Wood Properties Influencing Surface Cracking and Moisture Dynamics of Untreated Norway Spruce Exposed Outdoors

Sebastian Svensson Meulmann,[a,]* Åsa Rydell Blom,[a] and Tinh Sjökvist [b]

Untreated wood has excellent environmental benefits due to the lack of treatments; however, its durability needs to be great enough to provide a sufficient service life to not override the environmental benefits. The aim of this study was to investigate some wood properties of untreated, unfinished Norway spruce and their influence on moisture dynamics and crack development under natural exposure. Three field-trials were carried out, all under natural exposure during various exposure times. The specimens differed in their exposure direction (north/south), composition (heartwood/ sapwood), density, and thickness. Moisture measurements were carried out either by use of sensors or weighing the specimens, while the crack formation was measured using digital calipers. Generally, high-density spruce exhibited more rapid moisture fluctuations than low-density; this agreed well with the increased crack development observed in the field-trials. More cracks were observed for specimens containing sapwood rather than heartwood. This was likely caused by an increase in moisture uptake, generating greater moisture gradients. The results also showed that the crack tendency was greater in specimens within the high-density group placed facing south, which is likely due to an increase in moisture variation, and perhaps also faster UV-deterioration. No clear correlation between crack tendency and thickness was found.

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Contact information: a: Department of Forestry and Wood Technology, Linnaeus University, Växjö, SE-351 95, Sweden; b: Södra Innovation, Väröbacka, Sweden;
** Corresponding author: sebastian.svenssonmeulmann@lnu.se*

INTRODUCTION

Untreated, unfinished wooden claddings used outdoors are excellent from an environmental perspective due to both a lower embodied energy and global warming potential than modified boards (Hill *et al.* 2021). However, the properties of the untreated wood become more important due to a more rapid equilibrium with the surrounding climate caused by an increased sorption and desorption, in comparison to treated wood (De Meijer and Militz 2000; Bulian and Graystone 2009), which may cause increased internal stresses and lead to faster deterioration. It is therefore necessary to study these properties to gain a better understanding of what influences the cracking so that the environmental performance is not lost due to a lower service life.

Cracks can be caused either mechanically by external loads, or by internal strains caused by moisture disparities at different depths (Oltean *et al.* 2007). As claddings are not a load-bearing element, cracks that appear are generally caused by moisture gradients. This occurs when the moisture gradients generate stresses greater than the tensile strength perpendicular to the grain (Stamm 1964).

The function of sapwood is different from heartwood in the living tree. Several studies have shown a lower average water sorption in spruce heartwood compared to sapwood (Sandberg and Salin 2012; Fredriksson and Lindgren 2013; Sjökvist *et al*. 2018). However, the sapwood is found on the outermost part of the tree; thus, it contains less juvenile tissue (Saranpää 1994; Morén 2016). This may be important because juvenile wood has a lower strength than mature wood (Sandberg 1997).

In the European testing standard EN 927-3 (2019), the nominal thickness of the test panels is 20±2 mm. However, studies have shown that an increase in thickness also leads to a greater dimensional stability (Virta *et al*. 2005), which minimizes the risk of surface cracking. Besides thickness, studies have also shown that the density has an impact on the moisture uptake (Sandberg and Salin 2012; Fredriksson and Lindgren 2013; Sjökvist *et al*. 2018), which in turn affects the cracking potential. The density is affected by the ratio of cell wall material to the cell lumen. Thus, the greater the ratio of cell wall material to lumen, the greater the density. Since swelling is caused by water being bound to the cell wall, a greater dimensional shrinking and swelling can be observed in high-density wood (Stamm 1935), which also generates greater strains (Hassel *et al.* 2009).

In this study the total crack formation after several months of natural exposure was analyzed and compared to moisture- and temperature dynamics data collected for a similar exposure situation. The aim was to gain a better understanding of how these different parameters affect cracking in untreated wood.

EXPERIMENTAL

Three different field-trials in the area around Växjö, Southern Sweden were the base of this study. All specimens were made from Norway spruce (*Picea abies* L.) free from dead knots, cracks, and high resinous wood.

