Effects of Outdoor Weathering and Wood Properties on Liquid Water Absorption in Uncoated Norway Spruce Cladding

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Abstract

A comparison of liquid water absorption in uncoated Norway spruce (*Picea abies* L.) claddings before and after 1 year of outdoor weathering was performed. The study was based on 150 specimens from two sites with high-productive forest and two sites with low-productive forest in southern Norway. The specimens included inner and outer boards; density, annual ring width, and proportion of heartwood were recorded. Water absorption increased after weathering. The relative change of short-term absorption was larger for outer boards than for inner boards, whereas it did not vary between origins. The outer boards also had more cracks than the inner boards after weathering. The differences between inner and outer boards were explained by different heartwood proportion and different annual ring orientation. The variability of short-term absorption increased after weathering since the sample groups with the highest initial absorption also had the largest increase after weathering. The change of long-term absorption did not vary between inner and outer boards or between origins.

The ability to withstand changes in moisture content is one of the most important properties of wooden cladding, both because changes in moisture content below fiber saturation bring about dimensional changes and because high moisture content increases the vulnerability to biological deterioration (Eaton and Hale 1993). In order to carry out its purpose without coating or chemical modifications, the wood has to meet stringent demands regarding moisture absorption.

Partly because of its low permeability, Norway spruce (*Picea abies* L.) is the most commonly used cladding material in Norway (Øvrum 2002). Still, there may be both spatial and geographical variations, and the selection of raw materials is particularly important for uncoated claddings. It has been shown that the absorption of liquid water in uncoated claddings varies between boards cut from the inner and outer portion of Norway spruce logs (Sivertsen and Vestøl 2010). This difference was related to heartwood proportion and density. Differences between heartwood and sapwood regarding permeability are also known from other species (Johansson et al. 2006, Metsä-Kortelainen et al. 2006), and even though studies on Norway spruce heartwood are sparse, some have reported higher water uptake in sapwood than in heartwood (Metsä-Kortelainen et al. 2006, Sandberg 2006).

The water transport in wood depends on openings (pits) between the cells. The larger water permeability in spruce sapwood has been explained by the fact that ray tracheids, which remain unaspirated even in dried sapwood, are encrusted by extractives during heartwood formation (Liese and Bauch 1967a). A number of softwood species, predominantly those with visible heartwood, contain water repellent extractives. It is suggested that this feature plays an important role in decay resistance (Taylor et al. 2002). This is probably of smaller importance in Norway spruce, which has lower extractive content than Scots pine (Assarsson and Åkerlund 1966) and no difference in the amount of extractives between heartwood and sapwood (Nylinder and Hägglund 1954).

Water transport by diffusion across grain is slower in high-density wood since the cells have a larger proportion of cell walls, in which the diffusion rate is much slower than in

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the cell lumens (Siau 1984). Because of smaller cell lumen, capillary transport decreases with increasing density as well. Capillary absorption in Radiata pine wood has been shown to be lower in wood with high density (Booker and Kininmonth 1978), but in Norway spruce this effect is reduced by a lower aspiration ratio of bordered pits between tracheids in latewood than in earlywood (Liese and Bauch 1967b).

Wooden claddings are exposed to weathering, caused by solar radiation, water, and heat (Feist and Hon 1984). Both lignin and cellulose are depolymerized by solar radiation and leached by water (Derbyshire and Miller 1981), but lignin has been found to be degraded to a higher extent (Feist and Hon 1984). Kalnins and Feist (1993) suggested that weathering of wood increases the wettability by reducing or removing the water repellent effect of extractives, by degrading the hydrophobic lignin component of wood, and by allowing cellulose to become more abundant on the surface.

Weathering usually leads to some degree of cracking in the wood surface. Sandberg and Söderström (2006) explained crack formation by the growth of microcracks, photochemical reactions, or moisture-induced stress that appeared during weathering. Changes in moisture content below fiber saturation cause dimensional changes that vary with the grain direction and wood density. If the moisture changes are too quick or if deformations are restrained, the wood may crack and make the cladding more vulnerable to deterioration.

