mind that coatings with very high permeability might be affected by wood properties after short-term exposure.

If wood properties are intended objects of study the results presented here indicate that a prolonged EN 927-5 test can be used to evaluate the relative performance of different combinations of wood substrates and coating systems. The ANOVA results shown in tables 2 and 3 indicate that if both the amount of absorbed water and the resulting moisture content is of interest, 672 hours (4 weeks) is sufficient to distinguish between wood types. Based on the R^2-values the best fit was obtained after 1008 hours (6 weeks), and in a material showing smaller differences in wood properties 6 weeks of exposure could be advisable.

4.2 Mass of absorbed water per area (MWA) vs. moisture content gain (MCg)

Wood-degrading microorganisms are influenced by the moisture content rather than the amount of water in the wood, as they depend on available free water for colonisation. This indicates that the development in moisture content should be considered as well as the water uptake in weight units as long as the wood substrate is a subject of the study. The specified ranges in annual ring width and density given in the standard EN 927-5 are rather large (0.8–3 mm year inc., 0.4–0.5 g/cm^3 density) (CEN 2006), and can be expected to result in rather large differences in moisture content given the same amount of absorbed water.

The MCg was at approximately the same level in both types of specimens at the end of the experiment (Fig. 3a), and seemed to level out at values close to the fibre saturation point expected for Norway spruce wood (Rijsdijk and Laming 1994). The fibre saturation point (FSP) has been suggested as the upper moisture content limit for moisture penetrating through a surface coating (Derbyshire and Miller 1997). The explanation for this has been proposed to lie in the transition from moisture movement by diffusion to the very low rates of cell-wall flow above FSP (Derbyshire and Robson 1999). Our results seem to confirm this notion.

Coated SH specimens absorbed more water (larger MWA) than coated SL specimens, whereas the opposite was the case for uncoated specimens. No difference in amount of applied coating was found between the wood types. This indicates that the coating was more efficient in protecting the wood from liquid water on the SL specimens, or that the density of the specimens had an effect on the amount of water absorbed. The wood types had greater effect on the MWA as the experiment progressed, while the opposite was the case for MCg. The large difference in density and mean annual ring width between the two wood types indicates that the effect “wood type” was an effect of density, annual ring width or the two in combination. If density was included in the analyses, it replaced the effect of wood type. Annual ring width had significant effect on the results only if analysed alone, but yielded lower R^2-values than wood type or density analysed alone. Annual ring width never gave any significant effect in combination with wood type. This indicates that the effect of wood type found in this study was mainly caused by differences in density. The larger MCg in SL specimens reflects the fact that wood density plays an important role in regulating wood moisture content when testing liquid water uptake in coated specimens from the same wood species. The results regarding the effect of density on water uptake will be further discussed in Part 2 of the present study.

4.3 Absorption curves for uncoated controls

The MWA and MCg did not level out for uncoated specimens as it seemed to do for coated specimens (Figure 2 a, b; Figure 3 a, b). This could be due to the much shorter exposure time. Uptake of liquid water in uncoated wood is governed by both diffusion and capillary flow until the FSP is reached. Above FSP, capillary flow will continue until the wood is fully saturated (Voigt et al. 1940). De Meijer and Militz (2000) found that liquid water uptake in uncoated spruce was heavily influenced by capillary flow during prolonged sorption. Capillary flow was argued to be the governing mechanism when void-filling plotted against the square root of time divided by the porosity of the wood showed a linear relationship. Based on the formulas used in the work by de Meijer and Militz, this should imply a linear relationship between the amount of absorbed water and the square root of time. As shown in Figure 5 there were indications of two phases during absorption in the uncoated specimens where a linear relationship existed, but the second phase is uncertain due to few observations. The first linear phase corresponds to the linear phase during absorption in coated specimens shown in Figure 4c, but was of considerably shorter duration in uncoated specimens. Effects of wood properties on the mechanisms involved in liquid water absorption in uncoated spruce are studied further in an experiment performed subsequently to the one reported here (Sivertsen and Vestøl 2009, submitted for publication).

4.4 Linear regression

A plot of the dimensionless moisture concentration (E) by the square root of time will have the same slope as the MWA plotted by the square root of time (Figure 4). The slope of the regression line to the rectilinear portion of $E/\sqrt{t}$ is a component in the equation for calculation of diffusion coefficients found in e.g. Siau (1984) and adapted to liquid water uptake by de Meijer and Militz (2000). Hence, the regressions to the linear portion of the sorption curves, as exemplified in Figure 4 c, can be expected to be a good way to describe the “apparent diffusion” of water into the wood during liquid water uptake. The apparent diffusion coefficient in coated wood exposed to liquid water has been shown to be highly dependent on coating (de Meijer and Militz 2001). Against this background the coefficients from regression as shown in Figure 4 c could be expected to distinguish well between treatments. However, this approach did not seem to be any better for detecting differences between treatments than analysis on data observed at chosen points of time.

Regarding the evaluation of the relative performance of the wood types in this study, nothing is gained from using the regression coefficients from linear regression rather than analysing the data directly. The linear regression could have been done on dimensionless moisture concentration, yielding a diffusion coefficient. A potential benefit from determination of the diffusion coefficients of our specimens would be the opportunity to compare the results from this study with other studies where diffusion coefficients are given. In that case an apparent equilibrium moisture content would have to be determined, and the resulting coefficient would be an apparent diffusion coefficient (de Meijer and Militz 2000). The intention in the present study was to find a good but not too work-intensive means of evaluating the performance of different combinations of wood properties and coating systems. In that light evaluations based on single measurements were preferred, as the outcome was the same but the workload substantially smaller.

4.5 Conclusions

Prolonging the water exposure time in an experiment according to the standard EN 927-5 from 72 hours to four weeks allowed a significant effect of wood type on water uptake per test face area to develop. Six weeks of exposure yielded an even larger effect of wood type. Studying the increase in moisture content as well as the amount of absorbed water was shown to be of value in understanding the differences between wood types. Analysis on regression coefficients from linear regression to the sorption curve of each specimen did not yield better results than analysis of mass of absorbed water per area at specific points of time.

Acknowledgements

Sigrun Kolstad (The Norwegian Forest and Landscape Institute) and Bjørn Slette (Norwegian University of Life Sciences) are gratefully acknowledged for participating in the weighing of the specimens. Knut Magnar Sandland (Treteknisk) is greatly acknowledged for reading and commenting on the manuscript. Funding from The Research Council of Norway is greatly acknowledged as well.

References

Ahola, P. 1991. Moisture transport in wood coated with joinery paints. Holz Als Roh-Und Werkstoff 49(11):428-432.

Ahola, P., H. Derbyshire, G. Hora, and M.d. Meijer. 1999. Water protection of wooden window joinery painted with low organic solvent content paints with known composition. Part 1. Results of inter-laboratory tests. Holz Als Roh-Und Werkstoff 57(1):45-50.

Bergström, M., and A. Blom. 2007. Differences in properties between Norway spruce (Picea abies) heartwood and sapwood. Part 2. Vapour and Liquid permeability. *in* Proceedings of the Wood Protection Conference. Forest Products Society, New Orleans, Lousiana, USA, March 21-32, 2006.

CEN. 2000. EN 927-5. Paints and varnishes - Coating materials and coating systems for exterior wood - Part 5: Assessment of the liquid water permeability. European Committee for Standardisation, Brussels, Belgium.

CEN. 2006. EN 927-5. Paints and varnishes - Coating materials and coating systems for exterior wood - Part 5: Assessment of the liquid water permeability. European Committee for Standardization, Brussels, Belgium.

de Meijer, M. 2002. Comparison between laboratory water permeability tests and wood moisture content of full-scale window frames. Surface Coatings International Part B-Coatings Transactions 85(2):131-137.

de Meijer, M., and H. Militz. 2000. Moisture transport in coated wood. Part 1: Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz Als Roh-Und Werkstoff 58(5):354-362.

de Meijer, M., and H. Militz. 2001. Moisture transport in coated wood. Part 2: Influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional change. Holz Als Roh-Und Werkstoff 58(6):467-475.

Derbyshire, H., and E.R. Miller. 1997. Moisture conditions in coated exterior wood. Part 2: The relation between coating permeability and timber moisture content. Journal of the Institute of Wood Science 14(4):162-168.

Derbyshire, H., and D.J. Robson. 1999. Moisture conditions in coated exterior wood - Part 4: Theoretical basis for observed behaviour. A computer modelling study. Holz Als Roh-Und Werkstoff 57(2):105-113.

Eaton, R.A., and M.D.C. Hale. 1993. Wood. Decay, pests and protection. Chapman&Hall, London, Glasgow, New York, Tokyo, Melbourne, Madras. 469 p.

Ekstedt, J. 2002. Influence of coating additives on water vapour absorption and desorption in Norway spruce. Holzforschung 56(6):663-668.

Ekstedt, J. 2003. Influence of coating system composition on moisture dynamic performance of coated wood. Journal of Coatings Technology 75(938):27-37.

Ekstedt, J., and G. Östberg. 2001. Liquid water permeability of exterior wood coatings-testing according to a proposed European standard method. Journal of Coatings Technology 73(914):53-59.

Feist, W.C. 1985. The Moisture-Excluding Effectiveness of Finishes on Wood Surfaces. Forest Products Laboratory. 38 p.

Feist, W.C. 1990. Outdoor wood weathering and protection. Advances in Chemistry Series(225):263-298.

Kucera, B. 1992. Skandinaviske normer for testing av små feilfrie prøver av heltre (in Norwegian). Norwegian Forest Research Institute; Department of Forestry, Agricultural University of Norway. 104 p.

Metsa-Kortelainen, S., T. Antikainen, and P. Viitaniemi. 2006. The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170 degrees C, 190 degrees C, 210 degrees C and 230 degrees C. Holz Als Roh-Und Werkstoff 64(3):192-197.

Nussbaum, R.M., E.J. Sutcliffe, and A.C. Hellgren. 1998. Microautoradiographic studies of the penetration of alkyd, alkyd emulsion and linseed oil coatings into wood. Journal of Coatings Technology 70(878):49-57.

Rijsdijk, J.F., and P.B. Laming. 1994. Physical and related properties of 145 timbers: information for practice. Kluwer Academic Publishers, Dordrecht. 380 p.

Roux, M.L., E. Wozniak, E.R. Miller, J. Boxall, P. Bottcher, F. Kropf, and J. Sell. 1988. Natural Weathering of Various Surface-Coatings on 5 Species at 4 European Sites. Holz Als Roh-Und Werkstoff 46(5):165-170.

Siau, J.F. 1984. Transport processes in wood. Springer, Berlin. 245 p.

Virta, J., S. Koponen, and I. Absetz. 2006. Modelling moisture distribution in wooden cladding board as a result of short-term single-sided water soaking. Building and Environment 41(11):1593-1599.

Voigt, H., O. Kirscher, and H. Schauss. 1940. Die Feuchtigkeitsbewegung bei der Verdunstungstrocknung von Holz (in German). Holz Als Roh-Und Werkstoff 3(10):305-321.

Williams, R.S., and W.C. Feist. 1994. Effect of Preweathering, Surface-Roughness, and Wood Species on the Performance of Paint and Stains. Journal of Coatings Technology 66(828):109-121.

Water absorption in coated wood.

Part 2: Influence of different wood types and coatings.

Mari Sand Sivertsen[1] and Per Otto Flæte[2]

[1]: Norwegian University of Life Sciences, P.O.box 5003, NO-1432 Ås

[2]: Norsk Treteknisk Institutt, P.O.box 113 Blindern, NO-0314 Oslo

Abstract

During long-term exposure of specimens of three wood types (Scots pine heartwood and fast-grown and slow-grown Norway spruce) with three different coatings, the wood type was a more important factor than coating both with respect to the amount of absorbed water and with respect to the moisture content gain. Waterborne top coat without primer led to more water absorption than waterborne top coat with solvent-borne primer, and solvent-borne top coat with no primer led to the smallest amount of absorbed water. The performances of the coatings relative to each other were similar within each wood type. Regarding coated specimens slow-grown spruce absorbed more water than other wood types, but the resulting moisture content gain was higher in fast-grown spruce. Pine heartwood had lower uptake of liquid water and lower moisture content gain than any of the spruce types. With respect to uncoated reference specimens, slow-grown spruce specimens absorbed less water than pine heartwood specimens, while fast-grown spruce absorbed the largest amounts of water. The same was found for moisture content gain.

