A critical literature review of moisture and temperature conditions in wood exposed outdoors above ground

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Summary

In the majority of the field studies reviewed in this report samples were exposed outdoors above ground and only the average moisture content was determined. Therefore, no information is given about the moisture content in joints and other moisture traps. In many of the field studies, information on relative humidity, temperature, rainfalls etc. is missing and consequently these field studies cannot be used for relating the level of moisture content in the wood to the climate. Since the field studies are comparative studies it is, however, possible to summarise which parameters, wood properties and handling conditions, that do or do not affect the moisture uptake of wood. In some of the studies, factors affecting the growth of the tree are directly related to secondary wood properties such as the moisture uptake instead of to the primary wood properties such as density.

The influence of different paint systems on the moisture content of wood has been widely studied. However, most studies only compare the effect of different paint systems or the impact of various end grain sealers. The impact of coating colour has also been studied.

Few attempts have been made to study the impact of design on the moisture content. Most studies on this subject concern claddings. Studies on how duration of surface moisture is affected by design are also missing, as are studies relating climate to moisture content.

Preface

This report is part of WoodBuild, a research programme within the Sectoral R&D Programme 2006-2012 for the Swedish forest-based industry. This Programme is jointly funded by the government, industry and other stakeholders with interests related to the Swedish forest-based industry.

Contents

1. Introduction

The aim of this literature review is to establish what is known about moisture and temperature conditions in wood exposed outdoors above ground and what knowledge is missing. Central issues are the relation between meso-/microclimate and moisture content, how the moisture content is affected by surface treatments, wood material properties and design and also how these parameters affect the duration of surface moisture.

The literature review is limited to moisture and temperature conditions in wood exposed outdoors above ground, i.e. wood constructions exposed to rain. Consequently, claddings are included but wood constructions inside the building envelope are not. The review contains studies on untreated wood as well as coated and preservative treated wood. However, the moisture properties of the coatings are only treated superficially. The critical part of the review is mainly found in the conclusion.

2. Field tests

2.1. Moisture content measurements in samples exposed outdoors above ground

2.1.1 Untreated wood

Öqvist (1988), Elowson et al. (2003), Rydell et al. (2005) and Bergström et al. (2004) evaluated results from the same field test. Panels of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were exposed in Ultuna, Sweden and the moisture content was determined by weighing the samples regularly. Sapwood and heartwood was separated for Scots pine but not for Norway spruce. The panels were placed on a rack at 45° with the top ends covered and the lower ends on a metal plate with drainage holes, see Fig 1. Even though the lower metal plate had drainage holes it is likely that water could be accumulated and be absorbed through the end grain.

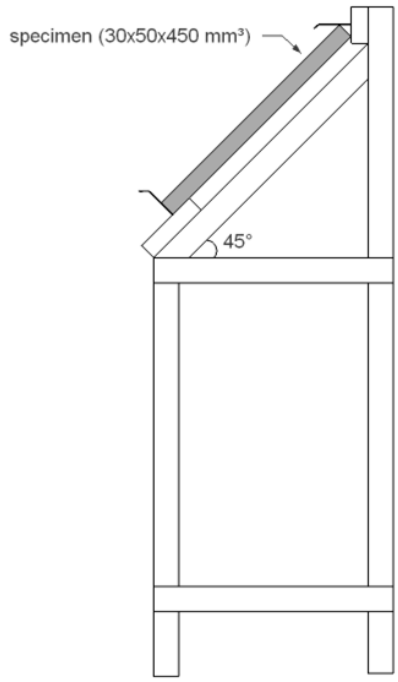

Figure 1. Exposure rack used in the field test started by Öqvist (1988).

The results after 2 years were presented in Öqvist (1988). Here, also information about the precipitation during the first two years of exposure was given. Generally, the mean moisture content of the pine sapwood varied between 10 and 42% while the mean moisture content of the pine heartwood was lower, between 10 and 22%. The moisture content of the Norway spruce samples varied between 10 and 37%. The moisture uptake of water stored pine sapwood was higher compared to pine sapwood that not had been water stored (pine heartwood was not included in this test). However, for Norway spruce only slight differences were seen between water stored and not water stored samples. Air dried samples reached slightly higher moisture contents than kiln dried samples. The felling season had no impact on the water uptake.

Elowson et al. (2003) evaluated the results from the same field test after 9 years and here the pine sapwood samples reached much higher moisture contents than the samples of pine heartwood and spruce. The pine heartwood had the lowest mean moisture content that never exceeded 30%. Both the mean moisture content and the moisture content fluctuations for the spruce samples were similar to the pine heartwood samples. The moisture content of pine sapwood increased if the wood had been air dried or water stored in accordance with the results of Öqvist (1988). However, for the spruce samples, no impact of drying method on the moisture content was found. The felling time or origin had no influence on the moisture content.

The Norway spruce (*Picea abies*) samples from the field test started by Öqvist (1988) were evaluated by Bergström et al. (2004). As in Elowson et al. (2003) the evaluation was made after nine years exposure but here more specimens were included to further investigate the impact of density, annual ring width, origin, storing, drying method and felling time on the moisture dynamics. The samples were taken from three different stands in northern, central and southern Sweden. The average moisture content of the samples from the three stands were 20.5%, 16.6% and 18% for the northern, central and southern stand respectively. Not only the average value but also the spread was highest for the samples from the northern stand. In accordance with the conclusions by Öqvist (1988) the moisture content of the air dried samples were higher than for the kiln dried samples. This contradicts Elowson et al. (2003) where no relationship was found between drying method and moisture content for the spruce samples. No relationship between moisture content and means of storage, felling time, density or annual ring width was found.

Rydell et al. (2005) also evaluated results from the field study reported by Öqvist (1988). However Rydell et al. (2005) only evaluated the results from samples of Scots pine (*Pinus sylvestris*). A larger amount of samples was included and more parameters added. The average moisture content was 25.4% for pine sapwood and 15.0% for pine heartwood. In accordance with the conclusions of Öqvist (1988) and Elowson et al. (2003) also this study showed that the pine sapwood samples were affected by water storage and air drying. The spread of the water stored samples was also large. However, means of storage and drying method had no influence on the moisture uptake of pine heartwood. Origin, felling time, annual ring width and density had no influence on the moisture uptake of either sapwood or heartwood.

In Blom & Bergström (2006) 230 samples of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were exposed out of ground contact for two years. The specimens consisted of two pieces of wood joined together with a third piece overlapping the other two, see Fig 2. This design was chosen to accelerate the experiment since the overlap should increase the moisture content. Neither the top ends nor the lower ends were covered. Climate data was available from a weather station at the site. The samples were taken from three different stands, all located in southern Sweden, representing the east coast, the west coast and central Sweden. The moisture content of the samples was determined by weighing the samples every month and large differences in moisture content were seen between pine heartwood and sapwood; the average moisture content was 46% for pine sapwood and 25.1% for pine heartwood. The moisture content of the pine sapwood samples was very fluctuating and reached values above 100%. The average moisture content of the spruce samples was 27.8%. The origin did not have any impact on the results.

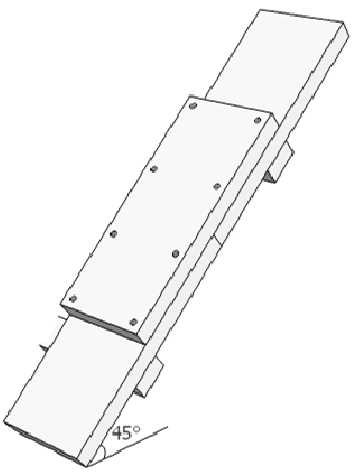

Figure 2. Specimen used in Blom & Bergström (2006).

Sandberg (2004) exposed specimens of Norway spruce (*Picea abies*) outdoors during 1.5 years. The study included specimens of both suppressed trees and dominant trees, trees that had grown on a dry site and trees that had grown on a wet site. Both specimens of heartwood and sapwood were included. Unlike the studies mentioned above the specimens in this study were exposed horizontally. The specimens were weighed regularly but the moisture content was not calculated. However the weight change was smaller for the heartwood specimens than for the sapwood specimens. A higher weight change was reported for the sapwood samples from the dry site than from the wet site, but this difference was not seen for the heartwood specimens. However, for the heartwood specimens the change in weight was lower for the suppressed trees than for the dominant trees. This difference was not seen for the sapwood samples.

Brischke & Rapp (2008b) monitored the moisture content, temperature and decay of specimens exposed at 23 different sites in Europe during 7 years. The specimens were made of pine sapwood (*Pinus sylvestris*) and Douglas fir heartwood (*Pseudotsuga menziesii*) and were exposed horizontally in double layer tests, see Fig 3.