The first field-trial consisted of 40 specimens placed at a 45-degree inclination outdoors for five years. The specimens were prepared in the dimension 375 x 100 x 22 mm. Twenty specimens were placed facing north and the other 20 facing south. Within each group, half of the specimens were fast-grown and half slow-grown (based on growth ring-width), of which half were made from sapwood and the other half were made from heartwood. The growth ring width varied from 1.2 to 10 mm with 4 mm being the median. Fast-grown spruce generally leads to a lower density, while slow-grown leads to a higher density, and hence will be denoted as low/high density hereafter (Table 1). The moisture content (MC) was measured regularly by weighing once every three months, and the total crack length on the specimens was measured once every year beginning at year two using a digital caliper including only visible cracks. The cracks are presented as the total crack length of the exposed surface within each specimen.

The second field trial consisted of 30 specimens mounted in the same way as in trial one, but only placed facing south. All the specimens were produced from spruce centered around the pith, similar to the center yield of 2- and 4 ex-log cutting. This was done to ensure most, or all the material was heartwood. This also made the specimens homogenous with regards to growth ring orientation. The specimens had the same length and width of 300 x 100 mm but with thicknesses of 22, 28, and 32 mm. The high/low density cut off was selected based on the median within each thickness group. The crack length was measured every three months during a total of 15 months. The same method of measuring the cracks as in trial one was used.

The third field-trial aimed to monitor the moisture dynamics within untreated wood under natural exposure. Here, only two specimens were used, one of high-density spruce, and one of low density. The specimens were fitted with Sensirion SHT-35 sensors at four different depths, 65, 55, 45, and 35 mm from the back of the panel. The total thickness of the specimens was 80 mm, meaning that the sensor placed 65 mm in was 15 mm from the exposed surface. The specimens were sealed with silicone along the edges to prevent capillary water uptake in the end grain. The sensors recorded the relative humidity (RH) and the temperature. Using the RH and temperature, the equilibrium moisture content (EMC) was calculated by using Eq. 1, (Simpson 1998) based on (Hailwood and Horrobin 1946).

$$EMC = \frac{1800}{W}\left(\frac{K\,h}{1\text{-}K\,h} + \frac{(K_1\,K\,h{+}2\,K_1\,K_2\,K^2\,h^2}{(1{+}K_1\,K\,h{+}K_1\,K_2\,K^2 h^2}\right) \tag{1}$$

where h is relative humidity, and W, K, K_1, and K_2 are coefficients based on the temperature T (°C).

Using the calculated EMC, the gradient G could be assessed by using Eq. 2, (Fragiacomo *et al*. 2011).

$$G = \frac{u_{\Delta L} - u_{surf}}{\Delta L} \tag{2}$$

where $u_{\Delta L}$ is the MC at given distance ΔL from the surface, u_{surf} is the MC at the surface, and ΔL is the distance from the surface (m).

These three individual field-trials were not to be compared to each other but analyzed separately to see if there were similar tendencies within each trial alone. See Table 1 for a summary of the test specimens used.

Table 1. Summary of all Test Specimens used for All Field-Trials

No. specimens	Trial No.	North(N)/ South(S) exposure	Heartwood(HW) /Sapwood(SW)	Low(L)/ High(H) density	Thickness (mm)	Average Density (Std. dev.) (kg m^{-3})
5	1	N	SW	L	22	312 (13)
5	1	N	SW	H	22	458 (21)
5	1	N	HW	L	22	325 (20)
5	1	N	HW	H	22	404 (26)
5	1	S	SW	L	22	355 (21)
5	1	S	SW	H	22	460 (25)
5	1	S	HW	L	22	341 (35)
5	1	S	HW	H	22	456 (41)
5	2	S	HW	L	22	365 (12)
5	2	S	HW	H	22	466 (34)
5	2	S	HW	L	28	361 (14)
5	2	S	HW	H	28	451 (31)
5	2	S	HW	L	32	350 (7)
5	2	S	HW	H	32	421 (10)
1	3	S	HW	L	80	419 (-)
1	3	S	HW	H	80	510 (-)

Note: The density presented is the oven dry density of all specimens within each group.

To assess the linear relationship of the density with regards to the total cracking length, an approximate linear model was calculated by minimizing the residual sum of squares. Linear regression was used to assess the statistical significance of the density, while Student's t-tests were performed to evaluate the difference between the contradicting properties (N-S, SW-HW, L-H, and 22-28-32).