Keywords: *liquid water absorption, wood properties, Norway spruce,* Picea abies*, Scots pine,* Pinus sylvestris*, coated wood*

1. Introduction

Coating of wood in exterior claddings is done mainly for two reasons: To obtain the desired aesthetical appearance and to protect the wood from water uptake and other external stress (de Meijer 2001; Sell 1975). Fungal degradation is a major threat to wood in outdoor utilisations. The water in the wood is a key factor; without available moisture, wood remains undegraded by fungi. As they need free water for their metabolism decay fungi cannot grow effectively below the fibre saturation point, and a commonly used moisture content limit to avoid risk of decay is 20 % (Zabel and Morrell 1992). Rapp et al. (2000) state that wood moisture contents below 25% involves minimal decay risk. During exposure to water the moisture content close to the wood–coating interface can be much larger than the mean moisture content of a piece of wood (de Meijer and Militz 2000; Ekstedt et al. 1992). This provides good living conditions for staining fungi which grow on the surface and are more dependent on the moisture content at the wood–coating interface than on moisture content further inside the wood.

The liquid water permeability of different coatings on a single type of wood substrate has been extensively studied (e.g. Ahola et al. 1999; de Meijer et al. 2001; de Meijer and Militz 2000; Derbyshire and Miller 1997; Ekstedt 2003). Some studies have included comparison of wood species and/or effects of preweathering (Ahola 1991; Ahola et al. 1999; de Meijer and Militz 2001; Williams and Feist 1994). Liquid water permeability measured according to the standard EN 927-5 has proven to correlate well with moisture content in full scale window frames in service (de Meijer 2002). Knowledge on the performance of wood qualities in interaction with different coatings during long-term exposure to liquid water is limited.

The most common coatings for wood in exterior claddings are film-forming paints, either solvent-borne or waterborne. As a rule, these lower the moisture uptake in wood both by preventing capillary uptake of liquid water and by lowering the diffusion coefficient (de Meijer and Militz 2000). A reduction in sorption rate gives a permanent reduction in moisture content because steady state conditions are never reached in an outdoor environment (de Meijer and Militz 2001). In coated wood capillary water uptake can be expected to be strongly reduced compared with uncoated wood. De Meijer and Militz (2000) found that the water uptake in coated wood exposed to liquid water was mainly governed by diffusion through the coating film, as opposed to the uptake in uncoated wood, which to a large extent was governed by capillary flow. Waterborne acrylic coatings are known to have higher liquid water permeability than solvent-borne alkyd coatings due to capillary flow through micropores (Greystone and Ekstedt 2004).

Wood properties are argued to be important for the performance of coated wood claddings (Williams et al. 2000; Øvrum 2002), and the effects of different wood properties in combination with different coating types are thus of great interest. In part 1 of the present study no differences were found with respect to liquid water absorption between high-density and low-density Norway spruce (*Picea abies* L. Karst) within the time span indicated in the standard EN 927-5. Prolongation of the exposure time to four weeks was shown to bring out differences between these two wood types when coated with a solvent-borne top coat. Studying both the amount of absorbed water measured as weight gain and increase in moisture content relative to the initial moisture content was found useful (Sivertsen and Flæte 2009, submitted for publication).

The objective of the present work was to study the effect upon long-term water absorption by different wood types in combination with different coatings, and to investigate whether prolonged water exposure according to the method described in the standard EN 927-5 is suitable for investigation of the effect of different combinations of coatings and wood types.

2. Material and methods

2.1 Preparation of test specimens

The material was Norway spruce and Scots pine (*Pinus sylvestris* L. Karst) sampled from air dried centre boards, sawn from butt logs in mature trees. The spruce material was sampled from fast grown, high density (SH) and slow grown, low density (SL) Norway spruce. The SH specimens were prepared from two mature Norway spruce stands in northern Norway, one stand in Bindal and one stand in Nærøy. The SL specimens were prepared from wood harvested from a single stand in Lier (south-eastern part of Norway). The Scots pine heartwood (PH specimens) was prepared from a material sampled from four mature pine stands in the south-western part of Norway. All stands were located at altitudes below 300 m.

A 50 cm section of clear wood was cut from each board, and the board sections were stored in a climate chamber at 20 °C and 65 % RH until they reached stable mass. Each board section was re-sawn to 20 mm x 50 mm dimensions. A 150 mm test specimen and an adjacent reference specimen for calculation of mean annual ring width, initial moisture content and density were cut from the centre part of each board section. Annual ring width and density (at 12 % moisture content) of the test specimens are given in Table 1.

Table 1: Annual ring width (ARW) and density at 12 % MC (D12) of the specimens in the sample groups. N = number of specimens in each group. SL = spruce with wide annual rings; SH = spruce with narrow annual rings; PH = pine heartwood. SB = solventborne coating; WB = waterborne coating; PW = waterborne coating with solventborne primer; U = uncoated.

Wood type	Coating	N	D12 (g/cm^3)		ARW (mm)	
			Mean	St.dev	Mean	St.dev
SL	SB	6	0.364	0.007	4.4	0.9
	WB	6	0.361	0.011	5.0	0.7
	PW	6	0.369	0.012	4.5	0.8
	U	5	0.357	0.007	5.2	0.6
SH	SB	6	0.522	0.031	1.3	0.4
	WB	6	0.518	0.032	1.3	0.4
	PW	6	0.522	0.031	1.3	0.3
	U	5	0.513	0.019	1.1	0.2
PH	SB	6	0.480	0.080	2.0	0.6
	WB	6	0.463	0.045	1.9	0.7
	PW	6	0.485	0.078	1.7	0.7
	U	5	0.476	0.044	2.0	1.0

The test specimens were conditioned to 20°C and 65 % RH before sealing with two layers of a two component solvent-borne lacquer (Pyrotect 2K (Rütgers Organics)) on ends, edges and back face. The specimens within each wood type were sorted by density and allotted to treatments according to the resulting sequence. This was done in order to avoid skewed density distributions within combinations of wood type and treatments.

Two coatings with different permeability properties were chosen; a waterborne top coat (WB) and a solvent-borne top coat (SB). In addition, a system with a solvent-borne primer and the same waterborne top coat (PW) was tested, in order to investigate the impact of the primer on liquid water permeability. All the coating products were commercially available. The coatings were applied in two layers and the primer in one layer according to the instructions given by the manufacturer.

2.2 Water absorption test

The specimens were placed test face down in de-ionised water as described in part 1 of this study (Sivertsen and Flæte 2009, submitted for publication). The coated specimens were exposed to water for 3024 hours (18 weeks), while the uncoated specimens were exposed for 1128 hours (almost 7 weeks). Data after 72 hours (3 days) and 672 hours (4 weeks) of absorption were used in analyses of absorption performance.

The water absorbed by each specimen was measured as mass of absorbed water per test face area (MWA, g/m^2) relative to the weight of the conditioned specimen prior to the test, in accordance with EN 927-5 (Equation 1).

$$MWA_1 = (w_0 – w_1)/A \qquad (1)$$

where MWA_1 = mass of absorbed water per area (g/m^2) at time 1; w_0 = weight (g) at time 0; w_1 = weight (g) at time 1; A = area of test face (m^2).

The moisture content gain in each specimen (MCg, %) was calculated according to Equation 2. The MCg was chosen in order to be able to evaluate the changes in moisture content as a result of the absorbed water. This was considered to give more relevant information than the moisture content, which had to be estimated based on the calculated equilibrium moisture content at the outset of the experiment. This value varied between 13.1 and 15.2, and differed significantly between SL specimens and the other wood types.

$$MCg_1 = ((w_0-w_1)/w_d) * 100 \qquad (2)$$

where MCg_1 = moisture content gain at time 1(%); w_0 = weight (g) at time 0; w_1 = weight (g) at time 1; w_d = dry weight, untreated (g, calculated based on the MC of the reference specimen).

2.3 Data analysis

Statistical tests were performed as analysis of variance (ANOVA) where only categorical or only continuous variables were studied, and as analysis of covariance (ANCOVA) where categorical and continuous variables were studied together. Residuals were assumed to be normally distributed. Effects with probability of type 1 error smaller than 0.05 were considered significant. Tukey HSD tests were performed to test differences between wood types, between coatings and between combinations of wood types and coatings.

3. Results

3.1 Coated specimens

Figure 1 shows the development in MWA for the different coatings within each wood type. Specimens with water-borne coating with no primer (WB) had highest MWA of the spruce wood types (Figure 1 a, b). Coating type appeared to have little effect on MWA in pine heartwood specimens, but SB was slightly higher than WB, and PW slightly lower (Figure 1 c).

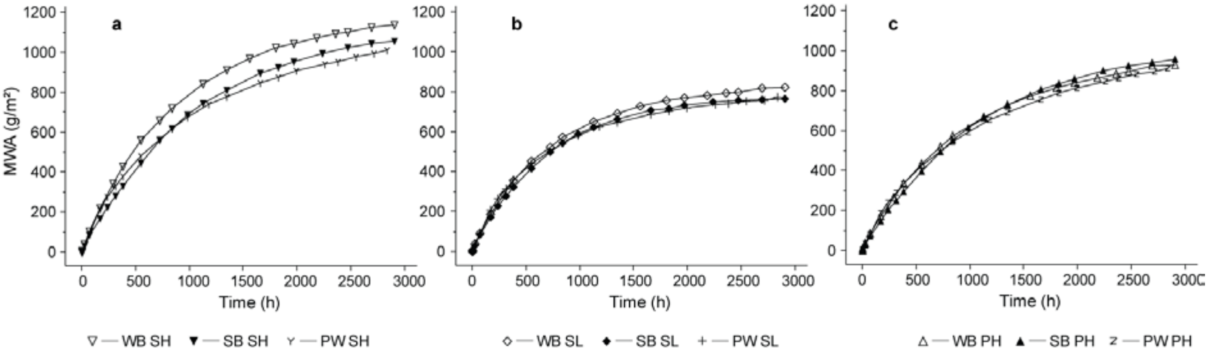

Figure 1. Development in weight gain (g/m^2) during the entire experiment shown as mean curves for each combination of wood type and coating. **a**: SH specimens, **b**: SL specimens, **c**: PH specimens.

The development in MWA and MCg for the different wood types within a single coating (water-borne coating, WB) are shown in Figure 2. SL specimens had lower MWA than SH specimens (Figure 2 a), and the highest MCg of all (Figure 2 b). SH specimens had higher MWA and lower MCg than SL specimens. SL specimens initially had higher MWA than PH specimens, but PH specimens surpassed SL specimens after approximately 800 hours. These trends were consistent for all three coatings.

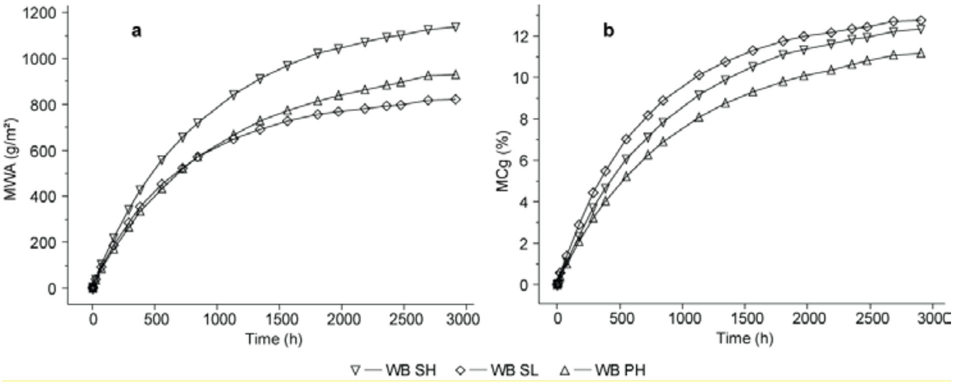

Figure 2. Development in **a**: MWA (g/cm^2) and **b**: MCg (%) in specimens with WB coating during the entire experiment shown as mean curves for each wood type.

The results from ANOVA at different times during the experiment are shown in Table 2. The goodness of the model fits, assessed by means of the R^2 values, was better with longer exposure times regarding MWA and lower with longer exposure time regarding MCg (Table 2). Coating and wood type had significant effect on both MWA and MCg after 72 hours (Table 2). After 672 hours interaction between wood type and coating as well as coating and wood type had significant effect on MWA. MCg was never significantly affected by interaction between wood type and coating.

Table 2. ANOVA results from analyses on MWA (g/m^2) and MCg (%) after 72 hours and 672 hours. R^2 for each final model, p values for each effect and F ratios for each significant effect. p values for effects not significant at 95 % confidence level are shown in parentheses, and the final models were re-calculated without these effects.