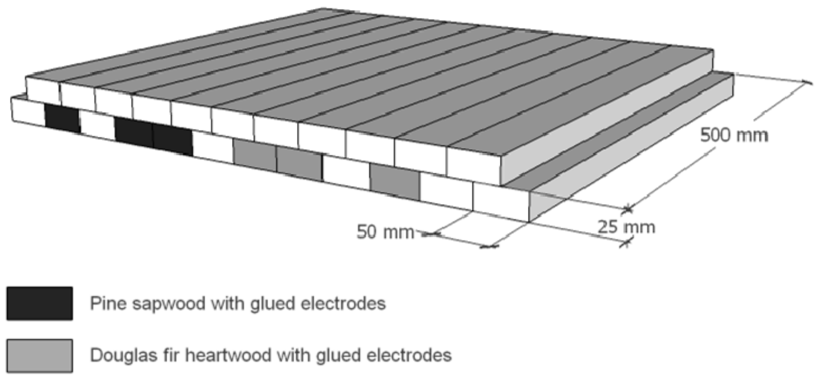

Figure 3. Specimens from Brischke & Rapp (2008b) exposed in double layer.

The upper layer consisted of six pine sapwood specimens and five Douglas fir specimens and the lower layer consisted of seven pine sapwood specimens and six Douglas fir specimens. The specimens were supported by beams and were separated from the beam by a bitumen foil. To cause differences in climate, sets with artificially shaded specimens were added at some sites. At one site, specimens were also placed in a greenhouse. The moisture content was monitored using glued electrodes (further described in 2.2.1) at depths of 25 and 120 mm from the end grain. Average, minimum and maximum temperatures below the bottom layer as well as between the layers were recorded. The results were presented as number of days above moisture content 20, 25, 30, 40 and 50% for the different test sites. The results from the temperature measurements were presented similarly. The shaded samples had both less cold days with a temperature below 0˚C and less hot days with a temperature exceeding 20˚C compared to the sun exposed samples. Differences in moisture content were also seen; the number of days with high moisture contents was generally higher for the shaded specimens than for the sun-exposed specimens. Brischke & Rapp (2008a) suggested a dose-response function to describe the decay of wood which correlated well with the decay rates observed in the field tests. The daily dose was assumed to be the product of a moisture induced component and a temperature induced component.

Evans (1989) investigated how the angle of exposure affects the weathering of wood surfaces in outdoor weathering tests. Samples of pine (*Pinus radiata*), 85 µm thick, were exposed at five angles: 0˚, 45˚, 60˚, 70˚ and 90˚. The weight loss and changes in chemical composition was measured during 50 days. The samples were exposed in Canberra, Australia and climate data for Canberra during the time of exposure was available. The weight loss increased with the angle of exposure; the samples exposed horizontally (0˚) lost most weight and the samples exposed vertically (90˚) the least. Also the results from the chemical composition measurements where the extractive, lignin and cellulose content were determined were correlated to the angle of exposure; the loss of extractives, lignin and cellulose increased with decreasing angle of exposure. Evans (1989) concluded that this probably was due to increased ultraviolet light levels at low angles of exposure but also because of the increased amount of free water that more easily is retained at lower angles of exposure, especially at an angle of 0˚.

Johansson (1997a) exposed specimens of spruce, pine sapwood and pine heartwood at angles of 0˚, 7˚ and 15˚ to investigate if the inclination affected the moisture content. The moisture content was determined by weighing the specimens once a week. Slight differences were seen between specimens exposed at different angles; the average moisture content of the specimens without inclination always had slightly higher moisture content although the difference was negligible. The reason why only very small differences were seen might be that only the average moisture content was determined by weighing whole samples. If the moisture content measurements had been more precise perhaps larger differences had been seen.

Lindegaard & Morsing (2003) exposed specimens of more than 30 European wood species to compare the natural durability. Both panel boards and lap-joints were exposed on racks. The lap-joints were exposed horizontally and the panel boards were exposed at three angles; horizontally, vertically facing both north and south and at 45° facing south. The panels that were exposed horizontally and vertically were exposed both without covering and under roof. Among all specimens, the locust tree had the lowest moisture content during the year. The locust tree specimens exposed at 45° without cover only exceeded 20% moisture content from December to February. Also oak had low moisture contents compared to other species. Among the coniferous species, thuja had the lowest moisture content during the year.

2.1.2 Coated/preservative treated wood

Schulz et al. (1973) studied the effect of paint system and colour on the moisture content of spruce, pine and sipo. Heartwood and sapwood were separated for the pine samples. The size of the specimens was 300×100×19 mm^3 and they were exposed at an angle of 45° during 27 months. The design of the exposure rack was not described in the paper. Totally, 24 different paint systems were tested and according to the authors all surface treatments were rather permeable. To investigate the influence of colour the specimens were painted with a dark, a medium dark and a light paint. For all paint systems, the dark colours gave the lowest moisture content and the light colour the highest. The difference in moisture content was about 5% comparing the darkest and the lightest paints. The influence of origin and orientation of the growth rings was also studied but neither had any influence on the moisture content.

The influence of paint system was also studied by Teichgräber (1973). Here, specimens (300×90×19 mm^3) of spruce and beech with both vertically and horizontally oriented growth rings were used. The specimens were conditioned to two different moisture contents, 12% and 19%, and eight different paint systems were applied. The angle of exposure was 45° and the upper ends of the specimens were covered. The design of the exposure rack is however unknown. The specimens were exposed for 36 months and relative humidity, temperature, precipitation and hours of sunshine were measured during the time of exposure. The moisture content of the specimens with the low initial moisture content (12%) had generally 5-6% lower moisture content than the specimens that were initially conditioned to 19%. However for some paint systems the difference tended to be smaller during the time of exposure. For some paint systems, specimens with horizontally oriented growth rings had slightly higher moisture contents.

Böttcher (1975) exposed specimens (720×80×18 mm^3) of spruce, pine, larch, douglas fir and oak on a rack at an angle of 45° facing southwest and also vertically on the top of a test house facing north, south, west and east. In some specimens, the temperature 1 mm below the surface treatment was measured every seventh hour but no results are presented in the paper. Generally, the highest moisture contents were found in the specimens facing north and the lowest in the specimens facing south with one exception; during summer, the moisture content of the specimens facing west was lower. Comparing the different species, pine had the highest moisture content followed by spruce. However, heartwood and sapwood was not separated for either pine or spruce.

Purslow & Williams (1978) evaluated trials with T-shaped specimens started in 1967. Pine sapwood, whitewood, hemlock and beech untreated and with various treatments were included. The specimens were exposed on racks at 45° facing south. The moisture content was monitored using microwave meters. Generally during weather, the moisture content of the untreated specimens was highest in the joint; it was sometimes doubled compared to the moisture content near the ends. If the specimens were treated with a water repellent treatment the moisture content profile was more uniform.

Sell (1982) exposed T-shaped specimens (Fig 4.) of spruce, beech, heartwood and sapwood of pine, heartwood of sipo and heartwood of dark red meranti. Before exposure, the specimens were conditioned to 20°C and 65% relative humidity. The specimens were exposed at an angle of 45° facing southwest but the design of the exposure rack is not described in the paper. The specimens were exposed during 3 years and were weighed ones a week during the first year, once a fortnight during the second year and once a month during the third year. Twelve different types of surface treatments were used. Some specimens were treated with a fungicide or hydrophobic oil before they were painted and some were not. All surface treatments were not applied on all wood species. Average moisture contents for some wood species and paint systems are presented and for spruce the average moisture content ranged between 12.2% and 43.8%. No moisture contents are given for the pine samples.

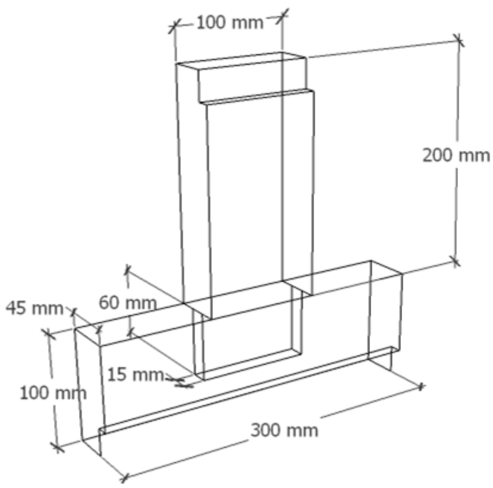

Figure 4. T-shaped specimen used by Sell (1982).

In Miller & Boxall (1984) painted and untreated L-joint specimens (Fig 5) both with and without end grain sealing were exposed on racks at a angle of 10° for 80 weeks. The wood species tested was spruce (*Picea abies*), heartwood and sapwood of Scots pine (*Pinus sylvestris*) and heartwood from Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). The moisture content along each arm was monitored with a microwave meter and the moisture content of the whole specimen was monitored by weighing. The results indicated that if end grain sealing was missing the presence of a coating was of secondary importance; a specimen with alkyd paint and no end grain sealing reached higher moisture contents (90%) than an unpainted specimen with end grain sealing (40%). The results after 4 years of weathering of the same specimens were reported by Miller & Boxall (1987). Similarly to the results after 80 weeks also these results showed that the end grain sealers reduced the moisture content of the L-joints. However, the effectiveness of the sealer decreased during the exposure.