Increased wettability and cracking caused by weathering may be expected to increase the rate of water absorption. If the initial water absorption is larger in sapwood than in heartwood, claddings with a small proportion of heartwood are expected to undergo larger variations in moisture content during outdoor exposure. This will make them more susceptible to cracking and subsequently lead to even larger absorption. The aim of this study was to analyze the effect of outdoor weathering on liquid water absorption in uncoated Norway spruce cladding and to examine the effects of origin, radial position in the stem, and wood properties.

Materials and Methods

The study was based on parts of the material described by Sivertsen and Vestøl (2010). It contained 150 specimens sampled from different boards with known origin. Materials were sampled from four sites, two from a relatively productive forest in southern Norway (Larvik) and the other two from slow-growing forests located at higher altitudes and somewhat farther north (Toten; Fig. 1). The trees from Larvik were from 45 to 57 years old and had large diameter and height growth and small tapering, whereas the trees from Toten were about 150 years old and were shorter with greater tapering (Sivertsen and Vestøl 2010).

Distributions of breast height diameter were recorded, and five trees with breast height diameters between 27 and 30 cm and five with breast height diameters between 32 and 35 cm were randomly sampled from each site. Butt logs and second logs were split in half through the pith, and one-half of each log was sawn into 100-mm-wide planks (Fig. 2). Before drying, the planks were scanned with a medical computed tomographic scanner in order to locate the heartwood and the sapwood. Three scans were made at specific locations along the board (Sivertsen and Vestøl 2010), and the proportion of heartwood in each board was calculated as a mean of the three scans. Mean values of inner and outer boards from both origins are presented in Table 1. The planks were subsequently kiln dried and resawn into 19-mm-thick, 98-mm-wide boards with dry-cut surfaces on all sides.

The boards used in this study were from the center of the inner plank and the outside of the outer plank (Fig. 2). Several specimens were taken from each board (Sivertsen and Vestøl 2010); one 20-cm specimen was used for assessing density and annual ring width, and one 7-cm specimen was used for the water absorption test. Annual

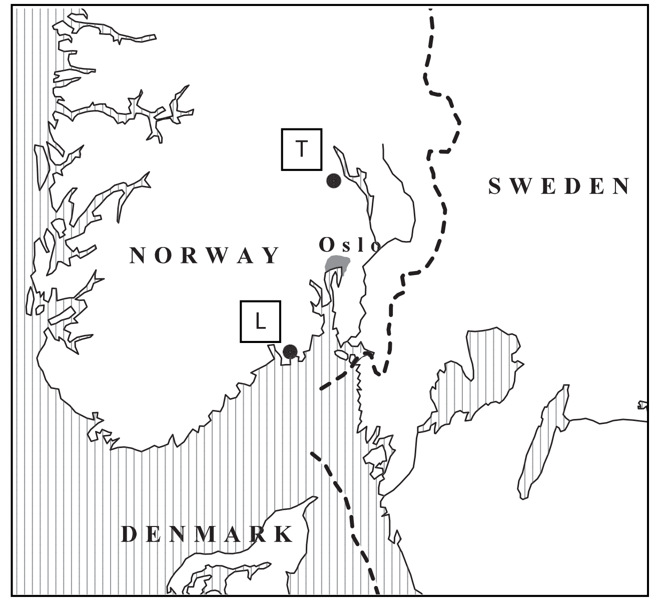

Figure 1.—The southern part of Norway with Toten (T) and Larvik (L) indicated by dots.