	72 h			**672 h**		
MWA (g/m^2)	p > F	F ratio	R^2	p > F	F ratio	R^2
Coating	0.0007	8.4	0.51	0.0004	9.4	0.68
Wood type	<0.0001	16.8		<0.0001	33.5	
Density	(0.9574)	-		(0.1401)	-	
Interaction coating/wood	(0.2888)	-		0.0361	2.8	
MCg (%)						
Coating	0.0026	6.7	0.80	0.0016	6.6	0.78
Wood type	<0.0001	16.1		<0.0001	14.5	
Density	<0.0001	20.1		<0.0001	22.1	
Interaction coating/wood	(0.6366)	-		(0.1004)	-	

Results from Tukey HSD tests between all combinations of wood and coating types after 72 and 672 hours are shown in Table 3. In a separate Tukey HSD test on wood types there was no significant difference in MWA between SH and SL specimens after 72 hours, but PH specimens had significantly lower MWA. This is illustrated in Table 3, where PH specimens are lower than all spruce specimens regardless of coating type after 72 hours. After 672 hours, SH specimens had higher MWA than SL or PH specimens regardless of coating type (Table 3). This was confirmed in a separate Tukey HSD test on wood types, where SH specimens had significantly higher MWA than other wood types after 672 hours. As can be seen from the lower half of Table 3, SL specimens clearly had higher MCg than other wood types both after 72 and 672 hours.

Table 3. Results from Tukey HSD analyses (Ty) on combinations (Comb.) between coating types and wood types. MWA and MCg after 72 and 672 hours. The combination SB / SH, for which results after 672 and 72 hours clearly differed, is shown in bold type. SL = spruce with wide annual rings; SH = spruce with narrow annual rings; PH = pine heartwood. SB = solventborne coating; WB = waterborne coating; PW = waterborne coating with solventborne primer.

	72 h			**672 h**	
Comb.	Ty	LSMean	Comb.	Ty	LSMean
MWA (g/m^2)					
WB,SH	A	105	WB,SH	A	630
PW,SH	AB	93	PW,SH	B	546
WB,SL	AB	92	**SB,SH**	BC	533
PW,SL	B	90	WB,SL	BC	505
SB,SL	BC	88	WB,PH	BC	496
SB,SH	BC	88	PW,SL	BC	489
WB,PH	BC	85	SB,SL	BC	483
PW,PH	BC	82	PW,PH	C	479
SB,PH	C	74	SB,PH	C	473
MCg (%)					
WB,SL	A	1.44	WB,SL	A	7.85
PW,SL	A	1.40	PW,SL	A	7.54
SB,SL	AB	1.33	SB ,SL	A	7.29
WB,SH	BC	1.14	WB ,SH	AB	6.85
WB,PH	C	1.02	WB,PH	BC	5.98
PW,SH	C	0.98	PW,SH	BC	5.75
PW,PH	C	0.95	SB,SH	BC	5.74
SB,SH	C	0.94	SB,PH	C	5.70
SB,PH	C	0.90	PW,PH	C	5.52

Density had no significant effect on MWA after 72 or 672 hours, but after 1008 hours density ($p < 0.0001$, F ratio 33.3) had larger effect on MWA than coating ($p = 0.0033$, Fratio 6.5), wood type ($p = 0.0018$, F ratio 7.3) or interaction between coating and wood type ($p = 0.0342$, F ratio 2.9). Regarding MCg density was the most important effect after both 72 and 672 hours, followed by wood type (Table 2). In Tukey HSD tests on wood types the difference between SL and SH specimens was not significant when the density effect was accounted for, but PH specimens had significantly lower MCg than other wood types both after 72 and 672 hours.

The sequence of coating types regarding MWA was the same within all wood types (Table 3). Specimens with WB coating absorbed more water than specimens with PW coating, while specimens with SB coating absorbed the smallest amounts of water. In a separate Tukey HSD test on coatings after 72 hours, the difference between WB and SB coated specimens was significant, while PW specimens were not significantly different from the others. After 672 hours WB specimens were significantly different from SB and PW samples regarding MWA, but SB and PW specimens were not different from each other. Similar results were found for MCg as for MWA; WB coated specimens gained significantly more in MC than SB coated specimens, while PW coated specimens were not different from the other coatings.

In Table 4 all the coated combinations are numbered according to the time they took to reach 20 % MC, based on the calculated initial MC of each specimen. SL specimens with PW coating reached this limit first; 24 hours earlier than SL specimens with WB coating. SL specimens reached the 20 % limit before all other wood types, while SH and PH specimens with WB coating reached this limit earlier than the same wood types with other coatings. The last group to reach 20 % MC was PH specimens with PW coating.

Table 4. All combinations of wood types and coating types used in the experiment, numbered according to the average number of hours it took the specimens in each group to reach 20 % moisture content. SL = spruce with wide annual rings; SH = spruce with narrow annual rings; PH = pine heartwood. SB = solventborne coating; WB = waterborne coating; PW = waterborne coating with solventborne primer.

	WB	**SB**	**PW**
SL	2 (384 h)	3 (408 h)	1 (360 h)
SH	4 (552 h)	6 (696 h)	8 (816 h)
PH	5 (672) h	7 (792 h)	9 (840 h)

3.2 Uncoated control specimens

Uncoated SL specimens had the highest MWA and MCg, followed by SH and PH specimens. The differences between wood types were larger for moisture content increase (Figure 3).

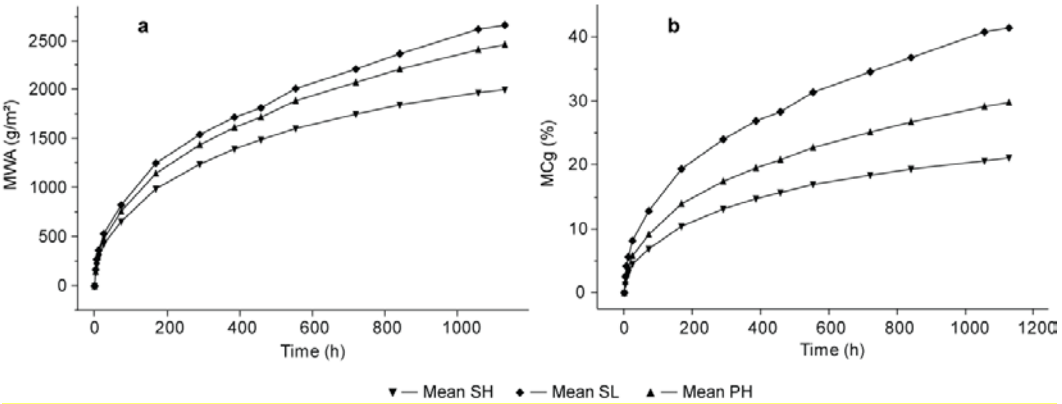

Figure 3. Development in **a**: weight gain per area and **b**: moisture content increase for uncoated specimens.

Results from Tukey HSD tests on uncoated specimens after 72 and 672 hours are shown in Table 5. The differences between wood types were more significant for moisture content gain than for weight gain and more significant after 672 hours than after 72 hours. If density was introduced in the analysis no significant effects were found. Analysed alone density had similar effect as wood type, but yielded somewhat lower R^2 values than wood type analysed alone.

Table 5. Results from Tukey HSD tests (Ty) on MWA (g/m2) and MCg (%) after 72 and 672 hours for uncoated specimens. One of the SH specimens absorbed water at an abnormally fast rate and was excluded from the analysis as an outlier. SL = spruce with wide annual rings; SH = spruce with narrow annual rings; PH = pine heartwood.

72 h			**672 h**		
Wood type	Ty	LSMean	Wood type	Ty	LSMean
MWA (g/m^2)					
SL	A	821	SL	A	2136
PH	AB	759	PH	A	2016
SH	B	659	SH	B	1706
MCg (%)					
SL	A	12.8	SL	A	33.3
PH	B	9.2	PH	B	24.4
SH	C	7.0	SH	C	18.0

4. Discussion

Coated SH specimens absorbed larger quantities of water than coated SL specimens. This could be seen for specimens with WB and PW coatings already after 72 hours (Table 3), but the difference was not significant until 672 hours in a separate Tukey HSD test on wood types. In part 1 of the present study (Sivertsen and Flæte 2009, submitted for publication) it was concluded that the standard EN 927-5 can safely be used for evaluation of coating performance on Norway spruce with substantial differences in density and annual ring width. The results shown here indicate that this holds for waterborne as well as for solvent-borne coatings.

The difference between coated SH and SL specimens was shown in part 1 of the present study to be a density effect (Sivertsen and Flæte 2009, submitted for publication). The lower density and wider annual rings in SL specimens implicates larger amounts of earlywood. Penetration of wood coatings has been shown to be deeper in earlywood than in latewood (de Meijer et al. 1998; Nussbaum et al. 1998; Williams et al. 1987), and this may have given better water protection of the SL specimens (Rijckaert et al. 2001). Additionally, the absorption rate through a coating into wood (water volume absorbed by area and time, water flux) is dependent on the diffusion coefficient of the coating and the moisture concentration gradient between the surroundings and the wood-coating interface. If the diffusion coefficient for a given coating is assumed to be a constant, the water flux will depend only on the concentration gradient (Derbyshire and Miller 1996). The moisture concentration in wood is a fractional value, dependent on the maximum potential moisture content. In coated wood the upper moisture content limit has been argued to be the fibre saturation point (FSP) (Derbyshire and Miller 1997). As the moisture content in the wood approaches FSP the absorption into the wood will decrease to a point where it is smaller than the transmission rate through the coating, and the water flux will decrease. When the entire piece of wood has reached FSP the moisture concentration will be 100 % of the potential both on the inside and the outside of the coating and the water flux will stop, provided that a diffusion tight sealant prevents moisture escape through the sides and/or back face. The FSP in Norway spruce is not likely to be different in specimens with different density, but the amount of water needed in the structure to approach FSP is lower in low-density wood. Thus, the total amount of water absorbed in wood with a coating that prevents capillary transport can be expected to be higher in wood with higher density (Greystone 2001). This can explain the larger MWA in SH specimens.

The rate of diffusion in wood, expressed by the diffusion coefficient, is derived from sorption isotherms based on dimensionless moisture concentration. This rate is dependent on diffusion through the cell wall material, which is slower than diffusion in air (Siau 1984; Skaar 1984; Wadsö 1993a). Diffusion in uncoated wood has been found to be slower in high-density than in low-density wood (e.g. Siau 1984; Wadsö 1993b). However, the results from this experiment indicate that any negative effect on MWA by differences in diffusivity between SH and SL specimens was overruled by the effect of density on water flux through the coating.

PH specimens had the lowest MWA of all the wood types after 72 and 672 hours but surpassed SL specimens in MWA after approximately 1300 hours, at which time the absorption in SL specimens was levelling out. As can be seen from Figure 1 (b, c) and Figure 2 (a) PH specimens had slightly higher MWA at the end of the experiment than SL specimens, but the difference was not significant in a test on MWA after 3024 hours. The mean density in PH specimens was significantly higher than in SL and lower than in SH specimens, but was substantially more different from SL than from SH specimens. Based on the effect of density on water flux a larger difference between PH and SL than between PH and SH specimens could be expected. As the Tukey HSD test showed significant difference only between PH and SH specimens, other explanations than the density effect must be sought. The FSP in pine heartwood is lower than that in pine sapwood or spruce (Kollmann and Cöté 1968), and as the water flux depends on the moisture concentration gradient lower FSP should cause lower water flux. In addition, low diffusivity in the wood will cause the moisture concentration at the wood-coating interface to increase earlier than in wood with higher diffusivity. The diffusivity in heartwood has been shown to be lower than in sapwood both for Scots pine (Sehlstedt-Persson 2001) and other *Pinus* species (Choong et al. 1999; Nzokou and Kamdem 2004), due to the high extractive content. The lower diffusivity in PH specimens is also illustrated by the lower moisture content gain showed in Figure 2 b.

The significant interaction between coating and wood regarding MWA after 672 hours was due to SH specimens with WB coating absorbing more water than the other combinations containing WB or SH. If water is transmitted through the coating at a higher rate than the wood can absorb, as can be the case with highly permeable coatings, the moisture content at the wood–coating interface will increase and the water flux decrease at an earlier point of time. The larger effect of the permeability of the waterborne coating on high-density spruce is interesting. Based on the considerations above regarding water flux through coatings, this effect could be caused by the high-density wood having higher capacity to absorb water. Thus the higher transmission rate through the WB coating can be kept stable at a more prolonged period of time on the SH specimens. Another possible explanation is the probable higher latewood proportion in SH specimens. As mentioned above coatings are known to penetrate deeper in earlywood than in latewood. In addition, waterborne acrylic coatings penetrate wood to a lesser degree than solventborne alkyd coatings (Rijckaert et al. 2001). If the coating penetrates the cell walls water repellency can be improved, as shown for wood with water repellent treatments (Militz and Peek 1993, Kabir 1992).