RESULTS AND DISCUSSION

Crack Development

The total crack length within the specimens was evaluated in field-trials one and two. Figure 1 shows the crack development in all specimens of the first field trial, and Fig. 2 of the second.

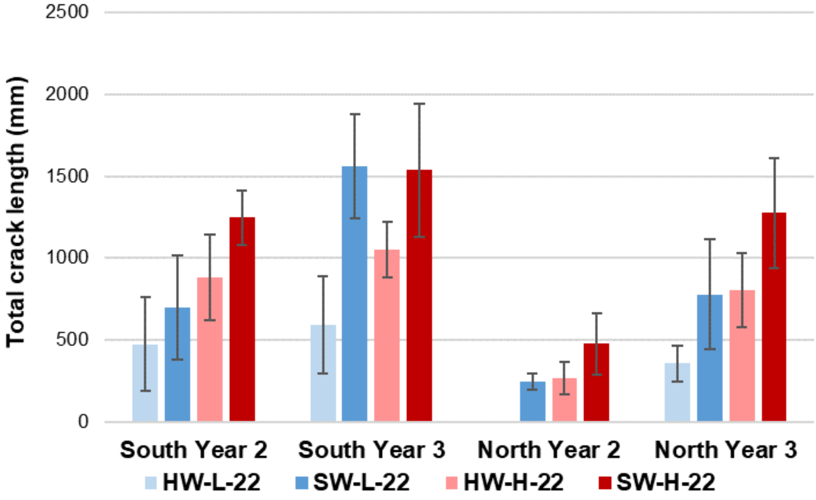

Fig. 1. Crack development of the specimens from field-trial one based on composition, exposure direction, density group, and year of measurement. All specimens had a thickness of 22 mm. The bars show the standard deviation.

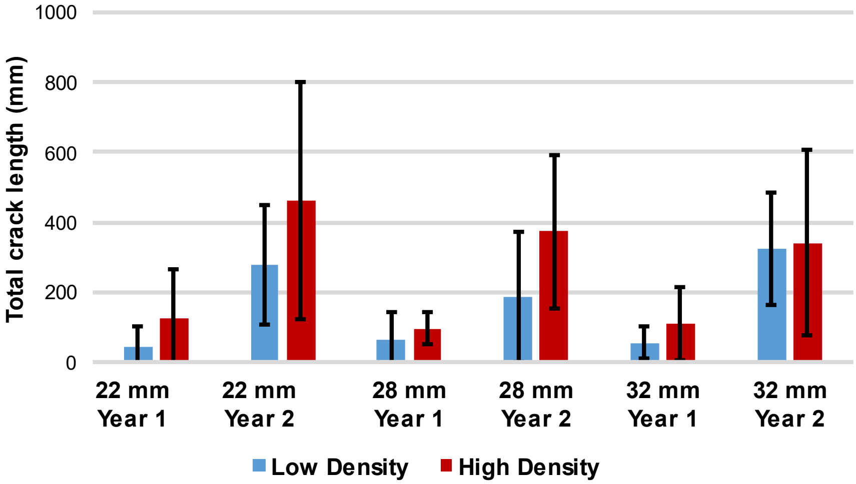

Fig. 2. Crack development of the specimens from field-trial two based on thickness, year of measurement, and density group. All specimens were composed of heartwood and exposed to the south. The bars show the standard deviation.

In Fig. 1, it is apparent that a higher density generally led to greater crack development, which was especially visible in the specimens of heartwood. The specimens placed facing south also had a greater average crack length than those placed facing north.

Figure 1 shows that the total crack length was greatest for the specimen group containing sapwood, while the lowest was found in heartwood. For all types of specimens, those exposed to the south had a greater crack length than those exposed to the north. This is likely due to the intense drying caused by an increase in solar radiation intensity, which is also affected by the inclination of the specimens. However, the consequences of cracks might be different due to an on average lower MC in the specimens facing south, as is shown in the next sub-chapter. For the first field-trial, crack length evaluation was only carried out during the second and third year of the test since after the third year, the cracking was so severe that they could not be properly examined. It is possible that for longer periods of evaluation, the differences between the total crack length for specimens facing north and south decreases.