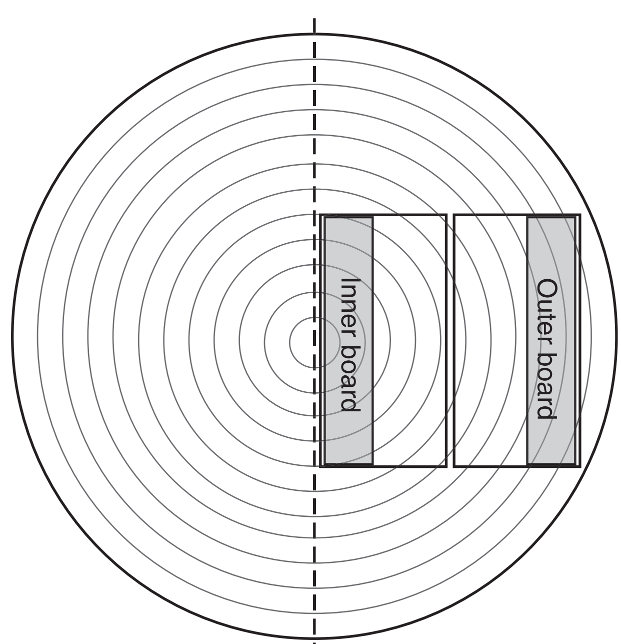

Figure 2.—Sawing pattern in the logs.

Table 1.—Means and correlations of wood properties.[a]

Origin	Board	n	Annual ring width (mm)	Density (g/cm^3)	Heartwood proportion (%)
Larvik	Inner	39	4.72	0.418	99.6
	Outer	35	2.76	0.482	45.6
Toten	Inner	38	1.56	0.456	99.5
	Outer	35	1.24	0.457	84.9
Correlation coefficients					
Annual ring width (mm)			1	-0.500^{***}	0.075^{NS}
Density (g/cm^3)				1	-0.376^{***}
Heartwood proportion (%)					1

[a] *** = $P < 0.001$; NS = $P \geq 0.05$.

ring width was measured as mean width of all complete annual rings in the cross section. Density and moisture content were measured after conditioning to 12 percent moisture content at 20°C and 65 percent relative humidity, and density was adjusted in accordance with EN 384 (European Committee for Standardization [CEN] 2004).

Water absorption test

The 7-cm specimens were conditioned to 12 percent moisture content at 20°C and 65 percent relative humidity and were sealed with two layers of a high-viscosity lacquer (Pyrotect Schutslack 2K; Rütgers Organics, Mannheim, Germany) on ends, edges, and back faces. After sealing, the specimens were again conditioned to 12 percent moisture content and weighed before the water absorption test. The specimens were placed on glass rods with the side facing the pith in deionized water (Fig. 3). The test followed EN 927-5 (CEN 2000), except that the test faces were sawn rather than planed, and the specimens were placed on glass rods rather than directly in the water containers. The specimens were removed from the water and weighed four times during the first 24 hours and then once a day for the next 3 days, twice a week for the next 2 weeks, and once a week for the rest of the period. After 15 weeks in water, the specimens were conditioned to 12 percent moisture content before being exposed to outdoor weathering. The water absorption test was repeated after 1 year of outdoor weathering.

Outdoor weathering and cracking

The specimens were exposed to outdoor weathering in an open field in Ås, Norway (59.6671°N, 10.7733°E; 100 m above sea level) from March 20, 2009, until March 17, 2010. Meteorological data from a local weather station are presented in Table 2. There was 811 mm of precipitation during the exposure time, and the temperature varied from –24.8°C to 30.4°C. The specimens were exposed on 45° racks facing south and with longitudinal direction oriented along the inclination. Each specimen rested on two nails and was held down with a screw on the upper side.

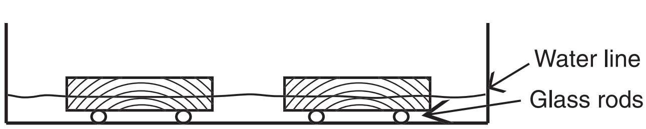

Figure 3.—Outline of the water absorption test. The specimens were sealed on ends, edges, and back faces and placed with the test face in water, resting on glass rods.