The most commonly used rule of thumb for prevention of decay is that the moisture content in the wood should not exceed 20 % (Eaton and Hale 1993; Forest Products Laboratory 1987). According to the results shown in Table 4, Norway spruce with low density (SL) showed the poorest performance of the wood types, while the waterborne coating (WB) gave the poorest protection against exposure to liquid water. Comparison between Table 4 and the results regarding MCg shows that waterborne coating with solvent-borne primer (PW) may perform better in the long run than after four weeks regarding moisture content in the wood substrate. The exception from this is the SL specimens, on which this coating system gave the shortest time to reach 20 % MC.

It should be noted, however, that the shortest time to reach 20 % MC for any of the coated combinations was 360 hours, i.e. 15 days. The probability of cladding boards in service being exposed to continuous rain for such a long time period is low, and no rain will give liquid water exposure equivalent to constant liquid water exposure of the coating film. Claddings in service are exposed to intermittent rain and dry periods. This should imply that all the coatings used in the experiment give good protection to the wood as long as the coating film is undamaged. Further investigations should include comparison of performance during cyclic wetting and drying of complete coating systems on wood with different properties, in order to see if the permeability to liquid water and water vapour of different systems causes risk of water accumulation in the wood. In order to fully understand the effects of coatings and wood properties on liquid water absorption and drying, monitoring of moisture content profiles (by CT scanning or other measures) should be performed.

Regarding uncoated specimens the average density of the wood types seemed to determine the results, both for MWA and MCg. However, the results found in literature regarding effect of density and annual ring width in spruce are unclear. On the one hand, the permeability has been found to be larger in latewood than in earlywood due to fewer aspirated bordered pits in latewood (Liese and Bauch 1967a). On the other hand, Salin (2008) claims that although absorption in the longitudinal direction in Norway spruce is quicker in latewood, the larger tracheid lumens will cause the absorbed amount of water to be higher in earlywood.

Heartwood content has been shown to influence longitudinal (Sandberg 2006) and transversal (Bergström and Blom 2007) liquid water uptake in uncoated Norway spruce. Heartwood formation is related to tree age, and the proportion of heartwood in a cross section is governed by the number of growth rings (Longuetaud et al. 2006). The specimens in the present study were taken from centre boards. Given the large differences in annual ring width, the SL specimens probably had lower heartwood proportion than the SH specimens. This could be the reason why the uncoated SL specimens absorbed more water than the uncoated SH specimens. Liquid water absorption has been shown to be similar in Scots pine heartwood as in heartwood or sapwood of Norway spruce, while Scots pine sapwood absorbed water substantially quicker (Johansson et al. 2006). Scots pine sapwood absorbs water readily, probably due to anatomical features in wood rays (Liese and Bauch 1967a; Sehlstedt-Persson et al. 2006) and a larger proportion of unaspirated bordered pits in latewood tracheids (Liese and Bauch 1967b). Thus the refractory nature of Scots pine heartwood is probably mainly due to encrustation of pit membranes and chambers with extractives as shown by Fengel (1970), and variations in degree of encrustation may cause variation in permeability to liquid water. The relative behaviour of the heartwood of Scots pine and Norway spruce regarding liquid water absorption should be subjected to further study.

5. Conclusions

High- and low-density Norway spruce specimens absorbed similar amounts of liquid water in the short run. The absorbed water caused low-density specimens to increase more in moisture content and reach values close to the fibre saturation point earlier, and as a result the high-density specimens took up more water in the long run. In the short run Scots pine heartwood specimens absorbed less water and increased less in moisture content than the Norway spruce specimens, probably due to lower diffusivity.

The larger permeability of the waterborne top coat had larger effect on the high-density spruce specimens than on other wood types. This illustrates that different wood substrates can lead to different results from tests on coating performance.

Acknowledgements

Sigrun Kolstad (The Norwegian Forest and Landscape Institute) and Bjørn Slette (Norwegian University of Life Sciences) are gratefully acknowledged for their participation in the weighing of the specimens. Funding from The Research Council of Norway is greatly acknowledged as well.

References

Ahola, P. 1991. Moisture transport in wood coated with joinery paints. Holz Als Roh-Und Werkstoff 49(11):428-432.

Ahola, P., H. Derbyshire, G. Hora, and M.d. Meijer. 1999. Water protection of wooden window joinery painted with low organic solvent content paints with known composition. Part 1. Results of inter-laboratory tests. Holz Als Roh-Und Werkstoff 57(1):45-50.

Bergström, M., and A. Blom. 2007. Differences in properties between Norway spruce (Picea abies) heartwood and sapwood. Part 2. Vapour and Liquid permeability. *in* Proceedings of the Wood Protection Conference. Forest Products Society, New Orleans, Lousiana, USA, March 21-32, 2006.

Choong, E.T., T.F. Shupe, and Y. Chen. 1999. Effect of steaming and hot-water soaking on extractive distribution and moisture diffusivity in southern pine during drying. Wood and Fiber Science 31(2):143-150.

de Meijer, M. 2001. Review on the durability of exterior wood coatings with reduced VOC-content. Progress in Organic Coatings 43(4):217-225.

de Meijer, M. 2002. Comparison between laboratory water permeability tests and wood moisture content of full-scale window frames. Surface Coatings International Part B-Coatings Transactions 85(2):131-137.

de Meijer, M., J. Creemers, and W. Cobben. 2001. Relationships between the performance of low-VOC wood coatings and the dimensional changes of the wooden substrate. Surface Coatings International Part B-Coatings Transactions 84(1):77-85.

de Meijer, M., and H. Militz. 2000. Moisture transport in coated wood. Part 1: Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz Als Roh-Und Werkstoff 58(5):354-362.

de Meijer, M., and H. Militz. 2001. Moisture transport in coated wood. Part 2: Influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional change. Holz Als Roh-Und Werkstoff 58(6):467-475.

de Meijer, M., K. Thurich, and H. Militz. 1998. Comparative study on penetration characteristics of modern wood coatings. Wood Science and Technology 32(5):347-365.

Derbyshire, H., and E.R. Miller. 1996. Moisture conditions in coated exterior wood. Part 1: An investigation of the moisture transmission characteristics of exterior wood coatings and the effect of coating on moisture permeability. Journal of the Institute of Wood Science 14(1):40-47.

Derbyshire, H., and E.R. Miller. 1997. Moisture conditions in coated exterior wood. Part 2: The relation between coating permeability and timber moisture content. Journal of the Institute of Wood Science 14(4):162-168.

Eaton, R.A., and M.D.C. Hale. 1993. Wood. Decay, pests and protection. Chapman&Hall, London, Glasgow, New York, Tokyo, Melbourne, Madras. 469 p.

Ekstedt, J. 2003. Influence of coating system composition on moisture dynamic performance of coated wood. Journal of Coatings Technology 75(938):27-37.

Ekstedt, J., O. Lindgren, and S. Grundberg. 1992. Moisture distribution in coated wooden panels. Studies of moisture dynamics by computerized axial tomography. in The International Research Group on Wood Preservation, 23rd Annual Meeting. IRG Secretariat, Harrogate, UK.

Fengel, D. 1970. Ultrastructural changes during aging of wood cells. Wood Science and Technology 4(3):176-188.

Forest Products Laboratory. 1987. Wood handbook: Wood as an engineering material. U.S. Department of Agriculture, Washington DC. 466 p.

Greystone, J. 2001. Moisture transport through wood coatings: The unanswered questions. Surface Coatings International Part B-Coatings Transactions 84(3):169-242.

Greystone, J., and J. Ekstedt. 2004. Current views on the role of water in the behaviour of coated wood substrates. *in* COST E18, High Performance Wood Coating. Final seminar, Paris, 26. - 27. April.

Johansson, D., M. Sehlstedt-Persson, and T. Morén. 2006. Effect of heat treatment on capillary water absorption of heat-treated pine, spruce and birch. in Proceedings from 5th IUFRO Symposium Wood Structure and Properties '06, Sliac - Sielnica, Slovakia.

Kollmann, F.F.P., and W.A. Cöté. 1968. Principles of wood science and technology. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. 551 p.

Liese, W., and J. Bauch. 1967a. On anatomical causes of the refractory behaviour of spruce and douglas fir. Journal of the Institute of Wood Science 19:3-14.

Liese, W., and J. Bauch. 1967b. On the closure of bordered pits in conifers. Wood Science and Technology 1:1-13.

Longuetaud, F., F. Mothe, J.M. Leban, and A. Makela. 2006. Picea abies sapwood width: variations within and between trees. Scandinavian Journal of Forest Research 21(1):41-53.

Nussbaum, R.M., E.J. Sutcliffe, and A.C. Hellgren. 1998. Microautoradiographic studies of the penetration of alkyd, alkyd emulsion and linseed oil coatings into wood. Journal of Coatings Technology 70(878):49-57.

Nzokou, P., and D.P. Kamdem. 2004. Influence of wood extractives on moisture sorption and wettability of red oak (Quercus rubra), black cherry (Prunus serotina), and red pine (Pinus resinosa). Wood and Fiber Science 36(4):483-492.

Rapp, A.O., R.-D. Peek, and M. Sailer. 2000. Modelling the Moisture Induced Risk of Decay for Treated and Untreated Wood Above Ground. Holzforschung 54:111-118.

Rijckaert, V., M. Stevens, J. Van Acker, M. de Meijer, and H. Militz. 2001. Quantitative assessment of the penetration of water-borne and solvent-borne wood coatings in Scots pine sapwood. Holz Als Roh-Und Werkstoff 59(4):278-287.

Salin, J.-G. 2008. Modelling water absorption in wood. Wood Material Science and Engineering 3(3):102 - 108.

Sandberg, K. 2006. Modelling water sorption gradients in spruce wood using CT scanned data. New Zealand Journal of Forestry Science 36(2-3):347-364.

Sehlstedt-Persson, M. 2001. The effect of extractive content on moisture diffusion properties for Scots pine and Norway spruce. *in* COST Action E15 Advances in the drying of wood (1999-2003). Proceedings of the 3rd workshop on Softwood Drying to Specific End-uses, 11.-13. June, Helsinki, Finland.

Sehlstedt-Persson, M., D. Johansson, and T. Morén. 2006. Effect of heat treatment on the microstructure of pine, spruce and birch and the influence on capillary absorption. *in* Proceedings from 5th IUFRO Symposium Wood Structure and Properties '06, Sliac - Sielnica, Slovakia.

Sell, J. 1975. Grundsätzlige Anforderungen an Oberflächenbehandlingen für Holz im Assenbau (Litteraturübersicht). Holz Als Roh-Und Werkstoff 33(9):336-340.

Siau, J.F. 1984. Transport processes in wood. Springer, Berlin. 245 p.

Skaar, C. 1984. Wood-Water Relationships. Advances in Chemistry Series(207):127-172.

Wadsö, L. 1993a. Measurements of water-wapor sorption in wood. 2. Results. Wood Science and Technology 28(1):59-65.

Wadsö, L. 1993b. Studies of water vapour transport and sorption in wood. Thesis for the degree of Philosophiae doctor (Ph.d.), Lund University. 101 p.

Williams, R.S., and W.C. Feist. 1994. Effect of Preweathering, Surface-Roughness, and Wood Species on the Performance of Paint and Stains. Journal of Coatings Technology 66(828):109-121.

Williams, R.S., C. Jourdain, G.I. Daisey, and R.E. Springate. 2000. Wood properties affecting finish service life. Journal of Coatings Technology 72(902):35-42.

Williams, R.S., J.E. Winandy, and W.C. Feist. 1987. Paint adhesion to weathered wood. Journal of Coatings Technology 59(749):43-49.

Zabel, R.A., and J.J. Morrell. 1992. Wood microbiology: decay and its prevention. Academic Press, San Diego, Calif. 476 p.

Øvrum, A. 2002. Fokus på tre nr 22. Utvendig kledning. 2. reviderte utgave (in Norwegian). Norsk Treteknisk Institutt, Oslo.

Liquid water absorption in uncoated Norway spruce claddings as affected by origin and wood properties

Mari Sand Sivertsen[1] and Geir Isak Vestøl[1]

[1]Norwegian University of Life Sciences
Department of Ecology and Natural Resource Management
PO Box 5003
NO-1432 Ås

e-mail: mari.sivertsen@umb.no
tel. +47 905 32 965
fax no. +47 64 96 58 01

Abstract

Uncoated Norway spruce specimens from different spatial positions within stems from two origins with different growth conditions were exposed to liquid water over a prolonged time, and apparent diffusion coefficients and rates of void filling were calculated from sorption curves. Both apparent diffusion and rate of void filling were significantly affected by origin and by the difference between inner and outer boards. The differences between inner and outer boards were fully explained by heartwood proportion and density, but some effects of origin remained when these properties were accounted for. Density had negative effects on both parts of the sorption. Heartwood proportion had a negative effect on rate of void filling, and an unexpected positive effect on apparent diffusion. Since the effect on apparent diffusion was more pronounced in the materials from the high-productive area, it was probably due to confounding with properties of juvenile wood.