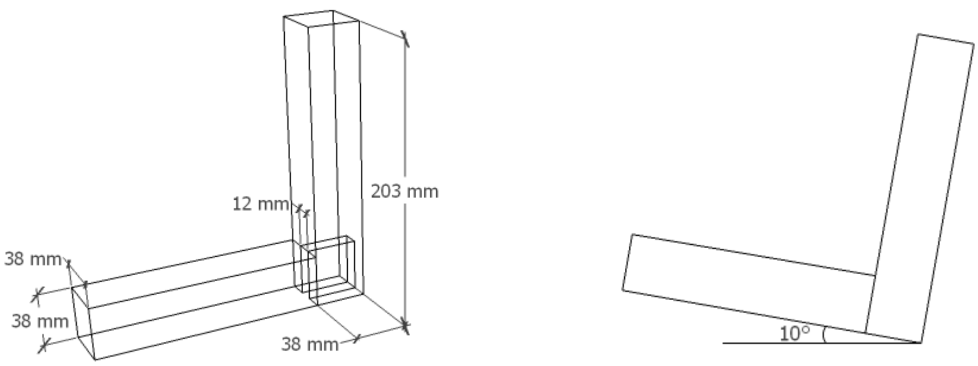

Figure 5. L-joint from Miller & Boxall (1984) exposed at an angle of 10˚.

L-joint specimens were also used by Boxall et al. (1992). The wood species tested were pine (sapwood and heartwood), spruce, iroko and lauan. Three types of coatings were used: one three coat alkyd gloss paint system, one solvent borne paint applied in three layers and one semi-transparent wood stain. The water vapour transmission rate was determined and the stain was the most permeable and the alkyd gloss paint was the least permeable among the three paint systems. Before painting, a solvent borne primer was applied as an end grain sealer on some of the specimens. The specimens were exposed during seven years on a rack at an angle of 10° so that the rainwater ran towards the joint. The moisture content of the tenon of each L-joint was monitored using a microwave meter and the moisture content of the whole specimen was monitored by weighing. Also the results of this study showed that end grain sealers reduced the moisture content of L-joints. However, both the wood stain and the alkyd paint system failed early in the test which allowed water to enter and the effect of the end grain sealer was lost. The end grain sealers were most effective in reducing the moisture content of pine sapwood and the lowest moisture contents during the exposure were found for the specimens painted with the most impermeable paint.

The field test reported by Öqvist (1988), Elowson et al. (2003) and Rydell et al. (2005), see 2.1.1, also included coated panels. The panels were painted with both primer and a finishing coat. The paint used was a dense polyurethane paint indented for windows. Among the painted panels there were both panels with end grain sealing and panels without. Two types of sealers were used; some panels were dipped in preservative oil and others were painted with two layers of primer and one layer of the finishing coat. The end protection was only used on the lower end of the panels. After two years exposure, Öqvist (1988) reported that the end grain sealers reduced the moisture uptake of the painted panels but differences were seen between the end painted samples and the samples that were dipped in oil. The samples with painted end grain continued having low moisture contents but the effect of the preservative oil decreased after a rather short period of time. After nine years of exposure also Elowson et al. (2003) came to the conclusion that surface treatment in combination with end grain sealing is the most effective way of lowering the moisture content. Rydell et al. (2005) found that the preservative oil protected the pine wood for different periods of time. The water stored samples that had been end grain sealed with oil were protected for a longer period of time than the samples that not had been water stored. Rydell et al. (2005) concluded that this is probably due to the increased permeability of the water stored samples which improves the penetration and thereby also the protection of the oil. The results of Rydell et al. (2005) also show that the moisture content of pine sapwood was lower if the wood was untreated than if the wood was painted but not end-sealed.

In Roux et al. (1988) specimens of beech (*Fagus sylvatica*), spruce (*Picea excelsa*), Scots pine (*Pinus sylvestris*), Douglas fir (*Pseudotsuga menziesii*) and dark red meranti (*Shorea* spp.) were exposed outdoors at four sites in Europe during two years. The specimens were coated with four different paint systems: an impregnating stain, a film forming stain, an acrylic latex paint and an alkyd paint. The panels were weighed every month but since the dry mass was unknown the moisture content could not be calculated. However, all specimens were conditioned in constant climate before the tests started and it was assumed that the change in mass corresponded well to the change in moisture content. The performance of the coatings varied; the impregnating and the film forming stain lost their moisture protection efficiency after a year of exposure. The alkyd paint was the most effective in dampening the changes of the moisture content in the wood.

Edlund & Sundman (1989) investigated the differences in moisture uptake between untreated wood and wood treated with different types of preservatives, paints and oils. Both pine (*Pinus sylvestris*) and spruce (*Picea abies*) were included in the test. The specimens ($20 \times 50 \times 500$ mm^3) were exposed on racks both horizontally and vertically on a roof located in Stockholm, Sweden. The moisture content was determined by weighing the specimens regularly. The moisture content in the specimens exposed horizontally reached higher moisture contents than the specimens exposed vertically. Some of the paint systems prevented the wood from drying and caused high moisture contents.

Specimens of both Scots pine sapwood (*Pinus sylvestris*) and Norway spruce (*Picea abies*) exposed outdoors on a rack at 45° were studied by Nussbaum (1993). The specimens were painted with 3 different paint systems and some of the specimens had been weathered before painting. The moisture content was monitored by weighing. Large differences in moisture content were seen comparing the spruce and pine specimens. The average moisture content of the spruce specimens varied between 15 and 30% and the moisture content of the pine sapwood specimens reached 110%. The panels that were weathered before being painted had a higher degree of cracking and reached higher moisture contents.

The moisture content 2 mm below the surface in coated wood panels was measured by Derbyshire & Miller (1997b). The moisture content was determined by measuring the resistance between two stainless steel screws inserted from the back of the panel. The panels were exposed on a rack at 45°. A metal cap was placed on the top of the panel so that water could only penetrate the test face. The permeability of the coatings was determined by Derbyshire & Miller (1996) and the relation of the permeability of the coating and the moisture content of the wood could therefore be established. During the early part of the tests the moisture content did not exceed the fibre saturation point in any of the panels. However, after a period of time large fluctuations in moisture content was seen for all coating systems. The length of the period with stable moisture content varied for the different coating systems. The more impermeable coatings managed to keep the wood dry longer than the more permeable coatings. However, the relation between coating permeability and moisture content of the wood was not as clear as in the laboratory test performed by Derbyshire & Miller (1997a), see 3.3. The high moisture contents during the latter part of the test were according to the authors probably due to micro cracks in the coatings allowing water to enter through the cracks. However, visible cracks were not always seen.

Militz et al. (1998) exposed both untreated and painted lap-joints of 11 wood species during 19 months. The contact area between the two parts of the lap-joint was not painted. Temperature, relative humidity and precipitation data during the exposure period is given in the paper. The moisture content of all specimens was determined gravimetrically and some specimens were also equipped with pins made of brass, insulated with an epoxy coating so that the moisture content also could be determined by resistance measurements with a moisture meter. The moisture content was determined monthly except during the first two months when it was determined twice a month. The moisture content of the lap-joints followed the seasonal variation in relative humidity but the level of moisture content was dependent on species and surface treatment. The moisture content of the painted lap-joints was higher than in the unpainted ones.

Rapp et al. (2000) studied the moisture sorption of four wood species exposed outdoors during two years. The samples were untreated, treated with a varnish and impregnated with melamine resin. Laboratory measurements of the moisture uptake of samples floating in a basin were also made. An attempt was made to find a correlation between the laboratory measurements and the field test by calculating an index called MRI (moisture induced risk index). The MRI was defined as the number of days per year when the moisture content of specimens exposed outdoors exceeded 25%. The index was determined by using gradients of the absorption and desorption curves from the laboratory measurements. The authors found this index to correlate well with the results from the field test irrespective of wood species or surface treatment.

2.2 Moisture content measurements in outdoor constructions

2.2.1 Claddings

The influence of an air gap on the moisture content of a cladding was investigated by Johansson et al. (2000). Three sections of spruce cladding facing north, south and east were exposed on a building in Skellefteå, Sweden. The claddings were fastened on a gypsum board and with varying air gap (0, 10, 20 and 30 mm). Before exposure, the panels were conditioned to about 12% moisture content. The moisture content of the cladding facing south was lower than the moisture content of the claddings facing north and east. However, no differences in moisture content were seen because of different air gaps.