Following Sandberg (1999), the lengths of all cracks with maximum width of at least 0.25 mm were measured after reconditioning to 12 percent moisture content.

Statistical analyses

Statistical analysis was performed on the amount of water absorbed during the first 72 hours (3 d) of floating (MWA[72h]) and during the first 672 hours (28 d) of floating (MWA[672h]). Two specimens were removed from the analysis because of abnormal water absorption prior to weathering. An additional sample was treated as an outlier because of mold growth during first floating and cracked seal and abnormal water absorption after weathering.

The overall effect of weathering was analyzed by pairwise t tests of water absorption before and after weathering. The change of water sorption by weathering was calculated as the difference in water absorption after and before weathering, and it was used as a dependent variable when comparing sample groups. Comparisons were made between origins and between inner and outer boards. Since the variance was larger in outer boards than in inner boards, particularly in the samples from high-productive forests, the comparisons were performed as linear mixed models with heterogeneous variances, where residual variances were estimated for inner and outer boards from both origins.

Models describing water absorption as functions of wood properties were developed as covariance analyses, where the effect of weathering was tested on all parameters. The tested wood properties were heartwood proportion, annual ring width, and density. The models were estimated as linear mixed models with heterogeneous variances, where residual variances were estimated for inner and outer boards before and after weathering.

The linear mixed models were calculated using the restricted maximum likelihood in SAS version 9.2 software (SAS 2008), following Littell et al. (2006). Levene's test of unequal variance was used to compare residuals. Residuals were assumed to have normal distribution, and hypotheses were rejected if the probability of a Type I error was larger than 0.05.

Table 2.—Meteorological data from a local weather station near the field test (59.6605°N, 10.782°E; 89 m above sea level).[a]

Year	Month	Temperature (°C) Mean	Min	Max	Precipitation (mm)
2009	Mar	0.6	−9.3	8.6	60.8
	Apr	7.0	−3.2	18.9	39.5
	May	11.1	0.0	24.3	52.9
	Jun	14.8	2.3	30.4	27.6
	Jul	16.4	8.0	29.9	150.9
	Aug	15.5	6.0	25.1	157.9
	Sep	12.2	−2.7	21.1	42.4
	Oct	3.5	−5.4	13.5	55.4
	Nov	3.7	−2.2	10.0	150.7
	Dec	−4.8	−22.7	4.3	75.8
2010	Jan	−9.5	−24.8	0.4	10.7
	Feb	−7.7	−20.3	0.9	36.1
	Mar	−1.3	−18.0	7.2	69.5

[a] Data were obtained from Thue-Hansen and Grimnes (2010, 2011).

Results

After 1 year of outdoor exposure, the specimens had obvious signs of weathering. All had grayed, and many had cracked. Crack length per unit area by origin and board is presented in Figure 4. Nonparametric comparisons showed significantly higher crack length per unit area in outer boards than in inner boards, both in the specimens from Larvik ($\chi^2 = 23.6$, $P < 0.0001$) and in the specimens from Toten ($\chi^2 = 10.4$, $P = 0.0012$). The crack length per unit area was positively correlated with density ($P = 0.0005$) and negatively correlated with heartwood proportion ($P < 0.0001$) but not significantly correlated with annual ring width ($P = 0.52$).

A few specimens had visible mold growth on the sealed edges close to the water line during the last 3 to 4 weeks of the first water absorption test. This occurred on a slightly larger number of specimens during the water absorption test after outdoor weathering, and two specimens had visible mold growth on the sealed edges both before and after outdoor weathering.

Amount of water absorbed during 72 hours of floating

The cumulative distributions of water absorbed during 72 hours of floating, before and after outdoor weathering, are presented in Figure 5, and means and standard deviations are presented in Table 3. The specimens absorbed more water after 1 year of weathering ($t = 16.4$, $P < 0.0001$), and the variation was also larger since the change was largest for the samples with the largest initial absorption (Fig. 5; Table 3). The mean change was 329 g/m^2, corresponding to a 36.8 percent increase.