Keywords: *liquid water absorption, wood properties, growth conditions, Norway spruce,* Picea abies

1. Introduction

Uncoated wood can potentially be a long-lasting, maintenance-free cladding material, and it has become popular among architects (Larsen and Mattsson 2009). For uncoated wooden cladding to fulfil its potential, proper construction principles must be followed and the wood has to fulfil high demands regarding moisture uptake. Moisture uptake is of great importance in wood intended for exterior use, both because moisture variations in the wood lead to warping and cracking and because degradation by microorganisms depends on available water.

Norway spruce (*Picea abies* (L.) Karst) is the most commonly used cladding material in Norway (Øvrum 2002). The alternative, Scots pine (*Pinus sylvestris* L.), has more durable heartwood (CEN 1994), but its sapwood is more permeable (Liese and Bauch 1967a) and less durable than Norway spruce wood (Tamminen 1979). As pure Scots pine heartwood is less readily available (Toverød et al. 2003) and thus rather expensive, this makes Norway spruce the preferred material. Traditionally, claddings have mainly been made from slow-grown spruce, which is considered a better cladding material than fast-grown spruce. Changes in Norwegian forestry during the 20th century have increased the increments in Norwegian forests, and large volumes of fast-grown Norway spruce wood will be ready for harvest in the coming decades (Vennesland et al. 2006). Currently about 30 % of the total harvest-ready Norway spruce volume is on high productivity sites, whereas for young stands and stands approaching maturity the volume on high productivity sites is about 60 % of the total (K. Hobbelstad, pers. comm.). More knowledge is needed regarding differences between fast-grown and slow-grown Norway spruce wood and possible implications for the performance of cladding materials, and properties regarding moisture change are among the most important factors.

Water uptake in wood occurs by means of diffusion and capillary flow. In wood with moisture content below the fibre saturation point (FSP), bound water in the cell walls and water vapour in the lumens is transported by diffusion. Since diffusion of water vapour in cell lumens is much faster than diffusion of bound water in the cell wall, the rate of transversal diffusion is strongly dependent on the ratio of cell wall substance to cell lumen volume (i.e. density) of the wood (Siau 1984; Tong 1989). However, studies have shown differences between species (de Meijer and Militz 2001; Time 1998), Scots pine heartwood and sapwood (Rydell 1982) and levels of heat treatment (Almeida et al. 2009) that cannot be explained by density differences alone. Even though most studies on diffusion are based on either adsorption or desorption of water vapour, de Meijer and Militz (2000) showed that the formulas in Siau (1984) based on Fick's law for diffusion are applicable to water uptake in wood exposed to liquid water.

In wood above the fibre saturation point, free water in the cell lumens is transported by capillary flow (Siau 1984). The permeability of softwood to liquids is dependent on anatomical features of the conducting tracheids. In green conifer wood liquid transport mainly occurs in the earlywood tracheids. After drying the bordered pits between these tracheids are aspirated, and the permeability drops substantially (Banks 1970; Comstock and Cöté 1968; Siau 1984). Most bordered pits in latewood tracheids are aspirated as well, but due to smaller pit apertures and stiffer margo some stay open (Liese and Bauch 1967a, b; Siau 1984). Liese and Bauch (1967a) found that bordered pits in ray tracheids are even smaller and are not aspirated at all, while bordered pits in the ray tracheids in Norway spruce heartwood are heavily encrustated – making the heartwood even more refractory than the sapwood. Recent studies have shown larger liquid water uptake in sapwood than in heartwood of Norway spruce (Bergström and Blom 2007; Sandberg 2002). No effect of heartwood has been found on diffusion in spruce wood (e.g. Tong 1989). A negative effect of density on liquid water sorption has been found (Booker and Kininmonth 1978). Since density is positively related to latewood proportion, the effect is reduced through the presence of fewer aspirated pits in latewood than in earlywood of Norway spruce (Salin 2008).

Wood properties in Norway spruce are known to vary both along the longitudinal and radial axes, and between dominant and suppressed trees (Kucera 1994; Molteberg and Høibø 2007; Wilhelmsson et al. 2002). Assuming that water sorption is affected by wood density and heartwood proportion, variations in these properties may be used to predict sorption properties. Within similar climate and growth conditions, density is negatively correlated with annual growth. This means that more dominant trees within a stand may be expected to have lower density than the more suppressed trees (Molteberg and Høibø 2007; Wilhelmsson et al. 2002). The typical radial pattern in planted Norway spruce is high density near the pith, dropping to low density in the first growth rings and then increasing outwards before it reaches stable values (Kucera 1994). Density tends to increase with increasing height in the trees (Kucera 1994), but this trend is small.

Molteberg and Høibø (2007) found decreasing density in the lower 5 meters, followed by an upward increase. Heartwood formation is related to the age of the trees, and the proportion of heartwood in a cross section is governed by the number of growth rings (Longuetaud et al. 2006). As a consequence, the widths of the growth rings in heartwood and sapwood respectively are important as well. In a planted stand where all trees are of equal age, the proportion of heartwood will be inversely proportional to the stem diameter (Taylor et al. 2002).

Knowledge about the effects of wood properties on sorption of liquid water in uncoated cladding of Norway spruce is crucial for its continued use, as increasing demands regarding service life predictions and maintenance costs will have to be met in the future. The aim of the present study is to analyse the effects of origin and position within stems on liquid water sorption, and to relate this to variations in annual ring width, density and heartwood proportion.

2. Material and methods

The material consisted of Norway spruce sampled from four stands in two areas in southern Norway, with distinctly different growth conditions (Figure 1). Two of the stands, representing high productive areas, were located in a lowland area near the coast (Larvik). The other two were from higher altitudes in an inland area further north, and represented low productivity areas (Toten). The trees from Larvik were comparatively young, and had large diameter and height growth. The Toten trees were much older, but had smaller height than the Larvik trees. Stand data are presented in Table 1.

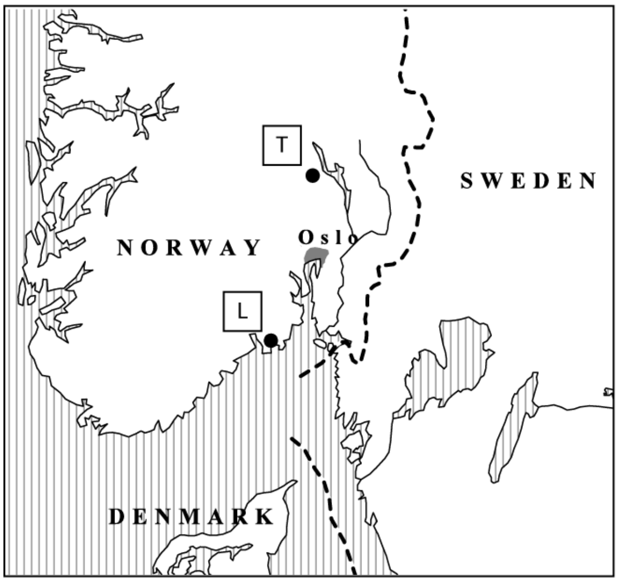

Figure 1: The southern part of Norway with the Toten (T) and Larvik (L) origins indicated by black dots.

Table 1. Stand data for the four stands. Altitude above sea level; stand age (Age); productivity class (H_{40})(Tveite 1977); basal area (G) (area of tree cross sections at 1.3 m above ground level per land area) and average diameter with bark (Diam.BH).

Stand	**Coordinates**	**Altitude (m)**	**Age(yrs)**	**H_{40} (m)**	**G(m^2/ha)**	**Diam. BH (mm)**
Larvik 1	N 59°04’07.8’’ E 9°57’16.5’’	120	57	G23	49.6	280
Larvik 2	N 59°04’06.9’’ E 9°57’06.6’’	125	45	G26	49.2	233
Toten 1	N 60°40’49.8’’ E 10°31’47.8’’	670	150	G8	22.2	232
Toten 2	N 60°42’08.9’’ E 10°32’00.2’’	600	150	G11	29.5	271

Diameter at breast height was recorded for all trees within a limited area of each stand. Subsequently, five trees with breast height diameter between 27 and 30 cm and five trees with breast height diameter between 32 and 35 cm, with bark, were randomly sampled from each site. These diameter intervals include trees from which the butt log or the second log respectively will give logs with a diameter suitable for sawing into 150 mm wide planks, which is the most commonly used dimension for cladding. External measures of the sampled trees are presented in Table 2.

Table 2. External measures of the sampled trees in each size groups. Number of trees (N); average breast height diameter without bark (DBHub); average tree height (H); average crown height (CH) (i.e. height to lowest living branch that is not separated from the rest of the crown by at least 3 whorls where all branches are dead).

Stand	**Size group**	**N**	**DBHub (mm)**	**H (cm)**	**CH (cm)**
Larvik 1	27–30	5	269	2432	826
	32–35	5	316	2580	1165
Larvik 2	27–30	5	277	2586	1110
	32–35	5	325	2754	877
Toten 1	27–30	5	254	1662	366
	32–35	5	298	1768	404
Toten 2	27–30	5	263	1894	560
	32–35	5	299	2038	358

The aim of the sampling from each tree was to procure one specimen from the lower part of the stem and one from the lower part of the crown, where the largest knots are located. Since tree heights were smaller in Toten than in Larvik, the butt logs from Toten were 4 m, and all other logs were 5 m. The butt logs and second logs were split through the pith, and one half was resawn into two planks. In butt logs from the smaller trees, an edge-grained plank was sawn from the other half (Figure 2a). The planks were kiln-dried and resawn into boards with a dry-cut surface on all faces. The desired board dimensions were 19 mm x 98 mm x log length. 98 mm width was not attainable on all planks, especially for some of the edge-grained planks. The boards closest to and furthest from the pith (inner and outer boards) were used as well as one board from each edge-grained plank (Figure 2a).

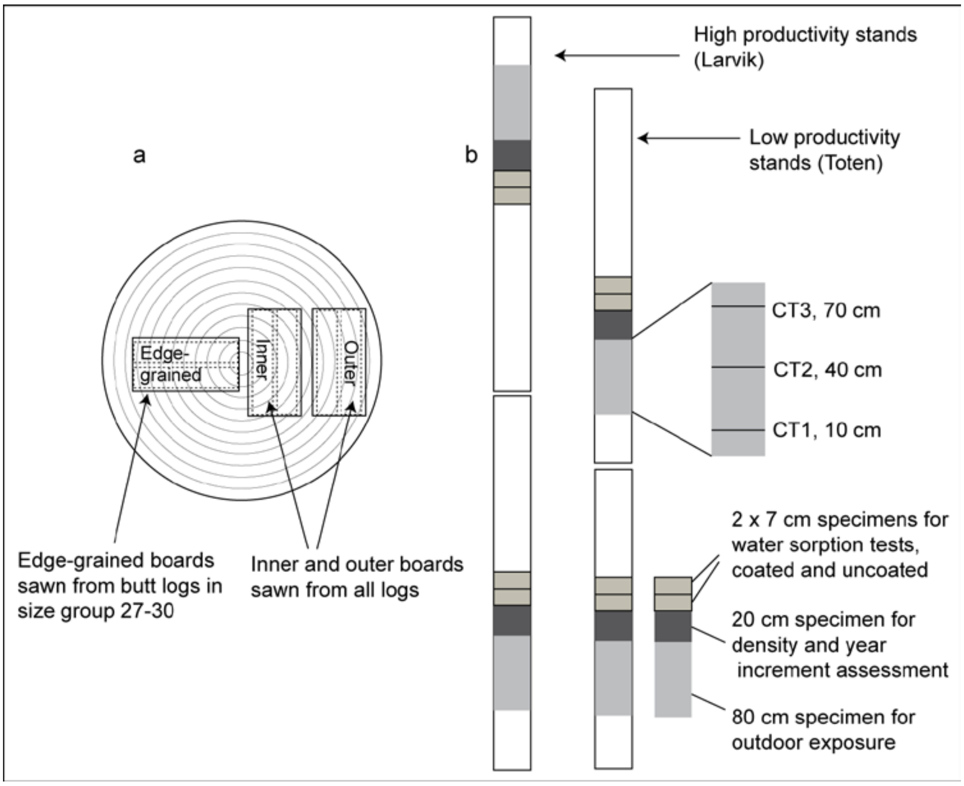

Figure 2. a: Sawing pattern in the logs. Inner and outer boards were sawn from all logs, while edge-grained boards were sawn from a smaller group of logs; **b:** location in the boards of specimens for the present study as well as specimens for outdoor exposure, determination of density and annual ring width and water sorption test of coated specimens. Locations of CT scans in specimens for outdoor exposure are indicated.