Lindegaard & Morsing (2004) exposed claddings, untreated and treated with various coatings, at racks in Copenhagen, Denmark. The moisture content was measured by resistance measurements four times a day, 3 mm below the surface, in the middle of the board, at butt joints and at the lower end grain. Besides untreated claddings, four types of treatments were used; a non-permeable water based coating, a permeable coating, a linseed oil based coating and a stabilising oil treatment where wet timber was heated in oil during vacuum. A reference coating system called ICP (International Comparison Product) were also used. Both Scots pine sapwood and Norway spruce were used in the tests. The temperature, relative humidity and rainfall were measured during the period of exposure. The moisture content near the butt joints was higher in the claddings treated with the ICP coating system than in the untreated claddings. However, the butt joints treated with the non-permeable coating were dryer than the butt joints in the untreated claddings.

In Geving et al. (2006) moisture gradients were measured in wooden claddings on a test house situated in Trondheim, Norway. The impact of orientation, growth rate of the wood and surface treatment on the moisture content was investigated as well as the influence of ventilation gap openings of different sizes (0 mm, 4 mm and 23 mm) in the top and bottom of the cladding. The moisture gradients were measured by resistance measurements with insulated pins. Measurements with uninsulated pins were also made at two heights. The moisture content varied between 12 and 28% and the higher values were measured during wintertime. Generally, larger variations were seen for the sections oriented to the west than for the eastern sections, see Fig 6. For the claddings oriented to the west, which were exposed to large amounts of driving rain, the moisture content was higher for the elements with no air gap openings at the top and bottom of the cladding. A summary of the results concerning impact of ventilation gap opening and orientation is presented in Fig 6.

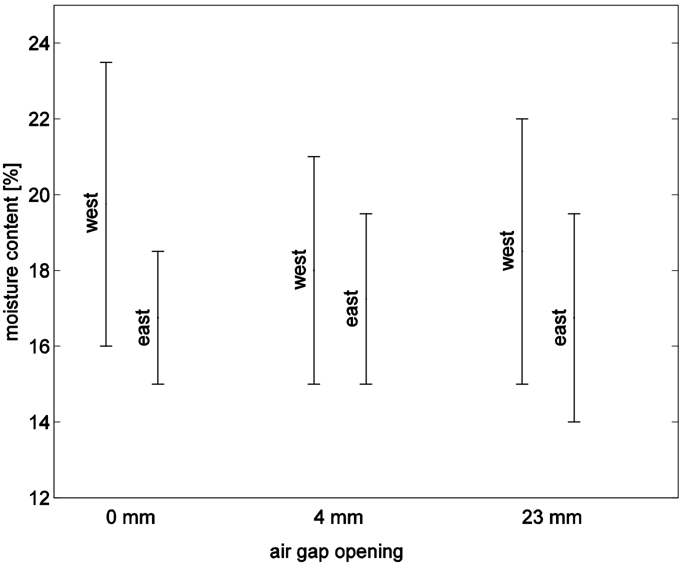

Figure 6. Summary of the results presented by Geving et al. (2006). The range of moisture contents measured in claddings with 0 mm, 4 mm and 23 mm air gap opening at the top and the bottom of the claddings facing east and west. The cladding was coated with oil based paint.

As expected, the moisture content of the untreated claddings was more fluctuating than the moisture content of the painted claddings; both the highest and the lowest moisture contents were found in the untreated claddings. The measurements of moisture gradients showed that the moisture content was highest in the outer part of the cladding and lowest in the inner part. The growth rate of the wood was not found to have any significant influence on the moisture content. Measurements of time of wetness and wind driven rain were also made and are described in Nore et al. (2006b), see chapter 5.

The results reported by Geving et al. (2006) have also been presented in various scientific articles (Lauter & Time 2005; Nore et al. 2005; Nore et al. 2006a; Nore et al. 2006b; Nore et al. 2006c; Nore et al. 2007; Nore & Thue 2008). In one of these (Nore & Thue 2008), difficulties with the measurements of moisture gradients are presented. Gravimetric measurements where the cladding was taken down, sliced and weighed were made and the moisture content from the gravimetric study did not correlate with the moisture contents from the resistance measurements. The resistance measurements showed a moisture profile were the outer part of the wood was wetter than the inner part. However, the results from the gravimetric measurements showed a moisture profile were the central part of the wood was wetter than the outside and the inside. The difference in moisture content between the central part and the edges was about 1 %. To investigate this further the authors did a laboratory study and conditioned claddings to two climates; 50% and 75% relative humidity. The results from the laboratory study showed a moisture profile where the highest moisture content was seen on the outside of the cladding and lowest on the inside even though the authors claim that the claddings were equilibrated. The difference between the wettest and the driest point was about 2%. The deviations were explained by differences in size of the electrical field caused by different distances to the surface. The conclusion given by Nore & Thue (2008) is therefore that moisture profile measurements with moisture pins are not recommended. However, they also state that it might be possible if a calibration is made for specimens conditioned in different climates.

Brischke et al. (2008b) studied the influence of a roof overhang on the moisture conditions in a cladding of Norway spruce situated in Taastrup, Denmark. The cladding was facing north and three different roof overhangs were used, 12, 62 and 112 cm. The upper and lower part of the cladding was separated with a horizontal board that formed a roof overhang of 4.5 cm for the lower part of the facade. The moisture content was measured at two heights, 65 cm and 170 cm in both the cover board and in the base board. The measurements in the base board were made in the over-lap, see Fig 7. The electrodes were inserted in pre-drilled holes and fastened with conductive glue at the tip. The holes were then filled with insulating glue. The method is further described in Brischke et al (2008a). The moisture content in the cladding ranged between 15% and 30% where moisture contents above 25% were reached between November and March. During the summer months the moisture content was about 16-18%. The differences in moisture content between the upper and lower part of the facade became more marked with increasing roof overhang. The differences were however larger between 62 and 112 cm roof overhang than between 12 and 62 cm roof overhang. The moisture content of the base board was generally lower than the moisture content of the cover board.

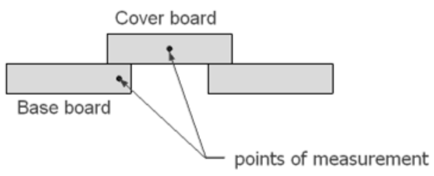

Figure 7. Locations where the moisture content was determined by Brischke et al. (2008b).

2.2.2 Decks and railings

Gaby & Duff (1978) monitored the moisture content and temperature in wood decks and railings. The wood deck was constructed around a small building in Georgia, USA. On three sides of the house the distance between the deck floor and the ground was 15 cm or more and on the fourth side, the distance was 2.5 cm or less. Two types of railings were constructed on three sides of the deck. The floor and railing components consisted of untreated, kiln-dried southern pine and the parts that supported the frame work was made of pine treated with chromate copper arsenate. The moisture content and temperature sensors were placed at joints and near end grain surfaces mostly in the parts consisting of untreated pine. However, some measurements were also made in the pine treated with preservatives. The amount of rain was also measured.

The measurements continued during 18 months and after 12 months a second wood deck was built around another building close to the first one to test improvements of the design. However, in the second deck no moisture content measurements were made, the deck was only observed visually. From the measurements in the first wood deck a ten-day period was chosen to investigate the relationship between rain and levels of moisture content in the wood. The points of measurement are shown in Figs. 8-12 below.

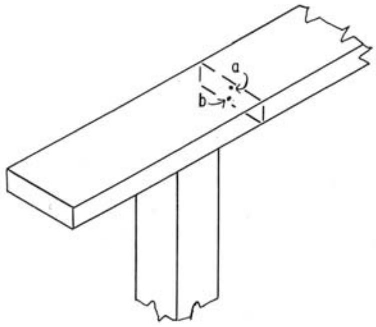

Figure 8. A railing with surface checks. The moisture content was determined near the upper (a) and lower (b) surface (Gaby & Duff 1978).

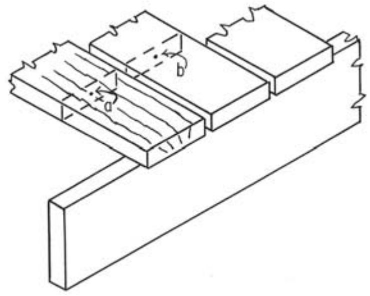

Figure 9. Deck boards with and without surface checks. The moisture content was determined in point a and b, 1 foot from the end of the board (Gaby & Duff 1978).

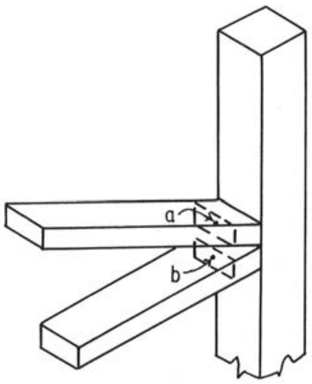

Figure 10. A part of the railing where the moisture content was determined at the ends of a sloping (a) and a horizontal (b) railing component (Gaby & Duff 1978).

