Mold Growth on Sapwood Boards Exposed Outdoors: The Impact of Wood Drying

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Abstract

Mold growth on dried Norway spruce and Scots pine sapwood boards was investigated in an accelerated outdoor field test for 96 days. The boards were dried using three different methods of stacking: single stacking, double stacking with the sapwood sides in each pair facing toward each other, and double stacking with sapwood sides facing outward. Drying was performed at three temperatures: 25°C, corresponding to air drying, and kiln drying at 70°C and 110°C. The degree of mold growth was visually assessed on both sides of each board. On average, pine boards showed a higher level of mold growth than the spruce boards. The highest average level of mold growth was found on the boards kiln dried at 70°C, whereas the air-dried boards and the boards kiln dried at 110°C showed considerably less mold growth. Stacking the boards during drying had a large impact on mold susceptibility of the sapwood. This study confirmed that, during the drying process, it is possible to direct the migration of nutrients in sapwood toward one chosen side of each board by double stacking; the opposite side leaches out, which has a great impact on surface mold growth. Chemical analyses of monosaccharide sugar gradients beneath the boards' surfaces confirmed the results.

The natural durability of wooden products is an urgent issue for the future use of wood as a competitive construction material. In a recent study on the moisture damage to Swedish houses performed by the Swedish National Board of Housing, Building, and Planning, 21 percent of the houses were reported to have problems with mold in unheated attics (Boverket 2010).

Mold growth on unpainted boards for outdoor applications above ground has been reported to be an increasing problem in building and construction, for example, where visible mold can appear after just a few months usage on unpainted soffit boards/eaves boards and carports (Nilsson and Samuelson 2006) or in unheated attics. The risk of the onset of mold growth clearly depends on the geographic location and the local climate (Häglund et al. 2010). The changing climate, with warmer and more humid conditions, supports mold growth on wood, but there are reasons to believe that increasingly faster industrial drying processes also contribute to this problem.

The sawn product used in the construction examples above is a thin tongue and groove board, commonly made of Norway spruce (*Picea abies* L.), but also Scots pine (*Pinus sylvestris* L.). These boards are sawn from the outermost sapwood, which has a high moisture content (MC). Sapwood, with its poor natural durability, contains high amounts of carbohydrates in the form of free sugars, which play an important role as nutrients for mold fungi. The concentration of soluble carbohydrates, such as glucose, fructose, and sucrose, in pine sapwood is greatest in the outer sapwood and gradually decreases toward the innermost sapwood (Saranpää and Höll 1989). The seasonal fluctuation of low-molecular-weight sugars is large, with the highest concentrations found during autumn and winter months in pine sapwood (Terziev et al. 1996), as well as in spruce sapwood (Höll 1985). The surfaces of dried, winter-

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felled pine sapwood were shown to be more susceptible to mold growth than spring-felled timber (Terziev and Boutelje 1998).

Mold fungi are dependent on nutrients such as low-molecular-weight carbohydrates, and they mainly grow on the surfaces of wood without penetrating the fiber cell walls. Mold fungi in general can germinate and grow without access to free water if the relative humidity (RH) is high enough. The duration of high and stable RH in combination with temperature has been shown to be crucial for the onset of mold growth. If the RH is above 95 percent, the critical time needed for the visual appearance of mold on pine and spruce sapwood is only a few days at temperatures between 25°C and 40°C. The minimum humidity conditions for the risk of mold growth on pine and spruce sapwood are between 80 and 100 percent RH depending on the temperature and length of exposure. If the RH fluctuates, a retardation of mold development occurs (Viitanen 1997, Isaksson et al. 2010).

Early on in the accelerated wood drying process, when the free water in sapwood moves toward the evaporation front just beneath the surface, an enrichment of carbohydrate and nitrogen compounds takes place at the surface (Theander et al. 1993). The drying rate has a significant effect on this redistribution of compounds, with a greater accumulation when the drying rate is high (Terziev et al. 1993).

At high drying temperatures, decomposition of the accumulated low-molecular-weight carbohydrates results in a visible darkening of the enriched zone called kiln brown stain (KBS), which is typically found just beneath the surfaces of boards. KBS is a particular problem in the high-temperature (HT) drying of Monterey pine (*Pinus radiata*) because this dark-colored surface is exposed when the boards are planed after drying. A lot of research has been conducted since the late 1990s, especially in New Zealand, with a view to achieving a full understanding and prevention of KBS (Kreber et al. 1998, McDonald et al. 2000, McCurdy et al. 2005).

Air-dried sapwood surfaces were shown to have smaller nutrient gradients than kiln-dried lumber (Terziev 1995). Planing kiln-dried sapwood removes the most enriched zone, whereas planing air-dried sapwood can expose wood with a higher nutrient concentration. This affects the susceptibility of the wood to mold, and mold growth was shown to be reduced in planed kiln-dried lumber, whereas the mold growth on planed air-dried surfaces increased compared with unplaned surfaces (Terziev et al. 1996). Mold growth has been shown to be more rapid and vigorous on original kiln-dried wood surfaces than on surfaces that have been resawn or planed (Terziev et al. 1996, Frühwald et al. 2008).

Figure 1 shows a wall in a carport made of unpainted tongue and groove boards after approximately one year's usage with fairly heavy mold growth. The distinct unmoldy areas reveal where stickers were positioned during kiln drying. This local blocking of evaporation from the board's surface appears to prevent the enrichment of nutrients at the board's surface and thus affect the subsequent mold growth in these blocked areas. This observation led to the hypothesis that it is possible to direct the migration of nutrients toward one chosen side of a board during drying by using different stacking techniques.