In the second field-trial, the same trend could be seen where the high-density specimens cracked to a greater extent than the low-density specimens. However, no clear influence of the thickness could be seen from these tests alone. Multiple specimens had not cracked at all, even during the last evaluation, resulting in a high variation.

There was a significant difference ($p \leq 0.05$) in the means of the contradicting specimen groups north-south, sapwood- heartwood, and low- and high density. However, no significant difference could be found in the different thickness groups.

When only considering the density and the crack development, the linear relation was poor (see Fig. 3 for field-trial one and Fig. 4 for field-trial two). In the first field-trial, correlation analysis was based on data acquired from the third year of exposure and for the second field-trial, the data was based on the second-year values. It should be noted that in field-trial one there was a slight overlap between the density groups due to the initial grouping being based on growth-rate rather than actual density.

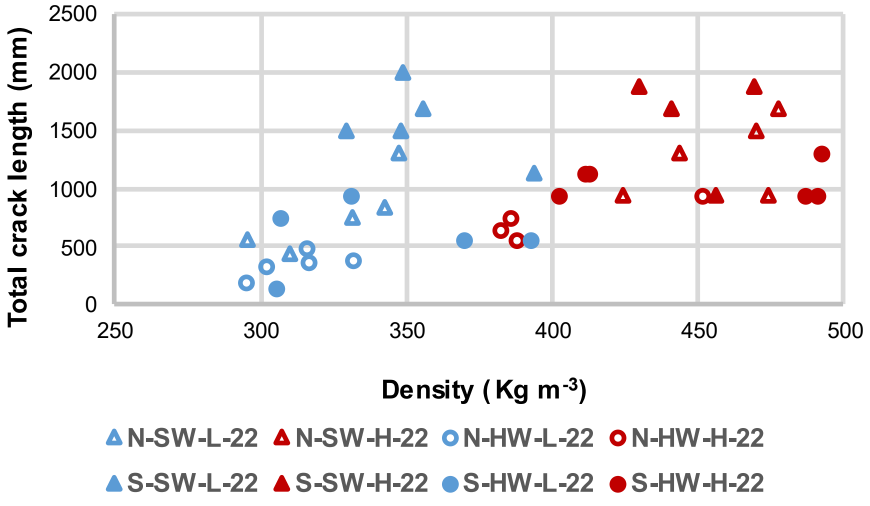

Fig. 3. Scatter plot of the density and crack development within the specimens in field-trial one. Blue-colored were from the low-density group, Red-colored were from the high-density group. Circular markers indicate heartwood, while triangular markers indicate sapwood. Specimens placed facing south have a solid marker fill, while those placed facing north have no fill.

The relationship between the density and total crack length was best explained by the function $y = 3.84x\text{-}500$ with a coefficient of determination (R^2) of 0.26. The correlation was relatively strong in the specimens placed facing north with the best linear fit being $y = 5.11x\text{-}1112$ and $R^2 = 0.63$.

In the second trial, the data was best explained by the function $y = 1.95x\text{-}457$ with $R^2 = 0.18$. No substantial linear relationship could be found in any of the groups alone, or when assessing all specimens together. The density was found to be a significant predictor ($p \leq 0.05$) of the total crack length in both field trials considered individually.