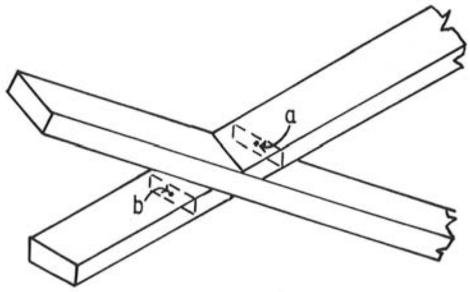

Figure 11. A crossed part of the railing. The moisture content was determined in point a and b (Gaby & Duff 1978)

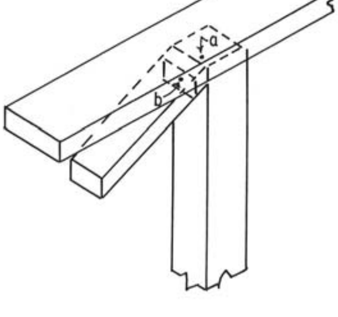

Figure 12. A part of the railing where the moisture content were determined in parts protected by the handrail (Gaby & Duff 1978).

Three different cases were seen; low stable moisture content, high stable moisture content and fluctuating moisture content. No response to rainfall was seen for the first two cases, however for the third case, the moisture content responded to rainfall which caused the fluctuations. Direct increases in moisture content after rainfall were seen for the parts of the railing in Fig. 10. Also the parts of the railing in Fig. 11 showed such tendencies. In general, the moisture content of all other points of measurement was either constantly low or constantly high with only small fluctuations. Note that moisture contents exceeding 30% could not be determined with the method used in this study. It is therefore possible that also the areas with constantly high moisture contents responded to rainfall without this being shown in the results. The moisture content levels at the points of measurement are summarised in Fig. 13 below.

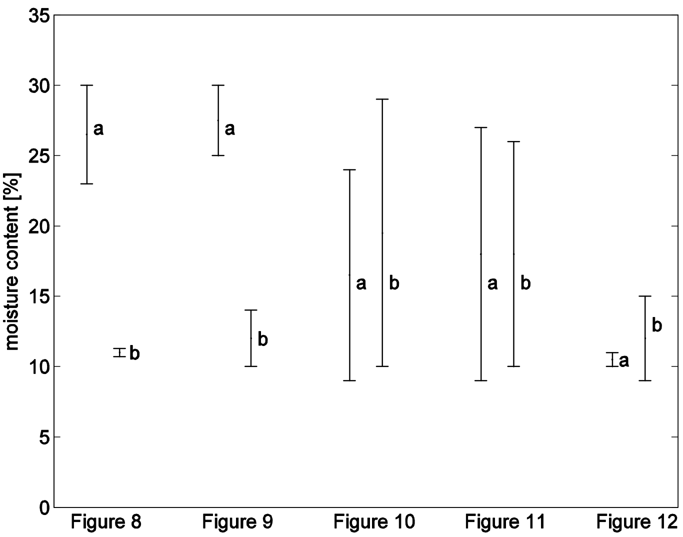

Figure 13. Summary of results from Gaby & Duff (1978). The moisture content levels during a 10-day period in the joints shown in Figs. 8-12.

The authors' general conclusion from the study was that for the railing, the components remained durable even without preservative treatments if care was taken so that water could not be trapped at end grain surfaces. For the deck boards however, the authors' conclusion was that the main problem was the development of surface checks after which the deterioration became rapid since water was held during longer periods of time. This also occurred for the handrail where the levels of moisture content were high near the upper surface (Fig.8a).

2.2.3 Bridges

The field performance of several stress-laminated timber bridges has been investigated in the United States. The monitoring program includes approximately 40 bridges and reports are available for about 20 of them (McCutcheon 1992; Wacker & Ritter 1992; Ritter et al. 1995; Wacker & Ritter 1995a; Wacker & Ritter 1995b; Hilbrich Lee et al. 1996; Hislop & Ritter 1996; Kainz et al. 1996; Ritter et al. 1996a; Ritter et al. 1996b; Wacker et al. 1996; Hilbrich Lee & Lauderdale 1997; Hilbrich Lee et al. 1997; Wacker et al. 1997; Hislop 1998; Kainz 1998; Wacker et al. 1998a; Wacker et al. 1998b; Dagher et al. 2000; Dagher et al. 2001a; Dagher et al. 2001b; Kainz et al. 2001). The general results from these measurements are presented in Ritter et al. (2000). Various parameters related to performance have been monitored and among these also moisture content and temperature. The moisture content was generally measured with resistance-type moisture meters at 6 to 12 locations every month or every sixth month. Sometimes samples were taken to determine the moisture content in laboratory if waterborne preservatives were used or if the moisture content exceeded the fibre saturation point. The temperature was determined by thermocouples installed in the bridge deck. To evaluate the bridge response to temperature change these values were compared to ambient temperatures. Ritter et al. (2000) concludes that the moisture content changes in stress-laminated timber decks can be considered as global and local changes. The global changes occur slowly and affect the whole structure when the moisture content changes from the initial moisture content at the time of construction towards equilibrium with the environment. The local changes include moisture content changes because of surface wetting and seasonal variations in relative humidity. These changes occurred more rapidly and only affected exposed parts of the bridge.

Jacobsson (2001) studied the moisture content distribution in three bridge elements (2970×800×360 mm^3) exposed 80 cm above ground in Skellefteå, Sweden, in Oslo, Norway and in Copenhagen, Denmark. The moisture content was monitored during 4-5 years and afterwards samples were taken to determine the moisture content gravimetrically. Each bridge element consisted of 22 glulam beams 135×360×800 mm^3 and was covered with 25 mm asphalt paving. The moisture content distributions and moisture content levels were similar for all three elements. The results show that the bridge elements were drier below the asphalt paving (12%) than at the lower edge (15-23%). The moisture content was also measured around the steel bars and it varied between 11 and 15%.

Field measurements in a timber bridge situated in Borlänge, Sweden was presented in Daerga & Fjellström (2001). The bridge consists of stress-laminated glulam box-beams made of spruce with no preservative treatment but all surfaces were painted with alkyd oil based paint. Temperature and relative humidity in the glulam flanges as well as ambient temperature and relative humidity was monitored. The temperature of the flanges followed the ambient temperature but had smaller fluctuations with one exception; during summer, especially the temperature of the top flange was higher than the ambient temperature. The relative humidity in the flanges correlated well with the changes in temperature but it did not follow the alterations in ambient relative humidity.

Johnson & Yazdani (2001) performed a field study to investigate the long-term performance of structural composite lumber (SCL) bridges. Two types of T-beams made of parallel strand lumber (PSL) and laminated veneer lumber (LVL) were included in the test. For each SCL-type, two wood species, Douglas fir and southern pine, were used. Besides untreated beams, also beams treated with chromium copper arsenate (CCA) and pentachlorophenol, were included. The beams were exposed outdoors on bearers of concrete. To simulate load, concrete blocks were placed on top of each beam. The dimensions of the beams were 610×406 mm^2, the flange and web thickness was 152 mm and 305 mm, respectively. Each beam had a span of 6.096 m. The beams were exposed in Tallahassee, Florida and were exposed to water at least three times a week, either by rainfall or by a garden hose. The temperature and relative humidity on the test site were recorded three times a week. To determine the moisture content of the beams, small samples were taken and the moisture content was determined gravimetrically four times a year. Only results from two measurement occasions are presented in the paper and it is therefore difficult to draw any conclusions from the results. However, great differences in moisture contents at the occasions presented in the paper can be seen comparing the different types of beams.

Brischke et al. (2008b) monitored the moisture content in a pedestrian bridge in Essing, Bavaria, Germany. The bridge was made of spruce glulam and was brush treated with an oil-borne preservative and a water repellent. The bridge was built in 1987 and was damaged by wood-destroying fungi. Besides electrodes to measure the moisture content, the temperature, relative humidity and rainfall was also measured on the bridge. The moisture content was determined using glued electrodes, see 2.2.1, however in this case the electrodes were inserted in wooden dowels before they were mounted in the bridge since the electrodes otherwise needed to be glued up-side-down in some cases. Higher moisture contents were measured close to nail plates at the bottom of the bridge. This was also the location were damages were seen. However the upper nail plates did not cause as high moisture content as the lower ones.

2.2.4 Balconies

No studies containing results from continuous measurements in wood balconies have been found. However, the results from an inspection of balconies is given in Sandberg (2006) and the handrail and the end grain at the top and bottom of posts were found to be critical points.

3. Laboratory studies

3.1 Moisture sorption during changes in relative humidity

The moisture sorption during varying relative humidity was studied by Chomcharn & Skaar (1983). Round specimens with a diameter of 20 mm and a length of 4 mm (along the grain) of green basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britton) and black cherry (*Prunus serotina* Ehrh.) were used. The specimens were placed in a test chamber where the temperature was kept constant at 25±0.25°C and the relative humidity was varied sinusoidally between 47 and 77% ±1.5%. Four different cycling periods were tested. A phase lag was seen between the relative humidity and the change in moisture content. The phase lag decreased with increasing number of cycles and increasing cycling periods.