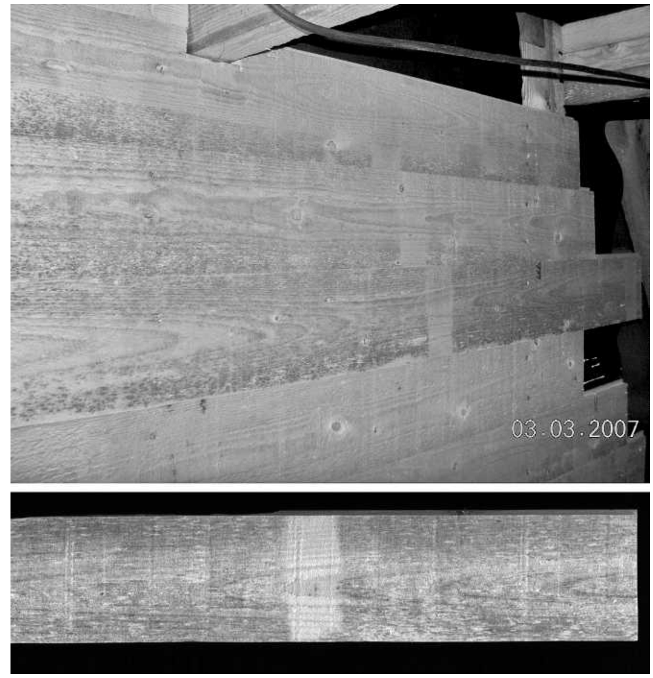

Figure 1.—Mold growth on a wall of tongue and groove boards of Norway spruce in an unheated outdoor carport after approximately one year's usage. Note the brighter areas without mold where stickers had been placed during kiln drying.

The aim of this work was thus to examine the hypothesis that, during the wood drying process, it is possible to control the migration of nutrients in sapwood boards toward one side of a board while the opposite side leaches out and to evaluate the effect of this on mold susceptibility in order to produce wood products that would be less prone to mold growth.

Materials and Methods

Initial test: Chemical analysis of the nutrition gradient

Two initial drying tests were performed in order to study the hypothesis that, during drying, it is possible to direct the migration of nutrients in sapwood toward one side of a board by double stacking. Short, end-sealed samples of green Scots pine and Norway spruce sapwood side boards were double stacked two ways during drying: with the sapwood sides of each pair facing outward, and with the sapwood sides of each pair facing toward each other, as shown in Figure 2.

The boards were dried at a constant temperature in a heating chamber with air circulation without relative

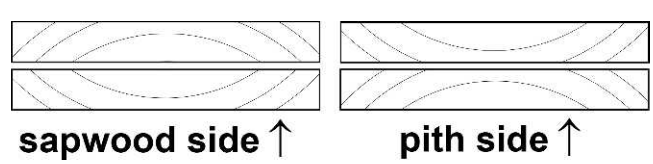

Figure 2.—Two different methods of double stacking the boards. (Left) Sapwood sides turned outward and pith sides facing each other in each pair. (Right) Sapwood sides facing each other and pith sides turned outward in each pair.

humidity regulation. The double-stacked board pairs were labeled with stickers, as shown in Figure 3, left, and compressed to ensure full contact between the surfaces of the boards.

In Test 1, four pine sapwood samples (11 by 85 by 150 mm) were dried at 90°C for 23 hours, and in Test 2 four spruce sapwood samples (11 by 85 by 150 mm) were dried at 115°C for 24 hours. In Test 1, a visual inspection of the boards' surfaces was made with respect to a visible KBS. In Test 2, a chemical analysis of the monosaccharide sugar gradients beneath the boards' surfaces was performed at different positions (Fig. 3, right). Chips were collected at a depth of 0 to 0.2 mm below the surface by scraping with a rasp. At depth of 0.2 to 1 mm below the surface, chips were collected using a hand plane. The chips were extracted with water (wood–water, 1:20) in an ultrasonic bath for 2 hours and then left for 12 hours before filtering. The concentration of monosaccharide sugars as acetylated alditols was analyzed using a gas chromatograph with deoxygalactose as the internal standard in double tests.

Main test: Lumber

Green side boards from winter-felled pine (19 by 125 mm) and Norway spruce (16 and 22 by 75 mm) were collected after sawing at a local sawmill near Skellefteå, Sweden, in February 2009. Boards with a wane on top were chosen for obtaining material from the outermost sapwood. The green boards were cut into four 0.96-m-long samples, numbered 1 to 4 from the butt to the top end, end sealed with a Sikaflex polyurethane sealant, and kept in a freezer at –15°C until the start of drying. A slice was cut from each sample for the initial MC control (ovendrying method) and for estimating the possible occurrence of heartwood in the cross section. All samples were sorted into three similar drying batches for each species with regard to sapwood content, board thickness, and position along the board.

Drying

Drying was performed in three different series. Owing to the time of year, Series A, considered similar to outdoor air drying, was performed indoors at the laboratory on stickers at 20°C to 25°C, ≈40 percent RH for 15 weeks. Two kiln-drying series with rapid moisture transport rates at MCs above the fiber saturation point were carried out at two temperature levels. Series B was dried according to a fast drying schedule used in industrial drying at sawmills in Sweden, at a maximum temperature of 74°C. Series C was HT dried at a high maximum temperature of 110°C. Kiln drying was performed in a small-scale laboratory air circulation kiln at SP Trätek, Skellefteå. The drying schedules used in Series B and C are shown in Figure 4. A summary of the drying series is shown in Table 1.

Stacking during drying

All air-dried boards in Series A were single stacked during drying (because double stacking of air-dried boards does not occur in practice). The boards in Series B and C were stacked in three ways: (1) single stacking, (2) double stacking with the sapwood sides of each pair turned outward and the pith sides facing each other, and (3) double stacking with the sapwood sides of each pair facing each other and the pith sides turned outward (Fig. 5).

Because a smaller quantity of pine boards was used in the test, there was no single stacking of pine boards in Series C: double stacking was given priority.