From each board, specimens for four different purposes were produced: an 80 cm specimen for outdoor exposure, a 20 cm specimen for measurements of annual ring width and density, a 7 cm specimen for water uptake testing on coated specimens, and a 7 cm specimen for the present study (Figure 2b). The width was 98 mm and the thickness 18 mm for all specimens, except for some of the edge-grained boards that were from trees of too small diameter to allow the full board width. The series of specimens from each board started 70 cm from the end closest to the stump, except for second logs from Larvik, where the series started 70 cm from the end closest to the top. This difference was made in order to obtain samples from the part of the stem with the largest knots from both areas, despite the difference in tree heights.

The material comprised 169 specimens, of which 77 were inner boards, 73 were outer boards and 19 were edge-grained boards. The amount of heartwood in inner and outer boards was registered by CT-scanning of three cross sections on green planks directly after sawing (Figure 2b). The positions were in the samples for outdoor exposure, and the mean value was used as an estimate of the inner and outer board specimens for the present study. Amount of heartwood was not measured in edge-grained planks. Annual ring width and density were measured on specimens located between the outdoor exposure specimens and the water uptake test specimens. Annual ring width was measured as mean width of all complete annual rings in the cross section. Density at 12 % moisture content was measured according to Scandinavian norm (Kucera 1992). The data are presented in Table 3.

Table 3. Distribution of the wood properties of the specimens in all sample groups. Number of specimens (N); annual ring width (ARW); density at 12 % MC (D12); and heartwood proportion (HW). The differing number of specimens between ARW/D12 and HW columns was due to the loss of some of the small specimens for measuring ARW and D12 and two of the CT scans from which HW was measured. Specimens lacking from one of the columns were not included in the ANCOVA, yielding an N of 142 for this analysis.

				ARW (mm)			**D12 (g/cm^3)**			**HW (%)**		
Origin	**Size group**	**Log no.**	**Board**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**
Larvik	27–30	1	Inner	9	4.0	0.8	9	0.418	0.042	10	99	2
			Outer	10	2.3	0.4	10	0.488	0.058	10	55	33
		2	Inner	10	4.7	1.6	10	0.432	0.035	10	100	1
			Outer	7	2.5	0.5	7	0.510	0.050	7	27	22
	32–35	1	Inner	9	5.0	1.2	9	0.393	0.030	9	100	0
			Outer	10	3.1	1.3	10	0.461	0.071	10	64	37
		2	Inner	10	5.1	1.6	10	0.429	0.047	10	100	1
			Outer	10	3.1	0.6	10	0.475	0.059	10	35	31
Toten	27–30	1	Inner	8	1.6	0.7	8	0.454	0.034	7	99	1
			Outer	9	1.3	0.3	9	0.446	0.023	8	91	15
		2	Inner	10	1.6	0.5	10	0.456	0.027	10	99	4
			Outer	9	1.3	0.5	9	0.452	0.032	10	84	20
	32–35	1	Inner	10	1.4	0.6	10	0.449	0.022	10	100	0
			Outer	8	1.2	0.5	8	0.467	0.047	8	76	34
		2	Inner	8	1.7	0.7	8	0.466	0.040	9	100	0
			Outer	8	1.1	0.3	8	0.467	0.049	8	79	36
			Sum N	*145*			*145*			*146*		
Larvik	27–30	1	Edge-grain	10	3.0	0.9	10	0.449	0.048	-	-	-
Toten	27–30	1	Edge-grain	9	1.1	0.4	9	0.465	0.036	-	-	-

Since inner boards, especially in the Larvik material, had wide annual rings, low density and high heartwood content the correlations between these properties were investigated. The results for the whole material and for each origin are shown in table 4. The highest values of the correlation coefficient R were found for density and annual ring width, followed by density and heartwood. The absolute values of R were larger in the Larvik material than in the Toten material.

Table 4. Correlations (R) between annual ring width (ARW), density at 12 % MC (D12) and heartwood proportion (HW) for the whole sample and for Larvik and Toten separately.

	ARW (mm)	**D12 (g/cm3)**	**HW (%)**
Larvik			
ARW (mm)	1.000		
D12 (g/cm3)	–0.693	1.000	
HW (%)	0.517	–0.528	1.000
Toten			
ARW (mm)	1.000		
D12 (g/cm3)	–0.441	1.000	
HW (%)	0.077	–0.038	1.000
Both			
ARW (mm)	1.000		
D12 (g/cm3)	–0.500	1.000	
HW (%)	0.089	–0.377	1.000

The specimens were conditioned at 20 °C and 65 % RH and weighed before sealing with two layers of a high viscosity laquer (“Pyrotect Schutslack 2K” by Rütgers Organics, Germany) on ends, edges and back face. After sealing, the specimens were conditioned at 20 °C and 65 % RH and weighed before the water absorption test. The test procedure was carried out according to EN 927-5 with certain modifications: the test faces were sawn rather than planed, and the specimens were placed on glass rods rather than directly in the water containers (Figure 3). In addition, the duration of the water exposure was longer; more than 2500 hours. At intervals (24 times, of which 4 times during the first 24 hours) the specimens were removed from the water, surface dried with tissue, weighed and returned to the water. Each specimen was out of the water for about five minutes during this procedure. After a period of desorption at 20 °C and 65 % RH the specimens were oven-dried at 103 °C in order to measure dry weight and volume.

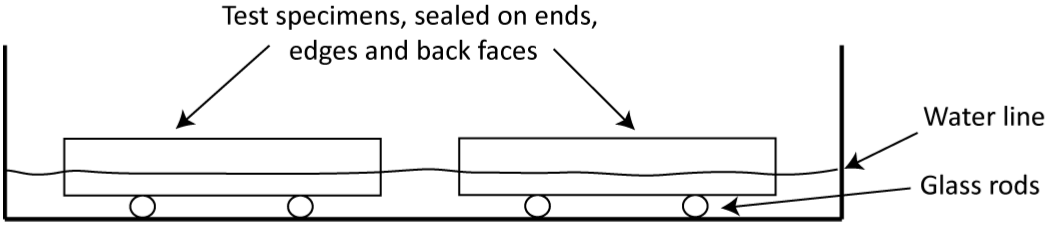

Figure 3. Outline of the water absorption test. The test specimens were placed with the test face in water, resting on glass rods.

The water absorption was calculated as apparent diffusion and capillary flow, using the formulas adapted from those given in Siau (1984) by de Meijer and Militz (2000). During the first 96 hours the moisture content plotted by the square root of time was linear for all specimens, and this part of the moisture uptake was termed “the apparent diffusion phase” (Figure 4b). The apparent diffusion coefficient (IDa) describing this part of the moisture uptake was calculated from equation 1, where the rate $d\bar{E}/d\sqrt{t}$ was found by linear regression of $\bar{E}$ against $\sqrt{t}$. Obtained values of R^2 for the linear regressions were between 0.96 and 0.98.

$$IDa = (l^2/5.1) * (d\bar{E}/d\sqrt{t}) \qquad (1.1)$$

$$\text{where } \bar{E} = (MC - MC_0)/(EMCa - MC_0) \qquad (1.2)$$

Where *IDa* = apparent diffusion coefficient (m^2s^{-1}); l = double thickness of specimen (m); $\bar{E}$ = average dimensionless moisture concentration; *MC* = wood moisture content at time t (%); MC_0 = initial wood moisture content (%); *EMCa* = apparent equilibrium moisture content (%).

The equilibrium moisture content (EMC), i.e. the moisture content that is in equilibrium with the relative humidity in the surrounding air, is a prerequisite for calculation of the diffusion coefficient of the wood (Siau 1984). If wood is exposed to both liquid water and air, an EMC dependent on the RH in the ambient air will eventually be reached (Baines and Levy 1979; Siau 1984). In the present study the wood was sealed against the ambient air, and there was thus no true equilibrium moisture content other than full water saturation. Use of the fibre saturation point as a measure for the EMC is not feasible since some cell lumens will contain water while the walls of other cells are still not saturated (Tiemann 1906). In order to find an estimate for the EMC corresponding to water uptake in the apparent diffusion phase, an apparent EMC (EMCa) was used. This value was found by nonlinear regression to a mechanistic growth model for each specimen, using the asymptote value of this model as a measure for the EMCa (Figure 4a). The mean value for EMCa obtained with this method was 44 %, with a range from 32 to 78 %. Compared to other methods for determining EMCa (de Meijer and Militz 2000, 2001; Fakhouri et al. 1993), this approach gave the opportunity to calculate a truly individual IDa for each specimen.

The moisture content plotted by the square root of time was linear for all specimens between 840 and 2520 hours (√s between 1700 and 3000 in Figure 4b), and in this phase the absorption was calculated as capillary flow. The fractional void filling of the wood (equation 2.1), which in this phase yielded a linear relationship with the square root of time divided by porosity (equation 2.2), was used to characterise the capillary water uptake. The increase of the void filling degree (F by $\sqrt{(t/V_a)}$)’ (termed VFR) was found by performing linear regression on this relationship. Obtained values of R^2 for the linear regressions were between 0.98 and 0.99.

$$F = w_1/\,(\rho_1 V_w v_a) \qquad (2.1)$$

$$\text{where} \quad v_a = 1 - G(0.667+0.01MC) \qquad (2.2)$$

$$\text{and} \quad G = w_{OD}/V_w\,\rho_1 \qquad (2.3)$$

Where F = fractional void filling; w_1 = weight of absorbed water (kg); ρ_1 = density of water (kg/m^3); V_w = volume of the specimen at moisture content MC (m^3); v_a = porosity of the wood at moisture content MC; G = specific gravity of the specimen at moisture content MC; MC = wood moisture content at time t (%); and w_{OD} = oven-dry weight of the specimen (kg).

Statistical tests were performed as analysis of variance (ANOVA), or as analysis of covariance (ANCOVA) when wood properties were included as covariates in the models. The residuals were assumed to have normal distribution. The distributions of IDa split by sample groups were close to the normal distribution, while the distributions of VFR were rather skewed in outer boards, particularly in Toten. The residuals of VFR derived from the model in table 6 had skewness 0.8 and kurtosis 4.6, which is within the range that with even moderate sizes of N can be ignored according to Lindman (1992). As N was large these values of skewness and kurtosis were not considered to inhibit the chosen analysis methods. In the ANOVA the effects of origin and site nested within origin were included in the initial model, as well as tree size group, log number and inner/outer board. Tests including edge-grained boards were performed on specimens from the butt logs in trees from the small size class only. In the ANCOVA the effects of wood properties (annual ring width, density and heartwood), as well as origin, were included in the initial model. Each effect was tested for interaction with origin if it was found to be significant. Effects with probability of type 1 error larger than 0.05 were considered non-significant and removed before re-estimating the final models.

3. Results

The moisture content increased quickly in all specimens, seemed to even out after about 300 hours, but then kept increasing at a slower pace until the experiment was stopped (Figure 4 a). At that point, growth of mould and blue stain had been observed on several specimens. The mean moisture content of the specimens at the end of the absorption phase was 64 %, with a range from 43 % to 138 %.

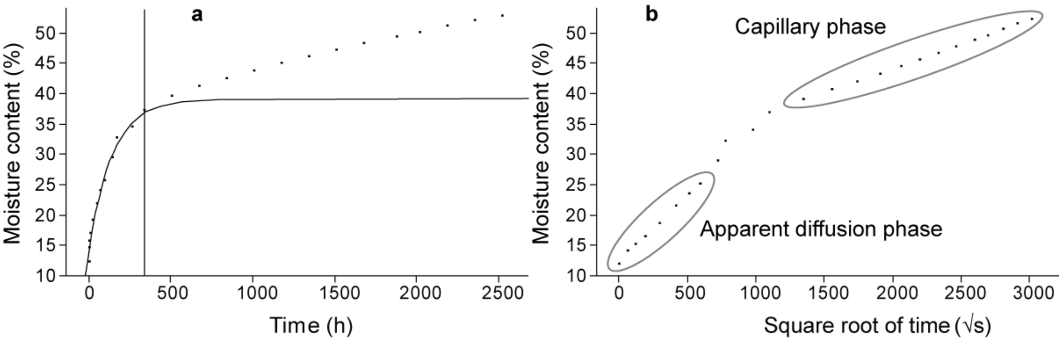

Figure 4. a: Plot of the development in moisture content in specimen 11 during absorption, plotted by time. The mechanistic growth model is fitted to moisture content data until the point where the curve is fully deflected (vertical line). The model follows the curve of the moisture content curve, and goes towards its asymptote as the moisture content continues to rise at a slower pace. **b:** Plot of the development in moisture content in sp 11, plotted by the square root of time (seconds). The curve deflects between 35 and 40 %, and the moisture content continues to increase at a slower pace. Two linear phases can be seen in the plot (rings).