The absorption after weathering was larger for all groups of specimens, including inner and outer boards from both origins (Table 3). The change did not vary significantly between origins ($F = 1.37$, $P = 0.24$), but it was significantly larger in outer boards than in inner boards ($F = 20.0$, $P < 0.0001$). This effect did not vary significantly between origins ($F = 0.13$, $P = 0.72$). The residual variance was significantly larger in outer boards than in inner boards ($P < 0.0001$), but it was not significantly different between origins ($P = 0.76$). The interaction effect was not significant ($P = 0.88$). The change of water absorption after weathering was negatively correlated with heartwood proportion ($P < 0.0001$) and positively correlated with crack length per unit area ($P < 0.0001$) and density ($P = 0.036$), whereas it was not significantly correlated with annual ring width ($P = 0.51$).

Amount of water absorbed during 672 hours of floating

The cumulative distributions of water absorbed during 672 hours of floating before and after outdoor weathering are presented in Figure 6, and means and standard deviations are presented in Table 4. The water absorption was larger after weathering ($t = 12.6$, $P < 0.0001$), and the mean change was 357 g/m^2, corresponding to a 15.1 percent increase.

The absorption was larger after weathering for all groups of specimens, but the relative changes were smaller compared with the differences after 72 hours of floating (Tables 3 and 4). The change did not vary significantly between origins ($F = 0.27$, $P = 0.60$) or between inner and outer boards ($F = 2.48$, $P = 0.12$). In addition, the interaction was not significant ($F = 2.30$, $P = 0.13$). The residual variance was not significantly different between origins ($P = 0.53$), but it was significantly larger in outer boards than in inner boards ($P = 0.0002$). This effect was not significantly different between origins ($P = 0.060$). The change of water absorption after weathering was not significantly correlated with crack length per unit area ($P = 0.056$), density ($P = 0.093$), heartwood proportion ($P = 0.78$), or annual ring width ($P = 0.60$).

Effects of wood properties

Models describing the amount of water absorbed during 72 hours of floating (MWA[72h]; Model 1) and during 672 hours of floating (MWA[672h]; Model 2) are presented in Table 5. Four specimens that were included in the previous analyses were removed as outliers before estimating the

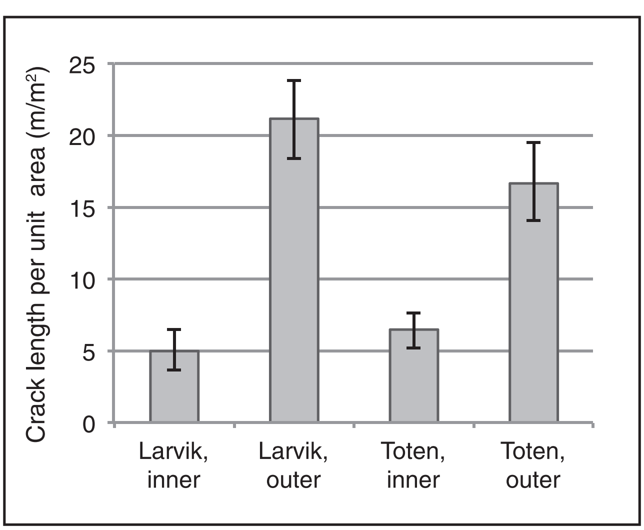

Figure 4.—Crack length per unit area after 1 year of outdoor weathering.