Time (2002a) studied the moisture sorption of Norway spruce (*Picea abies*) exposed to rapid changes in the ambient climate. The relative humidity varied between 54% and 94% and the temperature was kept constant at 25°C. The specimens were exposed to both weekly and daily changes in relative humidity and the average moisture content of small specimens was determined by weighing. Comparing the daily and weekly step changes, almost the same moisture contents were reached after 24 hours as after one week. Most of the increase in moisture content occurred within hours after the change in relative humidity and thereafter a slower sorption process took place. In Time (2002b) a model for transient moisture transport was presented and compared with the results from Time (2002a). When hysteresis was included in the model the calculations and the measurements agreed much better than if a mean sorption isotherm was used. Generally, the calculated and the measured curves corresponded well.

In Blom & Bergström (2005) samples of Scots pine (*Pinus sylvestris*), both sapwood and heartwood were exposed in a accelerated laboratory test called the Mycologg test. The samples were sprayed with fungal spores and were exposed to different relative humidities in a chamber. A humidifier in the chamber raised the relative humidity to 100% and when the humidifier was turned off the climate in the chamber became the same as the climate in the laboratory. The samples were exposed to 72 h cycles of 100% RH and laboratory climate (approximately 50% RH) during 10 weeks. The results from the Mycologg test were compared to results from a field test (reported in Blom & Bergström (2006)). The fungal discouloration after 10 weeks exposure in the climate chamber corresponded to 1-2 years of exposure in the field test. However, the moisture contents did not correspond; the moisture contents of the samples exposed outdoors were much higher than the moisture contents of the samples exposed in the Mycologg test. The average moisture contents of heartwood and sapwood in the Mycologg test were 19.2% and 26.7% while the average moisture contents in the field tests for heartwood and sapwood were 25.1% and 46% respectively. Note that the moisture content was determined with different methods. In the field test, whole samples were weighed and the samples were designed so that moisture could be trapped (see Fig 2.). In the laboratory test, the moisture content was determined by resistance measurements.

The Mycologg method was also used by Bergström & Blom (2005). Here, heartwood and sapwood of Norway spruce (*Picea abies*) from 4 different stands were tested and the moisture content was measured 3 mm below the surface. The difference in moisture content between the heartwood and sapwood were smaller than expected but the authors state that visually there were much more surface moisture on the sapwood samples than on the heartwood samples. To further investigate the difference between heartwood and sapwood the water vapour transmission resistance was measured by the cup method. Two water permeability tests were also performed. One where specimens were floating in deionised water and one where a droplet of deionised water were placed on the surface of a sample to determine the time it took for the water droplet to be fully absorbed by the wood. The water vapour transmission resistance was equal for heartwood and sapwood but was found to depend on annual ring width and density. However, the results from both of the water permeability tests showed that the water permeability was higher for spruce sapwood than for heartwood.

Moisture content profiles during drying at a distance from 0 to 500 µm from the surface was measured by Rosenkilde et al. (2004) using magnetic resonance imaging. The samples consisted of Scots pine (*Pinus sylvestris*) heartwood with an initial moisture content of 70.5%. The samples were dried at a temperature of 23±0.5°C and the relative humidity was kept at 55±2% for 21 hours. However, at the end of the drying period the relative humidity was lowered to 20±1% during 24 minutes and then raised to 98±2% for 114 minutes. The results showed that water close to the surface evaporates very fast and after 9 minutes the moisture content profile was almost flat. Within 60 min the moisture content of the surface layer decreased from 120% to 20%. When the relative humidity was raised to 100% a steep moisture content gradient was developed at the surface.

3.2 End grain water absorption

In Miller & Boxall (1984) specimens of four wood species painted with various sealers were tested. The specimens were placed on cotton wool saturated with water. The moisture content after 24 hours was determined every centimetre up to 10 centimetres. The specimens of Scots pine sapwood behaved differently than the other specimens. The moisture content of the pine sapwood specimens was above 30% at the height of 9-10 centimetres while the other specimens were dry at the height of 3 centimetres. End-sealed specimens of pine sapwood were also tested and the effectiveness of the sealers varied.

The effectiveness of various end grain sealers were also investigated in Ekstedt & Nordman-Edberg (1993). Specimens of both pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were placed with the end grain in water and were exposed to 14 cycles of sorption and drying. The weight change was registered but the moisture content was not determined. Some specimens were also examined using computed tomography.

Segerholm (2007) studied the moisture content of wood elements of Norway spruce exposed to artificial rain. The elements consisted of sills and studs joined together with staples instead of nails to minimize the influence of the fasteners on the moisture content. The elements were exposed to 6 minutes of rain each hour and moisture content profiles were measured by slicing the elements and weighing the slices. An interaction between sill and stud was found, during the drying phase; the stud supplied the sill with water. Despite the small size of the staples they increased the moisture content locally. The influence of a moisture barrier underneath the sill was also studied and the sills without the moisture barrier were found to dry faster.

Segerholm (2007) also studied the capillary suction of sticks made of Scots pine (*Pinus sylvestris*). The sticks were placed in water with four sides sealed but the ends left opened so that water could be absorbed in the longitudinal direction. Both specimens of sapwood and heartwood were included in the tests. The heartwood specimens had high moisture contents at the bottom and decreasing values towards the top of the specimen. The specimens of sapwood however had high moisture contents both at the bottom and at the top of the specimens with lower values in the middle.

Sandberg (2009) studied the end grain water absorption and desorption of Norway spruce (*Picea abies*). The specimens were placed in a basin with water and moisture profiles were measured using computed tomography (CT) after 1, 3, 7 and 14-15 days. Desorption was measured in room climate during six or seven days. The moisture absorption and desorption were studied during three absorption/desorption cycles. During the first cycle, the sapwood samples reached higher moisture contents than during cycle 2 and 3 but this difference was only small for the heartwood samples. The capillary water height was higher for sapwood than for heartwood. No differences were found between dominant and suppressed trees.

3.3 Moisture sorption/absorption of coated specimens

Janotta (1979) investigated the influence of the coating colour on the moisture distribution by exposing samples of spruce to artificial sunlight. The specimens (400×120×40 mm^3) were conditioned to three different moisture contents, 12%, 16% and 20% and three different surface treatments in three colours were applied. The first surface treatment was in white, grey and dark brown and the other two was in light brown, medium brown and dark brown. One series of specimens painted with coatings with similar permeability and 12 different colours was also prepared as well as one series with similar colour and different coating permeability. In the tests, one side of the specimens were exposed to 1×8, 3×8 or 6×8 hours of artificial sunlight. However, the paper contains no information about the surface temperature of the exposed surface or temperature and relative humidity in the air. Moisture content profiles were determined by slicing and weighing. The decrease in weight of whole samples after the exposure was also determined. The differences in weight loss between different colours were not very distinct but the specimens in dark brown had higher weight losses, especially after 6×8 hours of exposure. The weight loss of the specimens increased if the initial moisture content was increased. The results from moisture content profile measurements showed that the moisture content increased on the cold side and decreased on the warm side. This effect increased with the time of exposure. However, if the surface treatment was permeable, the cold side of the specimen tended to dry and the moisture content was not raised as much on the cold side as for the impermeable coatings. The shape of the moisture content profile therefore became different for the specimens with permeable surface treatments than for the specimens with more dense coatings. The moisture content profiles were also different for different colours; dark colour resulted in lower moisture contents on the warm side but also higher moisture contents on the cold side. The difference was not as large for the specimens painted in light brown, medium brown and dark brown as for the ones painted in white, grey and dark brown.

In Ahola (1991) water-vapour permeability tests and immersion tests were performed for specimens of spruce (*Picea abies*) and pine (*Pinus sylvestris*) with various coatings. Unweathered specimens, specimens that had been weathered for one year and specimens that had been weathered for three years were tested. The water uptake increased when cracks had formed in the impermeable paints but the drying was still slow.

The effect of nails on the moisture content in painted claddings was studied by Absetz (1994). Specimens of Scots pine (*Pinus sylvestris*), some painted before nailing and some painted after, were sprayed with water. All specimens were weighed to determine the average moisture content and some specimens were also sliced to determine the moisture distribution. High moisture contents were seen around the nails. Big nails caused higher moisture contents than small nails. Painting before or after nailing did not have any great influence on the moisture content but unexpectedly nailing before painting gave slightly higher moisture contents. However, when the nail holes were pre-drilled, the moisture content in the nail area was not increased.

The relation between the coating permeability and the moisture content of coated wood was investigated in Derbyshire & Miller (1997a). The moisture distribution was measured at three depths with hypodermic needles insulated with PVC-tubing. Calibrations were made by equilibrating samples to different moisture contents and then determining the moisture content gravimetrically. The samples were exposed to one week of water absorption and one week of drying and several coatings were tested, both water- and solvent-borne. The moisture levels were generally higher below the water-borne coatings than the solvent-borne coatings but the moisture content did not exceed the fibre saturation point in any of the coated samples. For the coatings with the lowest permeability no change in moisture content was detected. A model to predict the moisture content at different depths in coated and untreated pine sapwood was presented by Derbyshire & Robson (1999). The results are compared to the experimental results in Derbyshire & Miller (1996; 1997a; 1997b).