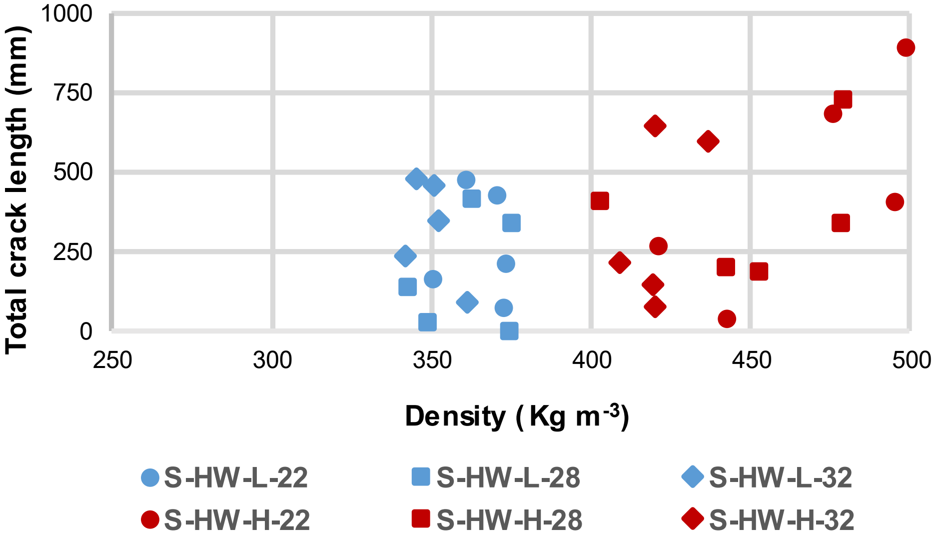

Fig. 4. Scatter plot of the density and crack development within the specimens in field-trial two. All data points colored blue were from the low-density group, while those colored red were from the high-density group. Circular markers indicate specimens with a thickness of 22 mm, square markers show the 28 mm-specimens, while the diamond-shaped markers show the 32 mm-specimens.

The increase in crack development in the specimens placed facing south could be explained in part by the increase of solar radiation, which dries out the surface material enough to generate greater strains that cause cracks to appear. Secondly a more long-term effect could be the deterioration caused by UV-radiation which first and foremost breaks down the lignin present in the wood (Kránitz 2014); this could lead to a decrease in the strength of the material and make it more susceptible to surface cracking (Evans *et al.* 2008).

Moisture Content

The variations in MC were assessed over a period of five years for the first trial, and 6 months during the third trial. The MC is presented in Table 2 and Fig. 5. Note that for field-trial one, the MC was measured by weighing the specimens, while for field-trial two the EMC was instead calculated by using the internal RH and temperature (meaning no MC-values can be achieved above the fiber saturation point (FSP)).

Table 2. The Average MC and Standard Deviation within each Specimen Group during the Entire Measurement Period of 5 years

Specimen group	MC (%)			
	Average	Max	Min	Std. dev.
N-SW-L-22	37.5	106.3	6.7	23.8
N-SW-H-22	34.3	77.3	8.1	19.2
N-HW-L-22	25.0	48.0	6.8	12.7
N-HW-H-22	23.3	46.1	6.4	11.3
S-SW-L-22	30.5	97.5	2.8	22.5
S-SW-H-22	24.9	53.4	5.6	14.1
S-HW-L-22	20.5	45.8	3.5	12.6
S-HW-H-22	17.5	34.5	3.1	9.3

Note: Maximum and minimum values are based on individual specimens within the groups. The specimen groups are defined as follows: (N)North/(S)South-(HW)Heartwood/(SW)Sapwood-(L)Low Density/(H)High Density-Thickness.

From Table 2 it can be observed that when assessing all specimens, the average MC in specimens facing north was 6.7% greater than those facing south, the average MC in sapwood was 10.2% greater than heartwood, and a lower density led to 3.3% greater MC than high density. Here, there was a significant difference between the groups N-S, and HW-SW ($p \leq 0.05$), but no significant difference between the mean MCs could be observed between high- and low-density specimens ($p > 0.05$).

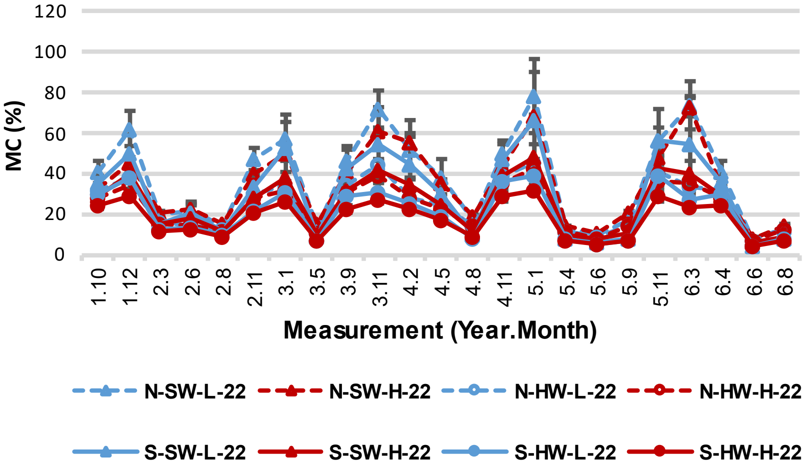

Fig. 5. The seasonal MC changes in all specimen groups of field trial one. Measurements were made about once every three months.