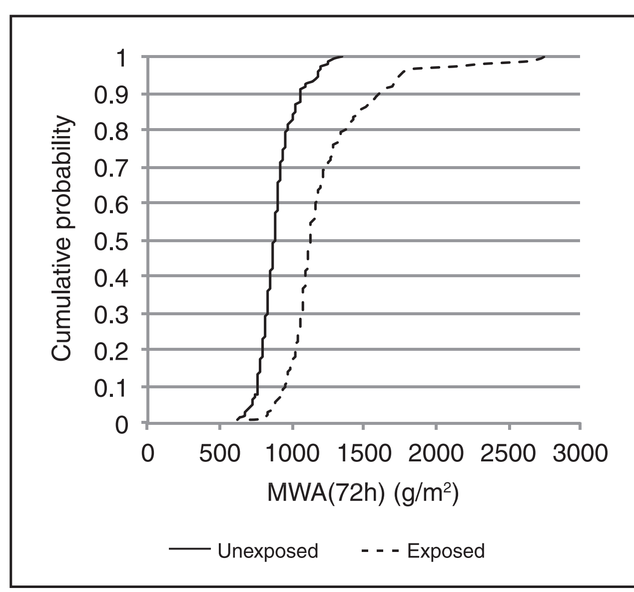

Figure 5.—Cumulative distribution of water absorption during 72 hours of floating, before and after outdoor weathering.

Table 3.—Water absorption during the first 3 days of floating before and after 1 year of outdoor weathering.

Origin	Board	n	MWA[72h] Before weathering, mean (SD) (g/m^2)	After weathering, mean (SD) (g/m^2)	Mean relative change (%)
Larvik	Inner	39	852 (89)	1,113 (136)	30.6
	Outer	35	988 (157)	1,438 (370)	45.5
Toten	Inner	38	863 (85)	1,092 (148)	26.5
	Outer	35	881 (136)	1,271 (449)	44.3
All	All	147	894 (130)	1,223 (329)	36.8

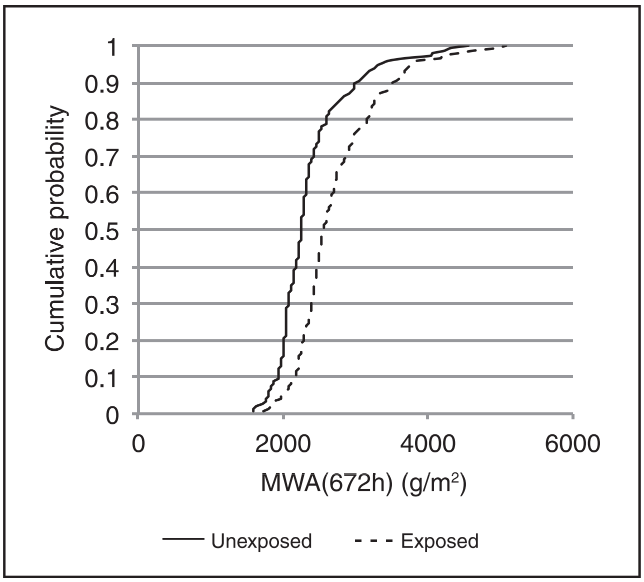

Figure 6.—Cumulative distribution of water absorption during 672 hours of floating, before and after outdoor weathering.

models since they had an influence on the parameter estimates and the residuals of the majority of the observations.

The most important variable describing MWA[72h] (Model 1 in Table 5) was heartwood proportion ($F = 117.9$, $P < 0.0001$), followed by weathering ($F = 72.8$, $P < 0.0001$) and their interaction ($F = 16.2$, $P < 0.0001$), whereas the effects of density ($F = 4.5$, $P = 0.034$) and annual ring width ($F = 4.5$, $P = 0.036$) were minor. The interaction effect described a stronger effect of heartwood proportion after weathering. The effects of density and annual ring width reduced the residual variance of the inner boards, of which almost all contained only heartwood. The residual variance increased after weathering and mostly in outer boards (Table 5). There were significant effects both of board ($P < 0.0001$) and of weathering ($P < 0.0001$) on the residual variance, whereas their interaction was not significant ($P = 0.057$).