In Ahola et al. (1999) specimens of pine (*Pinus sylvestris*) sapwood and spruce (*Picea abies*) painted with various coatings were exposed to liquid water in three tests. The moisture contents were determined by weighing the specimens. The water uptake for uncoated pine was about three times higher than for uncoated spruce but comparing the coated samples, the water uptake of the pine samples was only slightly higher than for the spruce samples.

In de Meijer & Militz (2000) wood samples of spruce (*Picea abies*) with different coatings were hanged with the test face in liquid water. The average moisture content was determined by weighing the samples regularly and samples were also sliced and weighed to determine the moisture profile at different times. Apparent diffusivities were calculated and the results were analysed using different models. However, the moisture profiles could not be predicted using an overall apparent diffusivity for the coated wood. The measured profiles coincided better with the theoretical predictions when the rate of the moisture content changes at the surface was taken into account and sorption data for untreated wood were used. The same authors also made sorption studies for spruce (*Picea abies*) and dark red meranti (*Shorea* spp.) at different temperatures. The results are presented in de Meijer & Militz (2001). The dimensional changes of the specimens were also measured and the influence of coating film thickness was investigated. The rate of the moisture sorption was found to be strongly dependent on the temperature but the coating film thickness only had a limited influence.

The water absorption of painted samples of Norway spruce (*Picea abies*) was studied in Ekstedt & Östberg (2001). The panels were exposed by floating on deionised water for 72 hours and the weight increase was registered but the moisture content of the wood was not measured. The samples were also exposed to several cycles of weathering to study the impact of aging on the water sorption. The weathering was found to influence the water protection properties of the coatings and the author state that measurements of water sorption of coated wood before weathering is not very useful to predict the long-term performance of a coating. Ekstedt (2003) studied the influence of coating system composition on the moisture dynamics of coated wood using the same method.

In Ekstedt (2002) Scots pine (*Pinus sylvestris*) with various coatings were exposed to artificial weathering containing rain and wind exposure, freezing and heat exposure. The moisture distribution was monitored by computed tomography (CT). High moisture contents were found around cracks and on the uncoated backside.

3.4 Full scale tests

The results from a full scale laboratory test of wood panels with different coating systems were presented by Dellming (1990). The moisture content was measured at the lower end of the panel, at the horizontal joints between two boards and in the middle of the board. At these three locations the moisture content was determined both at the edge were the cover-board overlaps the underlying board and in the middle of the cover-board, see Fig. 14. The panels were exposed to artificial rain with different durations and different drying times. The influence of higher drying temperature was also investigated. The highest moisture contents were found in the overlap between the cover-board and the underlying board especially in joints and in the panel endings. Some paint systems were more effective in keeping the joints dry than other.

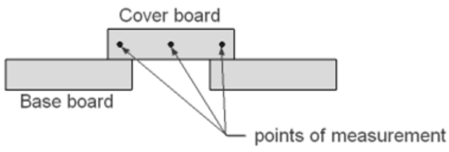

Figure 14. Locations where the moisture content was determined in Dellming (1990).

Full scale laboratory measurements were also performed by Hjort (1996) where the moisture balance in wood panels painted with different paint systems was studied. The panels were exposed to artificial rain during 2 days and were then dried until the moisture content was below 20%. The moisture content was determined by measuring the resistance between two stainless steel screws, inserted from the back of the panel with the tip 3 mm below the surface. The measurements were mostly made near butt joints and at the bottom of the panelling. A calibration was made for panels equilibrated to five different relative humidities and the influence of the distance between the probes and the size of the probes were also studied. A time-moisture-content (TMC) value was introduced to evaluate not only the level of moisture content but also the duration of moisture contents above 20%. The TMC was defined as the area enclosed by the time-moisture content curve and a line at 20% moisture content, see Fig. 15. In panels painted with permeable coatings the moisture content reached high levels of moisture content rapidly after wetting but on the other hand these panels also dried out quickly. Panels painted with less permeable coating did not reach as high levels of moisture content but the drying period was longer which means that the period of time with moisture content above 20% was longer. Note that the panels in this study were not weathered. The results from this study also show the importance of end grain sealing.

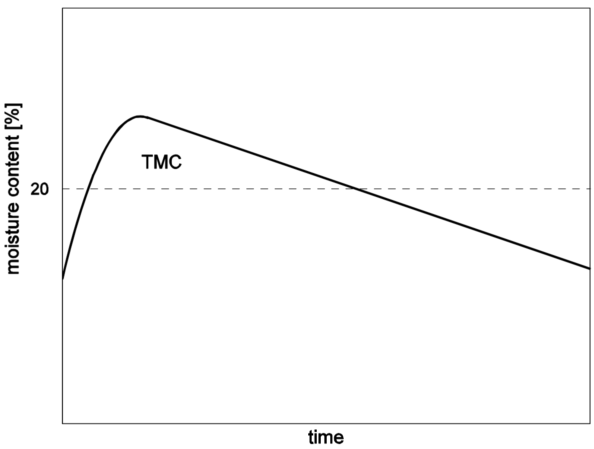

Figure 15. The definition of the time-moisture-content value (TMC) given by Hjort (1996). The TMC is defined as the area enclosed by the time-moisture content curve and a line at 20% moisture content.

Johansson (1997b) investigated how the moisture content of a cladding was affected by various gaps (0, 1.5, 1, 2, 4 and 8 mm) between the base board and the cover board. A wall was built up in the laboratory and was sprayed with water during 48 hours. The moisture content in the cover board was determined by computed tomography (CT) at four occasions; after 48 hours of water spraying and after 1, 25 and 192 hours of drying. After the wall had been sprayed with water, the lowest moisture content was found where the gap between the base board and the cover board was 0.5 and 1 mm. At the same occasion, the boards with no gap and a gap of 2 mm had the highest moisture content. Also after one hour of drying the boards with the 0.5 and 1 mm gap had the lowest moisture content but after 25 hours of drying the lowest moisture contents were found in the boards with a gap of 8 and 4 mm. After 192 hours the boards were equilibrated.

5. Duration of surface moisture

Norberg (1998; 1999; 2000) present a method to monitor surface moisture and time of wetness called the WETCORR method. A similar sensor was also used by Svennerstedt (1989; 1990). The sensors used in these studies are mounted on a facade and measure the time of wetness on the sensor itself rather than the time of wetness on the actual facade material.

Nore et al. (2006b) further evaluated the measurements of time of wetness, surface temperature and wind driven rain from the study reported by Geving et al. (2006), see 2.2. The measurements were performed on wooden claddings on a test house in Trondheim. The time of wetness was defined as the sum of time of wind driven rain, time of surface condensation and the time it takes for the surface to dry after a rainfall/condensation period:

$$t_{TOW} = t_{WDR} + t_{condensation} + t_{drying\ out\ period}$$ (Nore et al. 2006b)

The time of wetness was measured with electrodes in contact with the surface and the values were compared to the wind driven rain measurements and calculated values of surface condensation. The time of wetness exceeded the number of hours with wind driven rain and condensation which confirmed the drying out period in the equation. The time of wetness measurements were also compared to measurements of the moisture content in the cladding and a correlation was seen. The measurements were made on claddings with various ventilation gap openings and the longest time of wetness periods were measured for the claddings that had the largest ventilation gap opening. These claddings also had the longest condensation periods.

A model for calculation of duration of surface moisture was suggested by Svennerstedt (1989; 1990). The duration of surface moisture was defined as the time during which the thickness of the moisture film exceeds a certain critical level. To calculate the thickness of the moisture film a moisture balance equation were set up:

$$\frac{d(d_{film})}{dt} \cdot \sigma = \left(g_{driving\ rain} + g_{condensation}\right) - \left(g_{evaporation} + g_{in} + g_{flow}\right)$$

d_{film} – the thickness of the moisture film
σ – the density of water
$g_{driving\ rain}$ – amount of driving rain
$g_{condensation}$ – the condensation on the facade
$g_{evaporation}$ –the amount of moisture that evaporates from the surface
g_{in} – the amount of moisture that is absorbed by the facade material
g_{flow} – the amount of moisture that flows off the surface

Svennerstedt (1989) also described some of the included parameters. The condensation on the surface was defined as:

$$g_{condensation} = \beta \cdot (v - v_{s,surface}(T_{surface}))$$

where β is the moisture transfer coefficient, v is the vapour concentration in the air and v_s is the saturation vapour concentration of the surface. The same expression is given for determination of the amount of moisture that evaporates from the surface but with the opposite sign. The temperature at the surface, which is needed to determine the saturation vapour concentration, can be determined by setting up an energy balance equation for the surface. Svennerstedt (1989) concludes that it is difficult to determine g_{flow}. He says that nothing is found in literature but states that the term often can be neglected. For calculation of g_{in}, he suggests Fick's law. No model is given for calculation of $g_{driving\ rain}$ but results are presented from other studies.