The average MC of sapwood was greater than heartwood, which is to be expected and agrees with previous studies regarding water uptake in spruce (Sandberg and Salin 2012; Fredriksson and Lindgren 2013; Sjökvist *et al*. 2018). This effect is generally attributed to a greater degree of pit aspiration in the heartwood. In fact, the composition (sapwood/heartwood) had a greater influence on the MC than both exposure direction and density. The MC within the low-density specimens was also higher than the high-density specimens in the first field trial. The difference between the density groups was greater at high MC's (above the FSP). Since capillary water uptake to the lumen is faster and has a higher capacity than diffusion to the cell wall, a greater void filling rate with a decrease in density is to be expected (Sivertsen and Vestøl 2010).

The standard deviation was greater for all specimens facing south than north. This is likely caused by the increased drying caused by solar irradiance during the day which affects the southern-placed specimens more than those facing north. The maximum values for the two directions were similar due to the capillary uptake during precipitation. The highest average MC and standard deviation in MC was achieved in the specimens of high-density sapwood facing south.

In field-trial three, the calculated EMC based on the RH and temperature in the specimen was assessed. Great differences in seasonal moisture behavior could be observed, and the moisture distribution depended greatly on the outdoor temperature. There were also some differences between the different densities. See values acquired during a typical summer and winter day in Table 3. Since no EMC can be calculated over the FSP, the average and maximum EMC are likely lower than the true MC for the period.

Table 3. Values of Calculated EMC during a Typical Summer and Winter Day

24 hours Summer								
EMC (%)	35 mm		45 mm		55 mm		65 mm	
	High	Low	High	Low	High	Low	High	Low
Maximum	21.3	19.7	22.3	20.8	23.0	21.5	18.7	20.2
Minimum	11.3	11.8	11.6	12.4	11.4	12.3	11.8	11.8
Average	14.5	14.5	15.0	15.2	14.9	15.1	13.6	13.9
Std. deviation	2.5	2.1	3.0	2.4	3.3	2.7	2.2	2.7
24 hours Winter								
Maximum	29.1	27.9	29.1	28.7	28.3	28.3	28.3	28.3
Minimum	17.6	18.2	19.2	18.2	17.3	17.9	17.2	16.6
Average	24.3	23.0	24.6	23.7	23.0	23.3	21.8	22.1
Std. deviation	4.2	3.7	4.2	4.1	4.3	4.1	3.9	4.6

The outermost part of the specimen reached a lower MC than the innermost material. This is likely due to a faster equilibrium with the surrounding climate, as well as the influence of solar radiation. This behavior was observed both during the summer and the winter. The relatively similar behavior in the sensors placed closest to the core of the board likely has to do with the thermal insulation of wood, generating a similar temperature in the two middle-depths. The variation in calculated EMC was generally higher for the high-density specimen except for closest to the surface, where the low-density specimen had a higher variation. The EMC did not only vary substantially at the outermost section, but also closer to the center.

Using Equation (2) the moisture gradients were calculated (Table 4). Since the MC at the surface is unknown, the calculated EMC at 65 mm depth was used as u_{surf} *i.e.*, the initial MC when calculating the gradient.

The moisture gradients presented above can be interpreted as cracking potential. Thus, the greater the positive value, the greater the risk of surface cracking. This is caused by unequal swelling and shrinking in the different layers, where the dimensional restraints will generate stresses within. The results show a generally greater gradient in the specimen of high density than the specimen of low density. A negative gradient means that the calculated EMC was higher at the surface than closer to the core. This was observed more often during the winter when the solar radiation was limited. Around 65% of the calculated gradients during the summer months were positive, while only around 8% during the winter months were positive. The ratios were similar for both high and low density.

Table 4. The Moisture Gradient G during Summer (July-August) and Winter (December-January) within the Two Boards (High/Low) between the Depth 65 mm and 55, 45, and 35 mm, respectively

July-August						
G (m^{-1})	65-55		65-45		65-35	
	High	Low	High	Low	High	Low
Maximum	0.63	0.48	0.33	0.26	0.20	0.17
Avg. daily max.	0.23	0.19	0.13	0.11	0.08	0.07
December-January						
Maximum	0.42	0.33	0.22	0.17	0.14	0.09
Avg. daily max.	-0.17	-0.03	-0.03	-0.01	0.05	-0.01

Discussion

Through the field studies, the various properties’ influence on both MC and surface cracking has been quantified.