Analysis of variance showed that the apparent diffusion coefficient (IDa) was significantly influenced by boards ($p < 0.0001$; $F = 28.1$), origin ($p = 0.0040$; $F = 8.57$), and site nested within origin ($p = 0.0048$; $F = 5.54$), while it was not significantly influenced by size group ($p = 0.9743$) or by log number ($p = 0.2299$). Significant interaction between board and origin ($p = 0.0017$; $F = 10.2$) showed that the difference between inner and outer boards was larger in the material from Larvik than in the material from Toten. Least square means for origins and boards are presented in Table 5. The table also includes corresponding least square means of annual ring width, density and heartwood proportion.

Table 5. Differences in wood properties (annual ring width, ARW; density at 12 % MC, D12; heartwood proportion, HW) and derived parameters (apparent diffusion coefficient, IDa and rate of void filling degree, VFR) between origins and inner/outer boards. Number of specimens included in the analysis (N, not listed if equal to the property/parameter on the left), Least square means (LSM) and results from Tukey HSD test (Ty). Groups not connected by a common letter are significantly different.

		ARW (mm)			**D12 (g/cm^3)**		**HW (%)**			**ID a (10^{-10} m^2/s)**			**VFR (10^{-3} s$^{-1/2}$)**	
Origin	**Board**	**N**	**LSM**	**Ty**	**LSM**	**Ty**	**N**	**LSM**	**Ty**	**N**	**LSM**	**Ty**	**LSM**	**Ty**
Larvik	Inner	38	4.72	A	0.42	B	39	99.6	A	39	1.83	A	2.39	B
	Outer	37	2.77	B	0.48	A	37	46.44	C	37	1.48	B	4.07	A
Toten	Inner	36	1.56	C	0.46	A	36	99.51	A	38	1.58	B	2.41	B
	Outer	34	1.25	C	0.46	A	34	83.09	B	36	1.49	B	3.15	B
Grand mean		*2.62 (N=145)*			*0.45 (N=145)*		*82.1 (N=146)*			*1.60 (N=150)*			*2.99 (N=150)*	

Tukey HSD tests showed that IDa was higher in inner boards from Larvik than in all the other groups (Table 5). There was no significant difference between inner and outer boards in the Toten material. Edge-grained boards were not significantly different from neither inner nor outer boards from the same logs (Table 6).

Table 6. Differences in wood properties (annual ring width, ARW and density at 12 % MC, D12) and derived parameters (apparent diffusion coefficient, IDa and rate of void filling degree, VFR) between boards from butt logs in trees from size group 27–30. Number of specimens included in the analysis (N), Least square means (LSMean) and results from Tukey HSD test (Ty). Groups not connected by a common letter are significantly different.

		ARW (mm)		**D12 (g/cm^3)**		**ID a (10^{-10} m^2/s)**		**VFR (10^{-3} s$^{-1/2}$)**	
Board	N	**LSMean**	**Ty**	**LSMean**	**Ty**	**LSMean**	**Ty**	**LSMean**	**Ty**
Inner	19	2.88	A	0.43	A	1.66	A	2.44	B
Outer	20	1.86	B	0.47	A	1.55	A	3.23	A
Edge-grained	19	2.11	AB	0.46	A	1.65	A	2.67	AB

With respect to fractional void filling rate (VFR), the results showed significant effects of board ($p < 0.0001$; F = 33.9), origin (p = 0.0326; F = 4.66), and site nested within origin (p = 0.0745; F = 2.64), while the effects of size group (p = 0.5596) and log number (p = 0.2008) were not significant. Significant interaction between board and origin (p = 0.0266; F = 5.02) showed that the difference between inner and outer boards was larger in the material from Larvik than in the material from Toten. Least square means for origins and boards are presented in Table 5.

Tukey HSD tests showed that VFR was higher in outer boards from Larvik than in all other groups (Table 5). There was a significant difference between inner and outer boards in the Larvik material, but not in the Toten material. Edge-grained boards scored in between inner and outer boards of the same logs, but they were not significantly different from either (Table 6). The Tukey tests also show that the differences in VFR were larger than the differences in IDa. The difference between the highest and lowest scores for IDa was 23 %, while the highest and lowest scores for VFR differed by 70 % (Table 5).

ANCOVA models including both group effects and effects from wood properties are shown in Table 7. The apparent diffusion coefficient (IDa) was significantly affected by origin ($p < 0.0001$, $F = 22.6$), density (D12) ($p = 0.0015$, $F = 10.5$), and heartwood proportion ($p < 0.0001$, $F = 54.8$). Log number ($p = 0.8036$), Inner/outer board ($p = 0.7803$), size group ($p = 0.7426$) and annual ring width ($p = 0.4701$) had no significant influence, and were removed from the model. R^2 for the model was 0.45, and heartwood was the most important independent factor, indicated by the highest F ratio. IDa increased with increasing heartwood, and decreased with increasing density. The intercepts in the models show that specimens from Larvik had larger IDa than specimens from Toten, if density and heartwood proportion were accounted for (Table 7).

Table 7. ANCOVA models for the two dependent variables (Y) apparent diffusion coefficient (IDa) and rate of the void filling degree (VFR) modelled as functions of significant effects. Non-significant effects were removed from the final models, leaving only density (D12) and heartwood content (HW). Root mean square error (RMSE) and the coefficient of determination (R^2) are given for each model. Unit for the RMSE is m^2s^{-1} for IDa and $s^{-1/2}$ for VFR.

Y	**Origin**	**Model**	**RMSE**	**R^2**
IDa	**Larvik**	$1.9 \times 10^{-10} – 1.4 \times 10^{-10}$ D12 + 5.2×10^{-13} HW	**2.2e-11**	**0.45**
	Toten	$1.7 \times 10^{-10} – 1.4 \times 10^{-10}$ D12 + 5.2×10^{-13} HW		
VFR	**Larvik**	$7.9 \times 10^{-3} – 4.1 \times 10^{-3}$ D12 $– 3.8 \times 10^{-5}$ HW	**8.6e-4**	**0.66**
	Toten	$9.4 \times 10^{-3} – 4.1 \times 10^{-3}$ D12 $– 5.22 \times 10^{-5}$ HW		

Since the positive effect of heartwood proportion on apparent diffusion was an unexpected result the analyses were repeated for each origin separately. Within the Larvik specimens both density and heartwood proportion had significant effects ($p = 0.0241$ for D12, $p < 0.0001$ for HW), while within the Toten specimens only heartwood proportion had a significant effect ($p = 0.0830$ for D12, $p = 0.0002$ for HW). The parameter estimates were positive for heartwood proportion and negative for density in both origins.

The rate of the void filling degree (VFR) was significantly affected by origin ($p = 0.0257$, $F = 5.1$), density ($p = 0.0144$, $F = 6.2$), heartwood proportion ($p < 0.0001$, $F = 222.5$), and interaction between heartwood proportion and origin ($p = 0.0183$, $F = 5.7$) (Table 7). Annual ring width ($p = 0.6550$), log number ($p = 0.5014$), size group ($p = 0.4358$) and inner/outer board ($p = 0.2648$) had no significant additional influence on VFR, and were removed from the model. R^2 for the model was 0.66. Heartwood proportion explained the major part of the variation in this parameter. VFR decreased with increasing density and heartwood proportion. Specimens from Toten had larger VFR than specimens from Larvik, if density and heartwood proportion were accounted for. Interaction between heartwood proportion and origin resulted in a larger negative influence from heartwood on VFR for the Toten specimens than for the Larvik specimens.

In order to avoid confounding of density and heartwood content regarding VFR, a separate analysis of 41 Larvik specimens with 100 % heartwood was performed. The range in density within these specimens was 0.33 to 0.49 g/cm^3, with a mean value of 0.42 g/cm^3. Analysis on this reduced sample showed no significant effect of density ($p = 0.1391$) on VFR.

4. Discussion

The mean apparent diffusion coefficient (IDa) is in the same order of magnitude as that which has been found in studies regarding vapour sorption in uncoated Norway spruce (de Meijer and Militz 2001; Ekstedt 2002; Hukka 1999; Wadsö 1993a) (Table 8). This was unexpected since capillary forces may be expected to contribute to the absorption when wood is exposed to liquid water. Both Fakhouri et al. (1993) and de Meijer and Militz (2001) found substantially higher transversal diffusivities during liquid water exposure than what has been found in vapour sorption studies (Table 8). Also, diffusion in wood has been shown to be largely non-Fickian (Wadsö 1994), especially when the relative humidity is high. However, in the present study sorption curves were clearly linear in the first part of the water absorption, and the moisture uptake could be treated as diffusion even though the mechanism of absorption is not determined.

Table 8. Results regarding diffusion coefficients (ID), apparent diffusion coefficients (IDa), and apparent equilibrium moisture content (EMCa) in Norway spruce found in earlier studies.

Author(s)	EMCa	ID/IDa (e-10)	Comment
Ekstedt (2002)	EMC	ID 1.44	Mean value from Table 3.
Hukka (1999)	EMC	ID 2.5	Dependent on moisture content. Approximate mean value from Fig 11.
Wadsö (1993a)	EMC	ID 0.5-0.9	Dependent on specimen thickness.
de Meijer and Militz (2000)	30 %	IDa Mean 6.5	EMCa = theoretical FSP.
de Meijer and Militz (2001)	EMC	IDa 1.35	65 % – 98 % RH.
de Meijer and Militz (2001)	appr. 60 %	IDa 13.14	Specimens exposed to liquid water on all transversal faces.
Fakhouri et al. (1993)	40.2 %	IDa Appr. 35	Thin specimens (0.5 cm). Exact method of determination for EMCa not stated.

Log number did not have any significant effect on any of the parameters in the ANOVA and was therefore not included in the ANCOVA model. This implies that two specimens taken from the same tree are treated as independent observations in this analysis. Thus, the interpretation of the results from the ANCOVA model shown in table 5 should be done with prudence, as the number of degrees of freedom used could be on the large side, and there is a risk of underestimating the p values. Correlations between continuous variables are shown in table 4. The largest value is found for correlation between density and annual ring width in the Larvik material. Annual ring width is not included in the final models, and none of the variance inflation factors computed from the correlation coefficients between remaining effects exceed 1.3. This is far below the values that indicate serious collinearity (O'Brien 2007).

Even though there is a significant effect of origin that has not been accounted for, the model in Table 7 shows that some of the variation in diffusion coefficient can be explained by variations in wood properties. Since the difference in diffusion coefficient between inner boards and outer boards is only significant in the material from Larvik and not in the material from Toten (Table 5), it is probably caused by the larger radial variations in wood properties in the Larvik material. Models including effects of heartwood proportion and density (Table 7) explained the difference between inner and outer boards. As annual ring width and density are negatively correlated, and given the presumption regarding better performance from slow-grown Norway spruce, an effect of annual ring width could have been expected. The correlation depends on growth conditions and to some extent on genetic variations, however (Vestøl 2001; Wilhelmsson et al. 2002). The lower density in inner boards from Larvik is probably caused by the fact that the first 20–30 year rings from the pith in Norway spruce consist of juvenile wood (Boutelje 1968, in Thörnqvist 1989), which means that the juvenile wood cylinder will have a larger diameter in a fast-grown tree than in a slow-grown tree. Juvenile wood has lower density, shorter tracheids and larger grain angle than mature wood (Thörnquist 1989).

IDa was affected negatively by density (Table 7). This is in accordance with existing knowledge; diffusion within the cell wall material is slower than in air (Burr and Stamm 1947; Siau 1984; Stamm 1948; Wadsö 1993b), and more cell wall material (i.e. higher density) will cause slower diffusion. The effect of density was minor compared to the effect of heartwood proportion.