Even though no other attempts to model the duration of surface moisture seem to have been made, the parameters included in the above-mentioned models have been studied. For example, a state of the art of wind driven rain research in building science is given by Blocken & Carmeliet (2004) and a model of evaporation of water from a metal surface is given by Cole et al. (1995).

6. Conclusions

6.1 Influence of wood material properties and handling conditions

Almost all studies included in this review concerning the influence of wood material properties on the moisture content have in common that only the average moisture content was determined, often by weighing whole samples. The design of the exposure racks varies but most of them enable water to be trapped and thereby raise the moisture content locally. How much higher moisture contents that are reached in these locations is however unknown even though it somewhat affects the average values. Information of relative humidity, temperature, rainfalls etc. is missing in many of these studies and consequently these field studies cannot be used for relating the level of moisture content in the wood to climate. Since the design of the specimens and the exposure racks are different for different field studies also the moisture content of the specimens of course varies. For example, Rydell et al. (2005) report average moisture contents for heartwood and sapwood of Scots pine (*Pinus sylvestris*) of 15% and 25% and Blom & Bergström (2006) who used specimens that allowed water to be trapped to accelerate their tests report moisture contents of 25% and 46% for heartwood and sapwood of Scots pine. Since the field studies are comparative studies it is however possible to summarise which parameters, wood properties and handling conditions, that do or do not affect the moisture sorption of wood.

All studies in this literature review where both heartwood and sapwood of Scots pine (*Pinus sylvestris*) were included (Öqvist 1988; Elowson et al. 2003; Blom & Bergström 2006) agree that there is a great difference in moisture uptake between heartwood and sapwood. Elowson et al. (2003) reported that the average moisture content of the untreated pine heartwood samples in their study never exceeded 30%. The moisture content of pine sapwood also becomes higher than the moisture content of Norway spruce (Nussbaum 1993; Elowson et al. 2003) where heartwood and sapwood seldom are separated, however Sandberg (2009) report differences in moisture absorption between heartwood and sapwood also for Norway spruce. The results from different studies comparing the moisture content levels of Norway spruce and pine heartwood varies between similar (Elowson et al. 2003) and slightly higher moisture contents for Norway spruce (Öqvist 1988; Blom & Bergström 2006).

The handling conditions also sometimes affect the moisture content; water storage of pine sapwood seems to have a negative effect as the moisture content during exposure outdoors becomes higher (Öqvist 1988; Elowson et al. 2003; Rydell et al. 2005) and the spread larger (Rydell et al. 2005). However for Norway spruce the water storage seems to have no (Elowson et al. 2003; Bergström et al. 2004) or only a slight impact (Öqvist 1988). Also the drying method sometimes has an impact on the moisture content. The moisture uptake of pine sapwood increased if it had been air dried instead of kiln dried (Elowson et al. 2003; Rydell et al. 2005) and according to Bergström et al. (2004) this is the case also for Norway spruce. This is however contradicted by Elowson et al. (2003) who found no impact of drying method on the moisture content of Norway spruce. All studies (Öqvist 1988; Elowson et al. 2003; Bergström et al. 2004; Rydell et al. 2005) agree that felling season has no influence on the moisture content.

Many studies also agree that origin does not affect the moisture content of Norway spruce or Scots pine (Schulz et al. 1973; Öqvist 1988; Elowson et al. 2003; Rydell et al. 2005; Blom & Bergström 2006). This is however contradicted by Bergström et al. (2004) who found that samples from northern Sweden reached higher moisture contents than samples from southern and central parts of Sweden. Annual ring width have not been found to have any influence of the moisture content of either Scots pine (Rydell et al. 2005) or Norway spruce (Bergström et al. 2004). Also density had no influence of the moisture content of Scots pine (Rydell et al. 2005) or Norway spruce (Bergström et al. 2004).

Regarding the impact of the orientation of the growth rings on the moisture content the results differ. According to Schulz et al. (1973) the orientation has no influence. However Teichgräber (1973) found that specimens with horizontally oriented growth rings had slightly higher moisture contents.

In the studies summarized in this review, factors affecting the growth of the tree are sometimes directly related to the moisture uptake of wood. Since the growth conditions affects primary wood properties, for example density, it might be better to investigate how the growth factors affect the primary wood properties and then relate them to secondary wood properties such as moisture uptake, see Fig. 16.

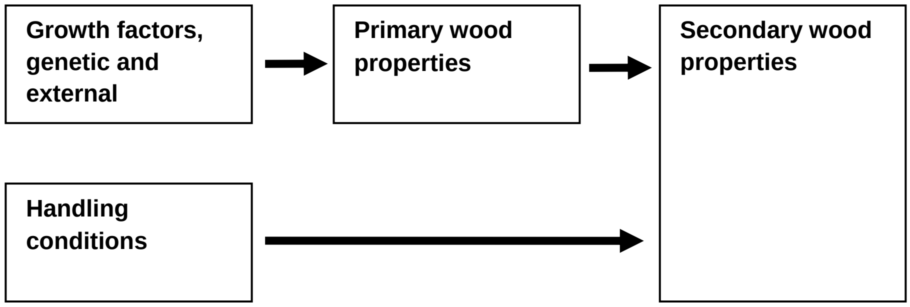

Figure 16. Factors affecting the secondary wood properties.

6.2 Influence of properties related to coatings

The influence of different paint systems on the moisture content of wood has been widely studied. Most studies compare the effect of different paint systems and the conclusion is often that the dense paint systems keep the moisture content low and are therefore the best ones to use (Boxall et al. 1992; Derbyshire & Miller 1997a; Derbyshire & Miller 1997b). There are however results contradicting this statement. Even though the moisture content of wood painted with permeable coatings becomes higher, the permeable coating also allows the wood to dry out faster (Hjort 1997). This means that the period of time with high moisture contents is not necessarily shorter with dense coatings than with permeable coatings (Hjort 1997). High moisture contents below dense coatings are also reached if cracks appear; the water uptake then increases but the drying is still slow (Ahola 1991).

The performance of a coating is influenced by weathering (Ahola 1991; Ekstedt & Östberg 2001) and the specimens are sometimes weathered before the tests to create more realistic circumstances. Results from studies where unweathered coated specimens have been used and tested only for a short period of time may not be very useful. At least not if the aim is to test the long term performance of a coating. The performance of coatings decreases with time, however the length of the period of time varies for different paint systems (Derbyshire & Miller 1997b).

The importance of end grain sealing is shown in many studies (Miller & Boxall 1984; Miller & Boxall 1987; Öqvist 1988; Elowson et al. 2003) although the effectiveness seem to decrease with time (Miller & Boxall 1987). If wood is painted but not end grain sealed the moisture content becomes higher than if it is left untreated (Rydell et al. 2005).

Not only the paint system but also the colour of the coating affects the moisture content; wood painted with dark coloured paints reach lower moisture contents than wood painted with light colours (Schulz et al. 1973).

6.3 Influence of design

Few attempts have been made to study the impact of design on the moisture content. Most studies on this subject concern claddings (Dellming 1990; Hjort 1997; Johansson 1997b; Johansson et al. 2000; Geving et al. 2006) but one study on wood decks and railings (Gaby & Duff 1978) has also been found. In claddings high moisture contents are reached at the lower end of the panel and at joints (Dellming 1990) but also around nails (Absetz 1994). Dellming (1990) also report higher moisture contents in the cover board where it overlaps the base board. Brischke et al. (2008b) found that the baseboard generally are dryer than the cover board in the overlap. Johansson et al. (2000) report that the moisture content of a cladding is independent of the existence of an air gap behind the cladding. The influence of a roof overhang has also been studied an increasing roof overhang lowers the moisture content, especially in the upper part of the panel (Brischke & Rapp 2008b).

Studies on the impact of design that not concern claddings are few. Gaby & Duff (1978) studied the moisture content at joints in railings and decks and how it was affected by rain. The main conclusion was that high moisture contents are reached when water is entrapped and hindered to dry out and such constructions needs to be avoided. This conclusion may not be very surprising but further studies in this area seem to be missing. Johansson (1997a) studied the influence of an inclination on horizontally exposed wood surfaces and reported that only very small differences were seen for different angels. These results are possibly due the inadequate method; if more precise determinations of the moisture content had been made perhaps larger differences had been seen. However, the moisture content of specimens exposed horizontally becomes higher than if they are exposed vertically (Edlund & Sundman 1989). No studies on how the duration of surface moisture is affected by design have been found.

6.4 Relation between climate and moisture content in wood

Most studies only compare wood of different species, the performance of various coatings etc. but some of them also include information about the relative humidity, temperature or precipitation at the exposure site. The most complete study from that point of view is the study on claddings reported by Geving et al. (2006). It includes complete weather data from a weather station near the test house, wind driven rain measurements, measurements of time of wetness and measurements of both temperature and moisture content in the cladding.

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