MWA[672h] was described by heartwood proportion and weathering (Model 2 in Table 5), whereas the effects of density and annual ring width were not significant and hence removed before estimating the model. The effect of heartwood proportion ($F = 176.5$, $P < 0.0001$) was the most important, but the effect of weathering was highly significant as well ($F = 70.0$, $P < 0.0001$). Differing from MWA[72h], the interaction effect was not significant. There were significant effects of both board ($P < 0.0001$) and weathering on the residual variance, whereas their interaction was not significant ($P = 0.84$).

Discussion

The increased water absorption after weathering shows that the ability to withstand changes in water content was reduced after 1 year of outdoor weathering. The surfaces had been exposed to photochemical degradation, and surface cracks were frequent. As Evans et al. (2008) pointed out, photodegradation of lignin may lead to the development of visible cracks in wood exposed outdoors. Sandberg (1999) described surface cracks after weathering as a result of stresses that arise as a consequence of anisotropic moisture movement of the wood. Surface cracks increase the contact area between wood and water in a water absorption test, and small cracks may serve as pathways for capillary transport into the wood.

Weathering is a surface phenomenon where the photochemical changes are limited to the outer 2 to 3 mm (Feist and Hon 1984). This may explain why the relative effect of weathering on long-term absorption was smaller than it was on short-term absorption. The long-term water absorption is more dependent on water transport deeper into the wood, and the relative effect of degradation in the surface layer is smaller.

The specimens had a weathered, gray surface after outdoor exposure. No analyses were undertaken in order to quantify growth of mold and bluestain fungi, but it is

Table 4.—Water absorption during the first 28 days of floating before and after 1 year of outdoor weathering.

Origin	Board	n	MWA[672h] Before weathering, mean (SD) (g/m^2)	After weathering, mean (SD) (g/m^2)	Mean relative change (%)
Larvik	Inner	39	2,130 (263)	2,503 (350)	17.5
	Outer	35	2,769 (696)	3,144 (602)	13.6
Toten	Inner	38	2,232 (241)	2,487 (343)	11.4
	Outer	35	2,369 (544)	2,803 (778)	18.3
All	All	147	2,365 (522)	2,723 (599)	15.1

Table 5.—Models describing MWA[72h] and MWA[672h] by wood properties before and after weathering.[a]

Model	Weathering	Covariate model	Residual variance [(g/m^2)^2]	
			Inner board	Outer board
1	Unexposed	$MWA[72h] = 892 - 2.44HW + 9.60ARW + 383D_{12}$	6,541	11,149
	Exposed	$MWA[72h] = 1{,}403 - 5.04HW + 9.60ARW + 383D_{12}$	18,658	38,635
2	Unexposed	$MWA[672h] = 3{,}259 - 11.11HW$	54,781	149,182
	Exposed	$MWA[672h] = 3{,}591 - 11.11HW$	114,453	196,138

[a] HW = heartwood proportion (%); ARW = annual ring width (mm); D_{12} = density (g/cm^3).

known that the gray surface that wood obtains during outdoor weathering is partially due to fungal growth (Sell 1975, Feist 1990). Fungal growth on the wood surface can be expected to increase the permeability of the wood, as several mold and bluestain fungi have cellulolytic abilities and can degrade pit tori (Eaton and Hale 1993).

Since the sample groups with the highest initial absorption also became most cracked and had the largest change in 72 hours of water absorption, the differences between the sample groups increased after weathering. The change was related to differences between inner and outer boards and in particular to the proportion of heartwood. Previous studies have also reported higher water uptake in sapwood than in heartwood of Norway spruce both in the longitudinal direction (Sandberg 2006) and transversally (Metsä-Kortelainen et al. 2006). The resistance against water absorption in heartwood might restrain the water absorption during outdoor exposure and consequently reduce the variation in moisture content and the risk of surface cracks due to shrinking during the subsequent drying.