Three stickers, 25 by 50 mm, were placed along the width of the boards. The position of the stickers was marked with a pen on the facing board. In order to ensure full contact between the double-stacked board surfaces, steel plate weights were placed on top of the stacked batch in the kiln during drying. Table 2 shows a summary of the number and

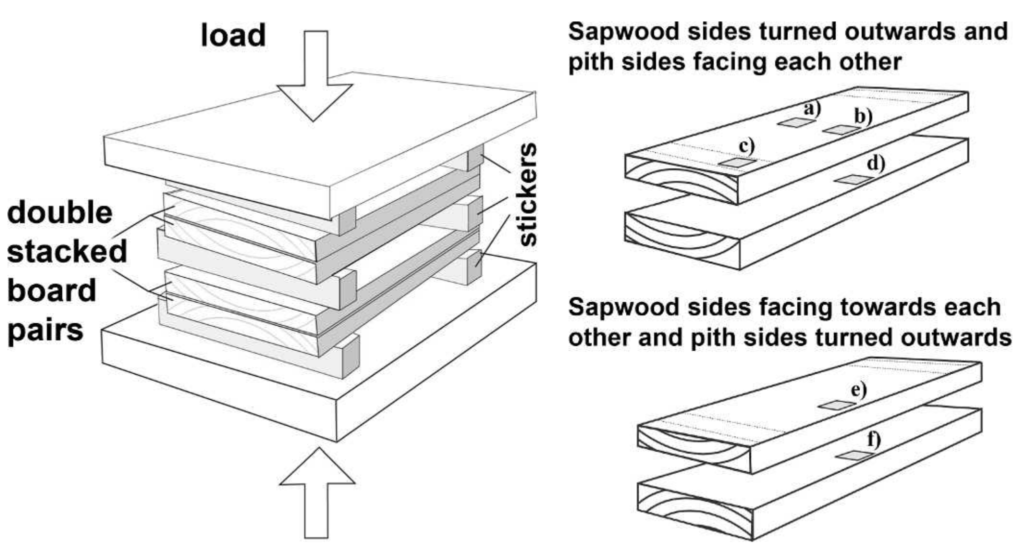

Figure 3.—(Left) Experimental setup of the two types of double-stacked board pairs with the stickers and loading during drying. (Right) Analysis of the monosaccharide sugar concentration on the surfaces of boards after drying in different positions for the double-stacked board pairs of the dried spruce sapwood in the initial drying Test 2. In positions a to f, the sugar concentration was measured at two depths below the surfaces of the boards: 0 to 0.2 mm and 0.2 to 1 mm. Position in the stacking variant with sapwood sides turned outward and pith sides facing each other in each pair: (a) in the center of the sapwood side, (b) on the edge of the sapwood side, (c) sapwood below the sticker, (d) on the edge of the pith side facing inward in the double-stacking variant. Position in the stacking variant with the sapwood sides facing toward each other and the pith sides facing outward for each pair: (e) on the edge of the pith side, (f) on the edge of the sapwood side facing inward in the double-stacking variant.

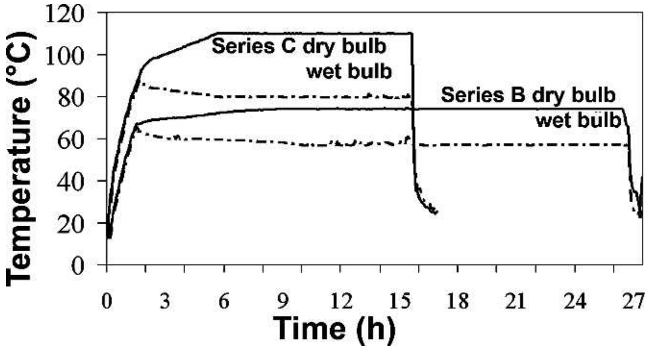

Figure 4.—Kiln-drying schedules for Series B and C.

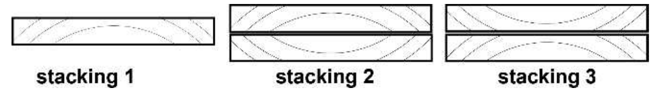

Figure 5.—Stacking variants during drying. Stacking 1: single stacking. Stacking 2: sapwood sides turned outward and pith sides facing each other in each pair. Stacking 3: sapwood sides facing each other and pith sides turned outward in each pair.

distribution of boards and stacking variants in Series A, B, and C.

After drying, both sides of each board were scanned using a high-resolution color line scan camera, Dalsa CLT72048W, under constant light conditions. This was done to avoid a false classification of mold growth during the visual inspection after the mold test by recording discoloration, dirt, and stick markers, for example, that were present before the mold test. After scanning, each batch was wrapped in plastic wrap and kept in a freezer until the start of the mold test. Drying and scanning was performed during March and April 2010.

Accelerated mold test

The mold test used was performed according to the accelerated above-ground field test recommended by Terziev and Edlund (2000), for the quick testing of natural durability, but modified with respect to sample size and arrangement of the test samples. What distinguished this test from the method used by Terziev and Edlund was that the samples were longer and placed lying on their sides with the grain horizontal instead of vertical, so that as much of the sample as possible would be exposed to the soil bed to avoid a mold growth gradient developing along the boards. On June 23, 2009, the test samples were arranged edgeways, in random order, on wooden racks 100 mm above the ground, in the shade, and protected from the rain by a sloping roof of translucent plastic foil. The top layer of the ground comprised unsterilized soil mixed with garden compost. An irrigation hose (with small holes on the surface for greenhouse irrigation) was lowered/laid in loops about 5 cm below the surface of the soil. Irrigation was programmed so that water was supplied for 10 minutes every 12th hour. During the summer, the soil bed was regularly inspected and vegetation was removed.

After 61 days, a casual sample inspection and an MC control were performed. The MC was measured using an electric hand held resistance moisture meter in the upper and lower edges of 14 randomly chosen sample boards at a depth of 5 mm. The average difference between the MC in the upper and lower edges was 2.5 percent. These differences decreased after wrapping. When the experiment was terminated, the average MCs were slightly higher and equal: the MC in the upper edge of 39 samples was 20.1 percent (standard deviation [SD] = 1.8) and the MC in the lower edge was 20.1 percent (SD = 2).