The influence of density on the tensile strength perpendicular to the grain in softwoods appears complex. Grekin and Surini (2008) found no relation between the two for Scots pine, while Siimes (1966) instead found a strong positive correlation. In the European standard EN 338, the characteristic tensile strength for softwood classes C14-C50 with mean densities between 350 and 520 kg/m^3 are all set equal to 0.4 N/mm^2 (CEN 2016). In the present studies, tendencies for greater crack formation in high-density spruce compared to lower densities are shown. However, if the increased moisture gradients caused by an increase in density is the only factor which affects the susceptibility of cracking, assuming the tensile strength is about the same for all specimens, one would suppose a greater correlation between the two. Evans *et al.* (2008) concluded that exposure to UV and visible light increases the development of cracks in lodgepole pine (*Pinus contorta*). Due to the high lignin content found in the middle lamellas (Sorvari *et al.* 1986), it is likely that the photodegradation of lignin causes the strength of the cellular adhesion to decrease. Thus, the photodegradation of lignin causes the tensile strength perpendicular to the grain to decrease over time, leading to an increased risk of cracking, as is presented in Derbyshire *et al.* (1996). This theory is also supported by the fact that R^2 between density and crack length decreased the longer the exposure time and was substantially greater for the specimens placed facing north than those facing south. However, since the degradation of lignin was not assessed during these trials, the reason cannot be said for certain.

It is possible that using just the crack length as an output is not sufficient for discerning the influence of density. It is also possible that the stress required to create the initial crack is greater than the force which is required to expand it. As Thuvander and Berglund (2000) demonstrated, the energy requirements for transverse-radial crack extensions are notably low during peeling of the middle lamella. Disregarding the total crack length and counting just the number of visible cracks observed on the exposed surface showed even less relation between density and cracking. However, this was only studied during the last evaluation of the cracks, where photodegradation had already occurred to a great degree.

Other factors such as growth ring orientation and presence of juvenile tissues have also been shown to affect the cracking of softwoods (Persson 1994; Sandberg 1996; Sandberg 1997; Thuvander and Berglund 2000). The difference in juvenile wood concentrations between the heartwood and sapwood and growth ring width in the low- and high-density specimens likely affected the cracking results, but to an unknown degree.

The average MC and moisture fluctuations were greater in high-density specimens than low-density. This was observed both in trial one and three. This should mean that density does affect the susceptibility of cracking of the exposed surface, which also has been seen in previous studies (Sjökvist *et al.* 2019), but as the relations in this study have shown, is likely not the only factor affecting it. Due to the frequency of MC measurements in field-trial one, the short-term behavior caused by weather changes could not be observed. This means that some levels of MC might appear to be seasonal effects when they could be caused by temporary weather. Somewhat surprisingly, the different thicknesses used in the second field-trial had no effect on crack formation, even though previous studies have shown a better dimensional stability to cupping when increasing the thickness. This could however be due to a small sample size used in this study. Hence, the authors do not rule out the influence of thickness as a possible parameter affecting the crack formation in wooden cladding boards.

The results acquired from the third field-test are based on measurements of the RH and temperature. It is uncertain whether the measurements of RH and temperature inside the wood give accurate measurements regarding the actual MC of the board, since the values are always fluctuating and never have the time to reach the EMC. However, the measurements should be valid in comparison to each other and sufficient in tracking moisture dynamics at different depths and at different densities. Naturally, using only one specimen for each specimen type is too few to draw any conclusions from, but the behavior seemed to agree well with the prior field-trials.

CONCLUSIONS

1. The results show some difference in crack tendency between high-density and low-density specimens. An increase in specimen thickness from 22 to 28 and 32 mm did not influence cracking.
2. The specimens facing north had less cracks than those facing south, likely due to less variation in moisture content (MC), but also less solar exposure.
3. The average MC was higher in sapwood than in heartwood and had an overall greater impact on the average annual MC than the density of the specimens.
4. An increased variation in MC was seen in high-density specimens below the fiber saturation point (FSP), suggesting that this could be one of the reasons as to why the crack tendency is greater in high-density spruce claddings.

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