The effect of heartwood proportion may have been confounded with density since these were correlated and since the sample group with the by far smallest heartwood proportion also had the highest density (Table 1). High-density wood has larger shrinking and swelling potential (Kollmann and Côté 1968), but it is less susceptible to moisture changes since the absorption is slower (Siau 1984). There was a positive correlation between density and crack length per unit area after weathering, but this may also be influenced by heartwood proportion since it was correlated with both. The correlation between heartwood proportion and density was most important for materials from high-productive forest, where the outer boards had higher density than the inner boards. But despite almost equal density, there was also a significant difference between inner and outer boards from the low-productive forest (Table 1). This indicates that the difference between inner and outer boards is probably due more to different heartwood proportions than to different density. This was also shown in Model 1 (Table 5), where the effect of density on water absorption was not different after weathering, and it was of minor importance compared with the effect of heartwood proportion.

The inner boards in our study had exposed faces that were approximately radial, while the outer boards had exposed faces that were closer to tangential (Fig. 2). The orientation of annual rings has a large influence on crack formation during weathering since tangential shrinking and swelling is about twice as large as it is in the radial direction. Sandberg (1999) and Sandberg and Söderström (2006) have shown that radial surfaces become less cracked than tangential surfaces during natural weathering. The difference was explained as a consequence of different shrinking and swelling in earlywood and latewood (Sandberg and Söderström 2006). Because of the higher density, latewood shrinks and swells more than earlywood. Since these are parallel in the tangential direction, stresses arise, and cracks may develop. In the radial direction, the layers of earlywood and latewood occur separately and can shrink and swell more independently, and only small stresses arise. This means that some of the change in the effect of heartwood proportion on water sorption after weathering (Model 1 in Table 5) may be due to a confounding effect of larger crack length per unit area of tangential surfaces in the outer boards than radial surfaces in the inner boards (Fig. 4). One might also expect some initial differences in water sorption due to different occurrence of pits in radial and tangential surfaces, but previous results of the same material showed no significant differences between radial and tangential faces before weathering (Sivertsen and Vestøl 2010).

The models presented in Table 5 are intended not for predictions but rather for evaluating effects of wood properties. The models are mainly describing the effect of heartwood proportion on water sorption before and after weathering. The different effect of heartwood proportion on MWA[72h] before and after weathering in Model 1 describes a larger effect of weathering on specimens with small heartwood proportion. The lack of such an effect on MWA[672h] indicates that the long-term water absorption is less affected by degradation due to moisture variations during weathering. The additional effects of density and annual ring width on water absorption after 72 hours of floating (Model 1) were minor, but because of collinearities, they were included in the model in order to obtain more reliable estimates of the effect of heartwood proportion (O'Brien 2007). The effects explained differences between inner boards, of which many contained only heartwood. A similar model without annual ring width and density increased the residual variance of inner boards.

Model 1 did not describe the water absorption of the samples with the highest absorption after weathering, and it was not possible to determine any reason for the abnormal behavior of the four specimens that were removed as outliers when estimating the models. They were from both origins and included both inner and outer boards. The crack lengths per unit area were above the mean value but not among those with the highest values. The specimens did not occur as outliers when modeling water absorption after 672 hours (Model 2). This indicates that it has to do with changes to the surface during weathering.

Conclusions and Future Studies

Weathering increased the water absorption of Norway spruce wood when measured both after 72 hours and after 672 hours in liquid water. Since the change of short-term absorption was largest for those with the highest initial absorption, the variability also increased after weathering. The change was larger in outer boards than in inner boards, and the outer boards also had larger crack lengths per unit area. The larger change in outer boards is probably caused by both smaller heartwood proportion and a more tangentially oriented surface. The relative importance of each of these effects cannot be determined from this study, and it should be analyzed by comparing radially and tangentially sawn boards from heartwood and sapwood, respectively.

Following Nordic sawmilling practice, inner boards have the wide face in a nearly radial direction, whereas outer boards have the wide face closer to a tangential direction. From a practical point of view, the inner boards will be the recommended choice for uncoated spruce cladding since they benefit from both a larger heartwood proportion and a more radial surface compared with outer boards.

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