After 61 days (August 24) the racks were wrapped with black plastic, which was carefully tightened down to the soil and at the ends, to form a tight chamber. In order to prevent condensation forming water droplets that could fall onto the samples, the roof of the chamber sloped. The water supply was increased to 10 minutes every sixth hour. The climate inside the wrapped chamber was measured throughout the experiment with a data logger Testostor 175 (Fig. 6). Note the increase in RH after 61 days when the samples were wrapped in plastic: the RH gradually became constant and close to 100 percent.

A number of agar plates were placed in the wrapped plastic chamber and analyzed at SP Borås. We found *Cladosporium* spp., *Penicillium* spp., and yeast in abundance, along with various other species.

The samples were observed weekly, and toward the end daily, and the experiment was stopped after 96 days when a very abundant mold growth was registered on some of the

Table 1.—Summary of the drying series.

	Series A	Series B	Series C
Norway spruce, 16 and 22 by 75 mm			
Avg. (SD) MC before drying (%)	77.5 (32.1)	106.6 (44.6)	88.2 (35.7)
Avg. (SD) MC after drying (%)	8.0 (0.9)	19[a] (5.3)	9.6 (1.6)
Preheating with steam (h)	—	1.4	1.5
Total drying time (h)	2,626	26	16
Maximum drying temp (°C)	26	74	110
Scots pine, 19 by 125 mm			
Avg. (SD) MC before drying (%)	95.7 (26.2)	109.5 (33.1)	99.7 (32.3)
Avg. (SD) MC after drying (%)	8.0 (0.9)	19[a] (5.3)	7.1 (1.1)
Preheating with steam (h)		1.4	1.7
Total drying time (h)	2,626	26	16
Maximum drying temp (°C)	26	74	110

[a] The drying schedule in Series B was taken from an industrial kiln schedule with a maintained drying time that led to a significantly higher moisture content (MC) after drying compared with Series A and C. The differences in MC between the three series equaled out during sample preparation and during the first weeks outdoors in the open tent.

Table 2.—Number and distribution of boards and stacking variants in Series A, B, and C.

	No. of boards		Total no. of boards
	Norway spruce	Scots pine	
Series A			
Stacking 1	10	10	20
Series B	30	17	47
Stacking 1	4	6	
Stacking 2	12	7	
Stacking 3	14	4	
Series C	25	9	34
Stacking 1	5	0	
Stacking 2	10	4	
Stacking 3	10	5	
Total no. of boards	65	36	101

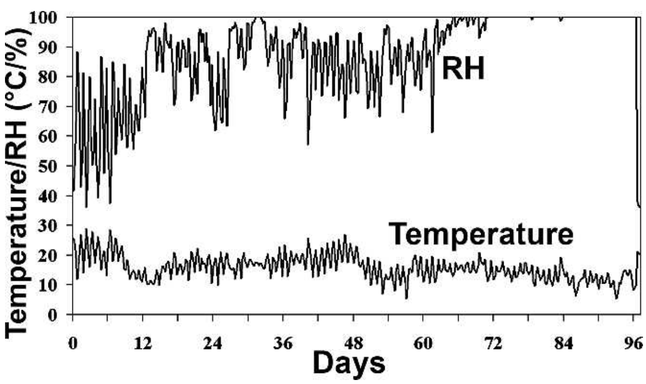

Figure 6.—Climate during the accelerated mold test. Note the change in the relative humidity (RH) after the wrapping was done, after 61 days.

surfaces. All of the samples were transported indoors for mold classification.

Assessment of mold growth

Two researchers performed a visual assessment of mold growth without the use of a loupe or a microscope. Both flat sides of all of the samples were assessed. Only the sapwood was assessed, i.e., any heartwood on the flat sides was ignored. Neither the boards' edges nor the surfaces under the stickers were included in the assessment.

The flat side of each sample that showed the most mold growth was assessed first. These flat sides were then ranked in descending order of mold growth. The mold growth was then divided into a total of seven scales from very abundant to no visible growth. The opposing flat sides were then ranked in the same way.

The routine that was developed by the two people who made the assessment was simple and rational, and there was good consistency in the assessment. At the boundary between two different mold grades is a degree of uncertainty. For this reason, we made a clear formulation of which conditions must be met for each mold grade. These formulations are described in detail in Table 3. An assessment of the practical usefulness of boards in the seven mold grades was also made by the two people: mold Grade 0 to 2 was classified as ''good to acceptable for use,'' mold Grade 3 was classified as ''questionable for use,'' and mold Grade 4 to 6 was classified as ''unacceptable for use.''

In connection with the mold level assessment, each sample was also classified into four classes with respect to the presence of wane and damage wounds from the debarking machine; see Table 4.

Results

Initial test: Chemical analysis of the nutrient gradient

In the two initial tests, a visual inspection of the surfaces of the boards was made with respect to the KBS. Marked, dark streaks, typically following the latewood areas, were clearly seen in both spruce and pine on surfaces that had been facing outward, whether these were sapwood sides or pith sides. This visible KBS was not found in the areas that had been blocked by the stickers during drying.

The results of the monosaccharide sugar concentration analyses in spruce board surfaces in Test 2 are shown in Figure 7. Measurements were made at various positions in the four samples at two different depths: 0 to 0.2 mm and 0.2 to 1 mm below the surface, as shown in Figure 7.