The positive effect of heartwood proportion on the apparent diffusion coefficient was unexpected, as earlier studies have found no difference in diffusivity in hygroscopic sorption between Norway spruce sapwood and heartwood (Bergström and Blom 2007; Tong 1989; Wadsö 1993a). As heartwood proportion was highly dependent on origin the effect could be confounded with differences between origins that are not covered in the investigations, but analysis within origins showed the same positive effect. One possible explanation is the effect of fibre angle. Longitudinal diffusion is much quicker than transversal diffusion in wood (Siau 1984), and there is thus a strong relation between diffusion and grain angle (Wengert and Skaar 1978). Tong (1989) suggested that much of the variation in reported moisture diffusion coefficients could be due to differing grain angle. Säll (2002) found that, on average, the grain angle in Norway spruce increases from approximately 0° at the pith to a maximum leftwards orientation of 3° between the 4th and 8th annual rings. After this the fibre angle slowly decreases until the 50th year ring, when the fibre angle passes 0° and slowly starts to increase towards the right. Grain angle in the tangential plane means that some end-grain will be exposed on radial surfaces in wood. Due to the curvature of the growth rings, the test faces in inner boards had relatively more radial surface exposed compared to test faces in outer boards, which had relatively more tangential surface exposed (Figure 2a). This means that inner boards are more prone to grain angle, and since these also contain more heartwood there is a possibility that the observed effect of heartwood is confounded with grain angle – which was not recorded on this material. The combined effect of grain angle and heartwood content on water uptake in uncoated wood should be further investigated.

The results show that the rate of fractional void filling was mainly affected by proportion of heartwood. Outer boards from Larvik were those with the smallest heartwood proportion, and the only group that had significantly higher rate of fractional void filling than the others (Table 5). This is also shown in the VFR model (Table 6), where the effect of heartwood proportion is far more important than the other effects. Grain angle has been found to have an effect on penetration of coatings (de Meijer et al. 1998), and the larger grain angle in the juvenile wood could have been expected to impact liquid water uptake as well as diffusion. The negative effect of heartwood seems to overrule any positive effect of grain angle on capillary flow in the present study, however, supporting the hypothesis that Norway spruce heartwood is considerably less permeable than Norway spruce sapwood (Bergström and Blom 2007; Sandberg 2009). The effect of heartwood proportion is related to changes in bordered pits during heartwood formation (Liese and Bauch 1967a).

The variation in density in the Toten material was very small (Table 5), indicating that the negative effect of density on VFR primarily originated in the Larvik material. The lack of effect of density within Larvik specimens with 100 % heartwood indicates that this effect was probably caused by a confounding of juvenile wood and high heartwood content, and that heartwood in reality was the only property affecting capillary flow in the wood. If a 99 % rather than a 95 % degree of confidence is used VFR was only significantly affected by heartwood content. On this background the effect of larger heartwood proportions in inner boards seems to exceed the effect of lower density and any possible effect of grain angle. This is in accordance with studies on liquid water absorption in the longitudinal direction in Norway spruce, where the absorption was found to be substantially smaller in heartwood than in sapwood (Sandberg 2009).

There were few obvious differences between size groups and logs regarding wood properties (Table 3), and log number and size class had no influence on any part of the water sorption. The lack of effect by size class can be explained by the small differences in diameter between classes. Vertical level in the stem has been found to affect basic density in wood at a constant number of annual rings from the pith; the density declined through the first 5 m from the butt, followed by an increase throughout the rest of the stem (Molteberg 2006). However, in this study the difference between the two positions was too small to make any significant difference between logs.

The results of the present study indicate that heartwood proportion is the most important wood property when it comes to effects on capillary uptake of water in uncoated Norway spruce wood. The effect of heartwood proportion on apparent diffusion is less clear since it may be confounded with grain angle and other wood properties that were not recorded in this study. The heartwood in trees from high productivity areas usually has a large proportion of juvenile wood, which has other properties than mature wood. Growth conditions (origin) and density had a significant effect on apparent diffusion but were less important for capillary flow. Annual ring width had no effect on the water uptake when density and origin were accounted for. However, Norway spruce wood with narrow annual rings taken close to the pith is likely to have large density and a very high proportion of heartwood. This might be part of the explanation why slow-grown Norway spruce has a good reputation as a cladding material. The negative effect of heartwood proportion on capillary flow during liquid water uptake should be taken into account in production of high quality cladding material from Norway spruce. The possible positive effect of grain angle in juvenile wood should be investigated further.

Acknowledgements

The authors greatly acknowledge Bjørn Slette (Norwegian University of Life Sciences, UMB) for assistance with specimen preparation and collection of data. Prof. Birger Eikenes (UMB) also assisted with data collection. Comments on the paper from ass. Prof. Olav Høibø (UMB) and Prof. Halvor Solheim (Norwegian Forest and Landscape Institute/UMB) are also greatly acknowledged, as well as the funding provided from the Norwegian Research Council.

References

Almeida, G., J.O. Brito, and P. Perre. 2009. Changes in wood-water relationship due to heat treatment assessed on micro-samples of three Eucalyptus species. Holzforschung 63(1):80-88.

Baines, E.F., and J.F. Levy. 1979. Movement of water through wood. Journal of the Institute of Wood Science 8(3):109-113.

Banks, W.B. 1970. Some Factors Affecting Permeability of Scots pine and Norway spruce. Journal of the Institute of Wood Science(25):10-17.

Bergström, M., and A. Blom. 2007. Differences in properties between Norway spruce (Picea abies) heartwood and sapwood. Part 2. Vapour and Liquid permeability. *in* Proceedings of the Wood Protection Conference. Forest Products Society, New Orleans, Lousiana, USA, March 21-32, 2006.

Booker, R.E., and J.A. Kininmonth. 1978. Variation in Longitudinal Permeability of Green Radiata Pine Wood. New Zealand Journal of Forestry Science 8(2):295-308.

Burr, H.K., and A.J. Stamm. 1947. Diffusion in wood. Journal of Physical and Colloid Chemistry 51(1):240-261.

CEN. 1994. EN 350-2. Durability of wood and wood-based products - Natural durability of solid wood - Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe. European Committee for Standardisation, Brussels, Belgium.

Comstock, G.L., and W.A. Cöté. 1968. Factors Affecting Permeability and Pit Aspiration in Coniferous Sapwood. Wood Science and Technology 2(4):279-291.

de Meijer, M., and H. Militz. 2000. Moisture transport in coated wood. Part 1: Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz Als Roh-Und Werkstoff 58(5):354-362.

de Meijer, M., and H. Militz. 2001. Moisture transport in coated wood. Part 2: Influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional change. Holz Als Roh-Und Werkstoff 58(6):467-475.

de Meijer, M., K. Thurich, and H. Militz. 1998. Comparative study on penetration characteristics of modern wood coatings. Wood Science and Technology 32(5):347-365.

Ekstedt, J. 2002. Influence of coating additives on water vapour absorption and desorption in Norway spruce. Holzforschung 56(6):663-668.

Fakhouri, B., H. Mounji, and J.M. Vergnaud. 1993. Comparison of the absorption and desorption of water between Scots pine and spruce after submersion in water. Holzforschung 47(4):271-277.

Hukka, A. 1999. The effective diffusion coefficient and mass transfer coefficient of Nordic softwoods as calculated from direct drying experiments. Holzforschung 53(5):534-540.

Kucera, B. 1992. Skandinaviske normer for testing av små feilfrie prøver av heltre (in Norwegian). Norwegian Forest Research Institute; Dep. of Forestry, Agricultural University of Norway, Ås.

Kucera, B. 1994. A hypothesis relating current annual height increment to juvenile wood formation in Norway spruce. Wood and Fiber Science 26(1):152-167.

Larsen, K.E., and J. Mattsson. 2009. Fokus på tre nr 30. Ubehandlede trefasader. Norsk Treteknisk Institutt, Oslo.

Liese, W., and J. Bauch. 1967a. On anatomical causes of the refractory behaviour of spruce and douglas fir. Journal of the Institute of Wood Science 19:3-14.

Liese, W., and J. Bauch. 1967b. On the Closure of Bordered Pits in Conifers. Wood Science and Technology 1:1-13.

Lindman, H.R. 1992. Analysis of variance in experiment design. Springer-Verlag, New York. 531 p.

Longuetaud, F., F. Mothe, J.M. Leban, and A. Makela. 2006. Picea abies sapwood width: variations within and between trees. Scandinavian Journal of Forest Research 21(1):41-53.

Molteberg, D. 2006. Modelling of variations in wood and fibre properties in Norway spruce. Thesis for the degree of Doctor scientiarum (Dr. scient), Norwegian University of Life Sciences, Ås. 56 p.

Molteberg, D., and O.A. Høibø. 2007. Modelling of wood density and fibre dimensions in mature Norway spruce. Can. J. For. Res.-Rev. Can. Rech. For. 37(8):1373-1389.

O'Brien, R.M. 2007. A caution regarding rules of thumb for variance inflation factors. Qual. Quant. 41(5):673-690.

Rydell, R. 1982. Samband mellan densitet och årsringsbredd samt några andra egenskaper hos svensk furu (in Swedish). STFI-meddelande serie A nr 763. P. 27 s. Svenska Träforskningsinstitutet, Stockholm.

Salin, J.-G. 2008. Modelling water absorption in wood. Wood Material Science and Engineering 3(3):102 - 108.

Sandberg, K. 2002. Influences of growth site on different wood properties in spruce sap-/heartwood using CT scanner measurements. *in* Workshop 4, Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software. IUFRO Working party S5.01-04, Harrison Hot Springs, BC, Canada.

Sandberg, K. 2009. Norway Spruce Heartwood - Properties Related to Outdoor use. Thesis for the degree of Philosophiae doctor (Ph.d.), Luleå University of Technology, Luleå. 50 p.

Siau, J.F. 1984. Transport processes in wood. Springer, Berlin. 245 p.

Stamm, A.J. 1948. The Passage of Water Through the Capillary Structure of Wood. Discussions of the Faraday Society 3:264-273.

Säll, H. 2002. Spiral grain in Norway spruce. Thesis for the degree of philosophiae doctor (Ph.d.), Växjö University Press, Växjö. 171 p.

Tamminen, Z. 1979. Rötskador hos 3-meters obarkad lagrad massaved av tall, gran, björk och klibbal (in Swedish). Rapport nr 112. Swedish University of Agricultural Sciences.

Taylor, A.M., B.L. Gartner, and J.J. Morrell. 2002. Heartwood formation and natural durability - A review. Wood and Fiber Science 34(4):587-611.

Thörnquist, T. 1989. Ungdomsved i barrträd (in Swedish). Sveriges Skogsvårdsförbunds Tidsskrift 4:21-25.

Tiemann, H.D. 1906. Effect of moisture upon the strength and stiffness of wood. U.S. Dept. of Agriculture, Forest Service, Washington, D.C.

Time, B. 1998. Hygroscopic moisture transport in wood. Thesis for the degree of Doktor ingeniør (Dr.ing.), Norges teknisk-naturvitenskapelige universitet, Instituttfor bygg- og anleggsteknikk, Trondheim. XVI, 216 s. p.

Tong, L. 1989. Moisture diffusivities and sorption isotherms of Swedish spruce and pine. TRITA-BYMA 1989:8. Dep. of Building Materials, The Royal Institute of Technology, Sweden. 60p.

Toverød, H., A. Øvrum, and P.O. Flæte. 2003. Potensial for uttak av kjernevedtrelast fra furutømmer (in Norwegian). Oppdragsrapport 1/03. Skogforsk.

Tveite, B. 1977. Bonitetskurver for gran. Meddelelser fra Norsk institutt for skogforskning nr. 33.1. P. 84 s., Ås.

Vennesland, B., K. Hobbelstad, T. Bolkesjø, S. Baardsen, J. Lileng, and J. Rolstad. 2006. Skogressursene i Norge 2006: Muligheter og aktuelle strategier for økt avvirkning (in Norwegian). Norsk institutt for skog og landskap.

Vestøl, G.I. 2001. Egenskaper til trelast med store dimensjoner fra grov gran på Vestlandet (in Norwegian). Rapport fra skogforskningen 1/01. Norsk institutt for skogforskning and Institutt for naturforvaltning, UMB.

Wadsö, L. 1993a. Measurements of water-wapor sorption in wood. 2. Results. Wood Science and Technology 28(1):59-65.

Wadsö, L. 1993b. Studies of Water Vapour Transport and Sorption in Wood. Thesis for the degree of Philosophiae doctor (Ph.d.), Lund University. 101 p.

Wadsö, L. 1994. Describing non-Fickian water-vapour sorption in wood. Journal of Materials Science 29:2367-2372.

Wengert, E.M., and C. Skaar. 1978. Additional consideration in measuring transverse moisture conductivity in wood. Wood Science 11(2):102-104.

Wilhelmsson, L., J. Arlinger, K. Spångberg, S.-O. Lundqvist, T. Grahn, Ö. Hedenberg, and L. Olsson. 2002. Models for Predicting Wood Properties in Stems of Picea abies and Pinus sylvestris in Sweden. Scandinavian Journal of Forest Research 17(4):330-350.

Øvrum, A. 2002. Fokus på tre nr 22. Utvendig kledning. 2. reviderte utgave. Norsk Treteknisk Institutt, Oslo.