The results showed that

- During the drying process an enrichment of monosaccharide sugars toward the surface of sapwood spruce boards took place with a measurable gradient.
- The surface that was blocked below a sticker (Fig. 7, position c) had less monosaccharide sugars compared with nonblocked surfaces (Fig. 7, positions a and b).
- The content of monosaccharide sugars in the sapwood surfaces differed between the two double-stacking variants: where the sapwood sides were turned outward the total nutrient content was much higher at surfaces (Fig. 7, positions a and b) compared with the sapwood sides turned inward (Fig. 7, position f).
- When the sapwood sides were turned outward, the monosaccharide sugar content of the pith sides facing toward each other was low (Fig. 7, position d).
- When the pith sides were turned outward, the content of monosaccharide sugars was higher on the surface (Fig. 7, position e) compared with when they were facing toward each other (Fig. 7, position d).
- The maximum surface concentration of monosaccharide sugars was found when the sapwood sides were turned outward (Fig. 7, positions a and b).
- The minimum surface concentration of monosaccharide sugars was found when pith sides were facing toward each other during drying (Fig. 7, position d).
- The monosaccharide sugar gradient in the sapwood sides was greater when the sapwood surfaces were turned outward during drying than when they were facing toward each other (Fig. 7, right graph, comparing averages of positions a and b with position f).

Main test: Accelerated mold test

The results of the mold grading of the boards after the accelerated mold test are reported as average values with 95 percent confidence intervals. The boards that were classified as wane/damage (W/D) Class 3 (a total of 11: nine spruce and two pine) were excluded from Figures 8 to 10. The influence of the W/D class is discussed later.

Comparison between pine and spruce.—In Figure 8, the

Table 3.—Description of the mold grades.

Mold grade	Description	Practical usefulness of board
0	No visible mold seen with the naked eye anywhere on the surface	0–2: good to acceptable for use
1	Small amount of mold growth: some doubt that it is not quite free from mold	
2	Sparse mold growth: no doubt that there is mold but on a small scale; isolated black/dark spots and islands, such as those occurring near the wane	
3	Moderate mold growth: mold found in more coherent strings and as black and colored spots and islands; however, most of the sapwood surface is not covered by mold	3: questionable for use
4	Heavy mold growth: mold covers the entire sapwood surface; sapwood surfaces viewed from the side are covered with fluffy mycelia and spores	4–6: unacceptable for use
5	Very heavy mold growth: mold covers the entire sapwood surface; in addition to black mold, multicolored mold is also present; sapwood surfaces viewed from the side are covered with fluffy mycelia and multicolored spores	
6	Extremely heavy mold growth[a]	

[a] Only pine was given this grade.

Table 4.—Description of wane/damage (W/D) classes.

W/D class	Description
0	Free from wane and machine damage
1	No wane, some machine damage
2	Wane and machine damage
3	Extreme wane, machine damage, low quality

mold grades for the pine and spruce boards are presented as average values of all drying Series A to C without division into the different stacking methods. The results show that pine, on average, exhibited significantly higher mold susceptibility than spruce.

Comparison between the drying series.—Figure 9 shows the frequency distribution of mold grades in the drying Series A to C for both sapwood sides and pith sides of the spruce and pine boards without division into the different stacking methods. Boards classified as W/D Class 3 were excluded from this figure, making the number of classified board surfaces in Series A, B, and C for spruce 20, 46, and 46, and for pine 18, 34, and 16, respectively.

The results showed that

- Pine exhibited higher mold grades than spruce in all three drying series. No spruce board was classified as mold Grade 6.
- The lowest mold grades were found for spruce in Series A and Series C, with an approximately equivalent distribution frequency of mold grades: about 90 percent of all of these surfaces were classified as being good to acceptable for use (Grade 0 to 2).
- Drying Series B showed the highest mold grades, especially in pine but also in spruce. Only about 15 percent of the pine and 40 percent of the spruce board surfaces were classified as being good to acceptable for use (Grade 0 to 2).

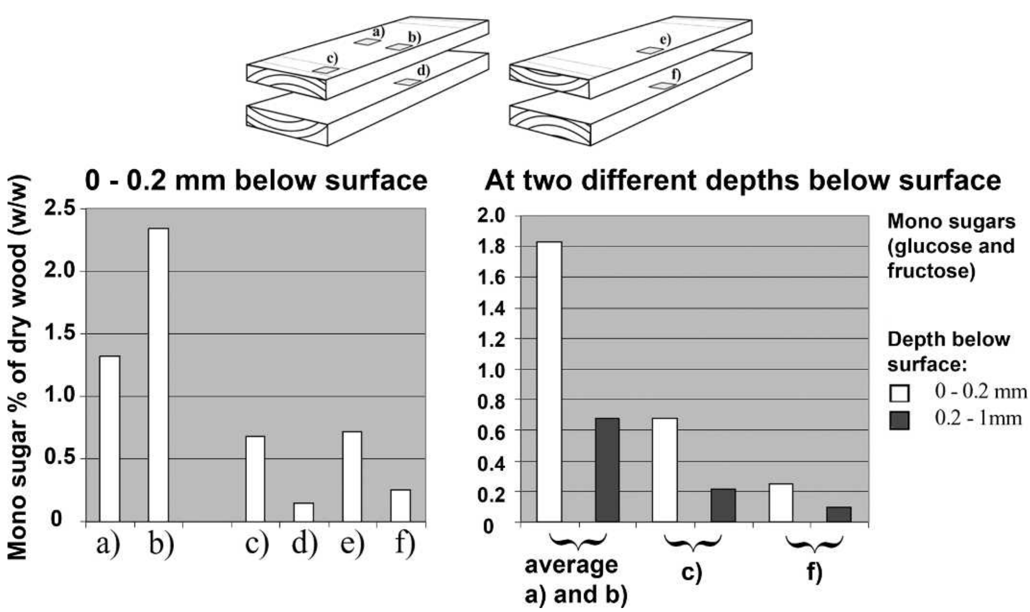

Figure 7.—Analysis of monosaccharide sugars near the surface of the double-stacked spruce boards in the initial test where they were dried at 115°C. Measurements were made at different positions on four samples double stacked in two different ways: sapwood sides turned outward and pith sides facing each other in each pair, and sapwood sides facing each other and pith sides turned outward in each pair. (Left) Concentration of monosaccharide sugars (glucose and fructose) in percentage of dry wood weight at a depth of 0 to 0.2 mm below the surface. (Right) Concentration of monosaccharide sugars (glucose and fructose) in percentage of dry wood weight at two depths: 0 to 0.2 mm and 0.2 to 1 mm below the surface.

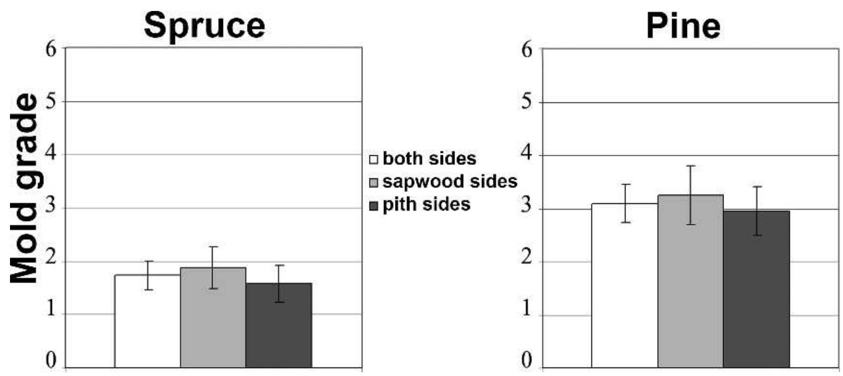

Figure 8.—Mold grades after the accelerated mold test for pine and spruce boards in drying Series A to C without division into the different stacking methods. Average values with 95 percent confidence intervals.

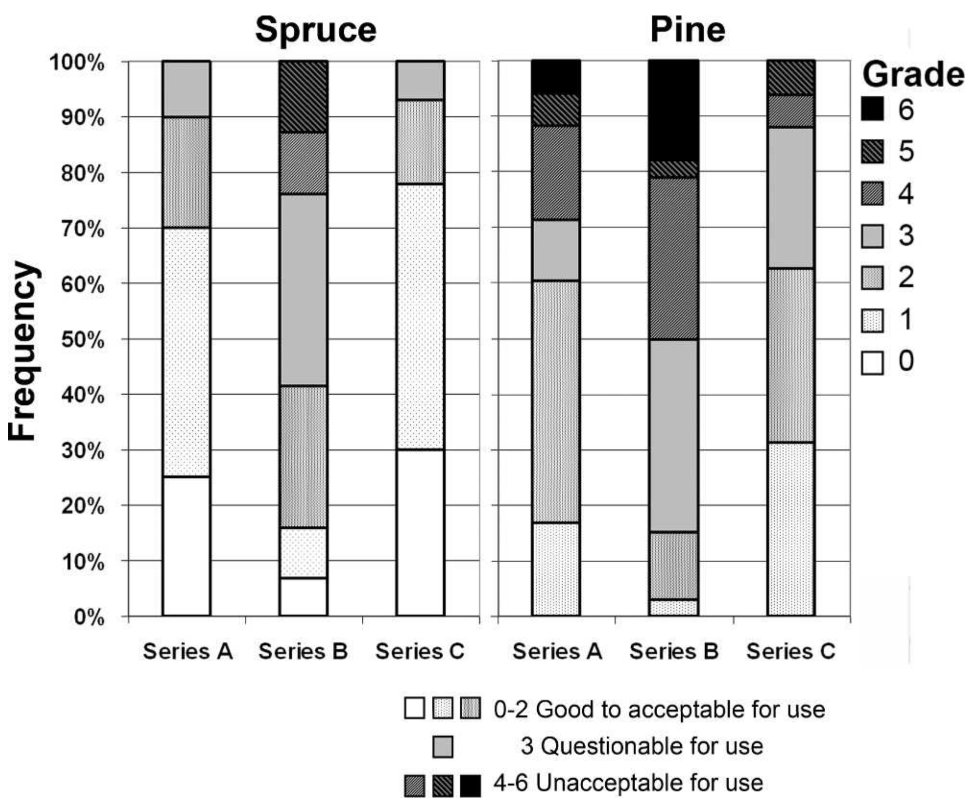

Figure 9.—Frequency distribution of mold grades in the drying Series A to C for spruce and pine, without division into the different stacking methods.

- The lowest amount of mold growth was shown for the pine drying Series C, with over 60 percent of the board surfaces classified as good to acceptable for use (Grade 0 to 2).

Comparison between the different stacking methods.—Figure 10 shows the impact of single and double stacking on the degree of mold on spruce and pine boards in drying Series A to C. Only single stacking was used in Series A, whereas no single stacking was used for pine boards in Series C. The result in Series B for the single-stacked spruce boards is an average of only two boards (the other two boards were excluded here because they were classed as W/D 3); therefore, this result is shown without a confidence interval. Since only a few boards were single stacked (except in Series A), these results should be interpreted with caution.

The results showed that

- Mold growth on board surfaces was influenced by how the boards were stacked during the drying process.
- The pine boards in Series B showed the highest mold grades, especially on the sides that were facing outward when double stacked.
- The lowest mold grades in Series B and C were found on pith sides that had been double stacked facing each other.
- The pith sides that were facing outward when double stacked in Series B and C, on average, showed a higher mold grade than when they were facing each other. This

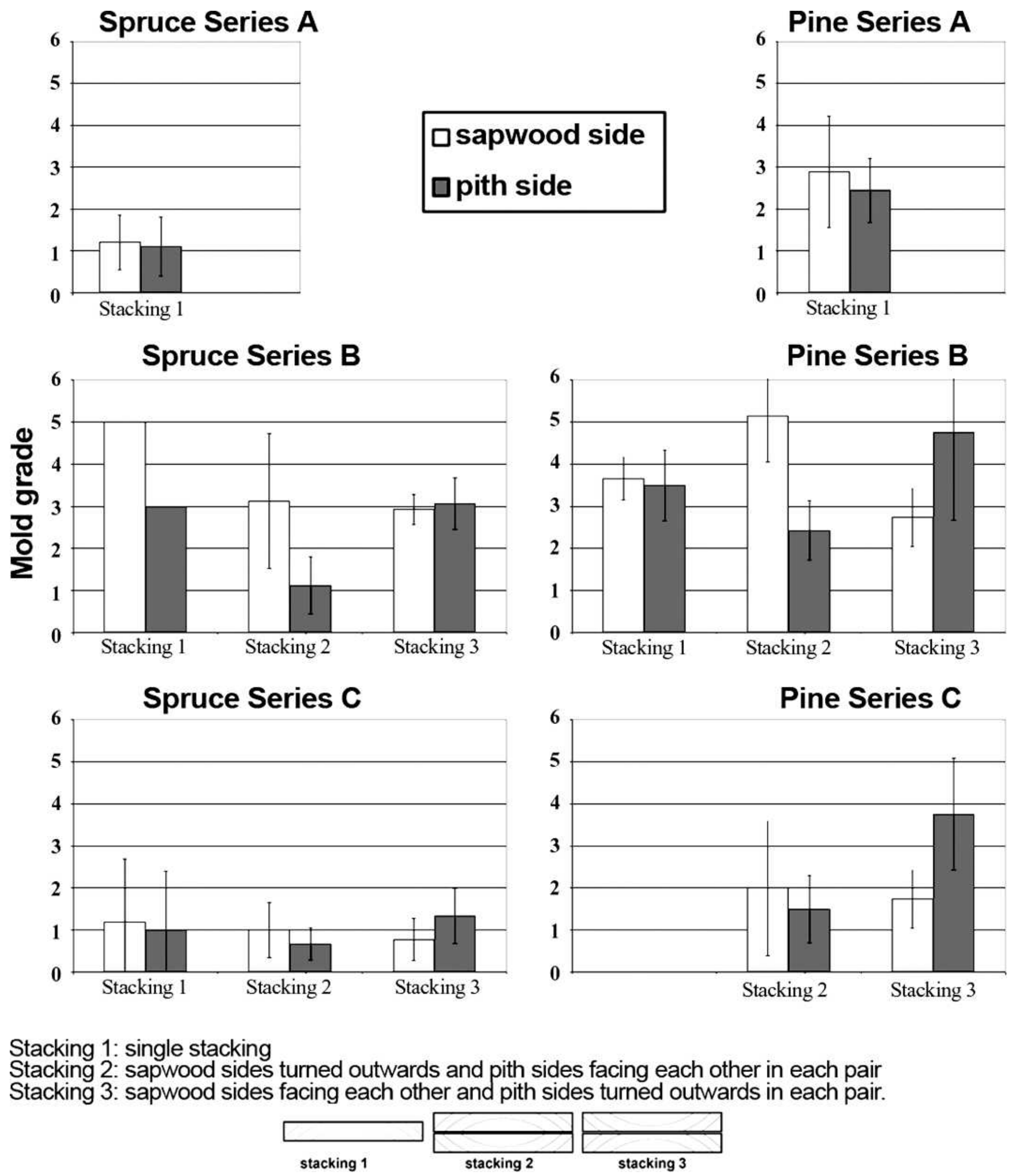

Figure 10.—Impact of single and double stacking on mold grade of the sapwood sides and pith sides in drying Series A to C for spruce and pine boards, given as average values with 95 percent confidence intervals.

difference was only significant at the 5 percent level for spruce in Series B and pine in Series C.

Discussion

This study showed that mold growth on the surface of sapwood boards is clearly affected by the drying process and by how the boards are stacked during drying. Figure 11 shows two pine samples after the accelerated mold test, originally cut from the same green sawn board. The sample marked 16.3 was dried at a maximum temperature of 74°C in Series B, and the sample marked 16.2 was dried at a maximum temperature of 110°C in Series C. Both were double stacked during drying: the sapwood sides of sample 16.3 were turned outward in the double-stacked pair, and the sapwood sides of sample 16.2 faced inward. The upper photo shows the sapwood sides with a clear difference in mold growth (the surfaces of samples 16.3 and 16.2 were classified as Grades 6 and 2, respectively). Furthermore, the opposing pith sides of the same two samples also showed a clear difference in mold growth (lower photo). Sample 16.3, with a sapwood side classified as mold Grade 6, had a pith side classified as mold Grade 3. Sample 16.2, which was HT dried and had a sapwood side classified as mold Grade 2, had a pith side classified as mold Grade 5. Note also the areas where the stickers were on the surfaces of the boards that were facing outward in the double-stacked board pairs.

Visible KBS

The KBS on the enriched board sides after drying, whether sapwood sides or pith sides, occurs when the drying reaches sufficiently high temperatures to allow visible staining of the nutrients. This might occur when carameli-zation temperature has been reached for the nutrients or

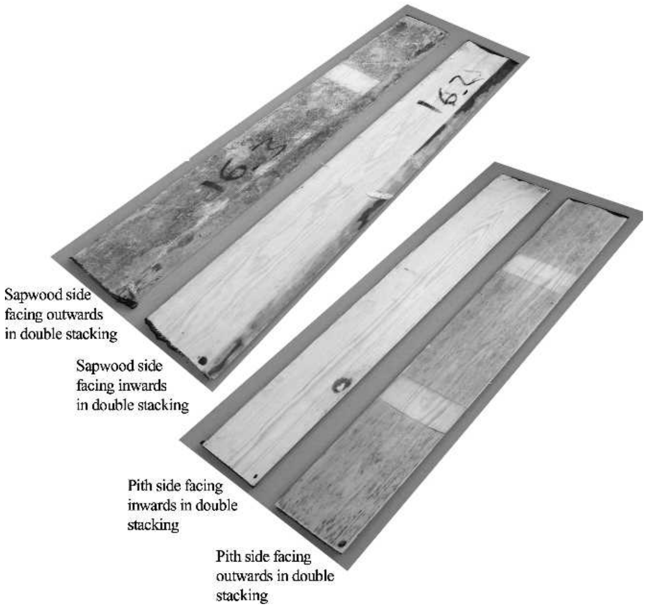

Figure 11.—Effect of double stacking during drying on mold growth on pine boards. Both samples were originally cut from the same green board. The sample marked 16.3 was dried in Series B, and the sample marked 16.2 was dried in Series C. The upper photo shows the sapwood sides, and the lower photo the opposing pith sides of the same samples.

some specific components of the nutrients. Fructose, found in the superficial parts, melts and decomposes at 112.7°C to 113.9°C, whereas the decomposition of glucose takes place at higher temperatures (146.5°C to 152.0°C; Hurtta et al. 2004). However, the carbohydrate analysis of the enriched layer in the initial test indicated a higher content of fructose than glucose. It is interesting to note that the mold growth on HT-dried wood (Series C) was lower than on boards dried at 70°C (Series B). These results were rather surprising because the migration of sugars should not be lower at 110°C than it is during drying at 70°C. Thus, a more elaborate analysis of the sugars and degradation products near enriched wood surfaces where the influence of the drying temperature is studied is of interest.

Impact of distance from the cambium

In the single-stacking method there was a tendency (not significant) for the sapwood sides to show a greater amount of mold growth than the pith sides. Higher nutrient concentrations in the wood beneath the bark and cambium (Saranpää and Höll 1989) might explain this, since the sapwood sides of the sawn boards are always closer to the cambium than pith sides. Moreover, if wane is present in the boards, it is always on the sapwood side.

Impact of good contact between the surfaces

In some of the double-stacked board pairs the contact surface between the boards during the drying process was not perfect along the entire length of the board due to deformation (twisting) of one board in the pair during drying. In Series C in particular, it was clearly visible to the naked eye that the contact surface was not perfect because of the appearance of visible streaks of KBS during HT drying. Streaks of mold were often seen on such surfaces along the edges of the boards after the mold test. Furthermore, when one sapwood side in a double-stacked pair with the sapwood sides facing each other had wane, the same phenomenon was observed. These surfaces—both the waning surface and the corresponding surface of the board that the wane had been in contact with—were more easily attacked by mold along the edges. This highlights the importance of good contact between double-stacked boards during drying in order to direct the migration of nutrients toward the chosen side.

Impact of W/D class

When choosing the test material the aim was to obtain as much sapwood as possible. For side boards, this means that the top end of a sawn board may contain more or less wane but also damage from debarking machines. Because each board was cut into 4 by 1-m-long sample boards, some of these contained a lot of wane and damage on the sapwood side. All of the sample boards were classified according to the presence of wane and damage (four classes: 0 to 3). The boards with sapwood sides that were placed in Class 3 were completely excluded, even if the opposing pith sides were of good quality. This was done because it was found that sapwood sides in injury Class 3 usually showed extremely rich mold growth, which was often found to ‘‘creep over’’ to the pith side during the mold test, and which led to misleading results. Boards with wane and damage in Class 3 are not used in practice. For the boards in W/D Class 0 to 2, it was obvious that presence of wane and damage clearly increased the risk of mold growth on the sapwood sides. However, the study also showed that by double stacking boards of low quality with respect to wane and damage with these sides facing outward, the pith sides of the boards might show a lower mold susceptibility when the low-quality sides and edges are planed and grooved. A strong wane, however, makes a good contact surface between double-stacked board pairs in the pile hard to achieve during drying.

Evaluation of the relevance of the methods used

The accelerated outdoor mold test, used as the evaluation method, was simple, robust, and worked well for its intended purpose. The test was performed during the same weeks of the year that Terziev et al. (1996) performed their tests, during the mid-1990s in Uppsala, and the mold growth developed over the same time period described by Terziev. It was not until the full plastic wrapping had been put in place and the RH increased to a nearly constant 100 percent that the mold growth seriously started. This confirms that the risk of mold growth substantially increases at a constantly high RH, whereas a fluctuating RH, even if it is sometimes high, does not favor mold growth in the same manner, but instead may cause a retardation of mold development (Viitanen 1997, Isaksson et al. 2010).

A disadvantage of the method used is the lack of test repeatability. Owing to variations in climate and soil type, for example, comparing the results of two different outdoor tests is hard to do. In cases such as this, however, when different variables are compared and evaluated in one test, the method used works well.

The visual assessment (without microscope) of the mold level performed by two researchers was effective, simple, and rational. The grading routine that was developed for the visual assessment is recommended for continued use.

Conclusions

The hypothesis in this work—that during drying it is possible to direct the migration of nutrients in sapwood toward one chosen side of each board by double stacking while the opposite side leaches out in order to influence mold susceptibility—is supported by the following findings.

- The KBS could be seen by the naked eye on the enriched board sides of both sapwood sides and pith sides, provided that the drying temperature had been high enough to allow visible staining of the nutrients.
- Chemical analysis of the nutrient gradients beneath the surfaces of the boards confirmed the proposal that it is possible to direct the migration of nutrients by double stacking during drying.
- The highest concentration of nutrients was found on the sapwood sides of the boards turned outward when double stacked.
- The lowest concentration of nutrients was found on the pith sides of the boards facing each other when double stacked.
- The enriched nutrients on the sapwood board sides during drying had a major impact on mold susceptibility.
- Pine sapwood is more prone to mold than spruce sapwood.
- HT drying at 110°C showed a low degree of mold growth for both single-stacked and double-stacked spruce boards.
- Air-dried single-stacked spruce boards showed a low degree of mold growth.
- Forced drying at 70°C exhibited the most mold growth on both spruce and pine boards.
- Double-stacked spruce boards dried at 70°C showed a low mold grade on pith sides that were turned toward each other.
- The presence of wane and injuries from debarking machines on the sapwood sides of the boards increased the risk of mold growth.
- The accelerated outdoor mold test, used as an evaluation method, worked well.

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