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ORIGINAL ARTICLE

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Wood drying process: impact on Scots pine lumber durability

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Abstract There are indications that the drying process may have negative effects on the natural durability of wood. The impact of various drying processes on the durability of Scots pine lumber has been evaluated with mass loss in a decay test with brown rot fungus, *Coniophora puteana*, as measure of the decay resistance of sapwood and inner and outer heartwood. Drying with or without steam conditioning was performed in six different series: air drying, kiln drying at temperature ranges commonly used in Swedish sawmills at 70°C and 90°C with two different regulation principles, and one high-temperature drying at 110°C. Durability varied considerably both between and within boards. Sapwood showed considerable less durability than heartwood. No difference in durability was found between inner heartwood and outer heartwood. Air-dried heartwood showed the highest durability compared to other drying series. The lowest durability in sapwood and heartwood was found for series dried at the 90°C temperature level with high material temperature early in drying. The interpretation is that the duration of high material temperature at high moisture content (MC) is the critical combination for decay resistance in heartwood. Steam conditioning after drying decreased durability in sapwood.

Key words Drying · Conditioning · Durability · Scots pine

Introduction

Durability of wooden products for outdoor applications above ground is an urgent issue for the future utilization of wood as a competitive construction material. During recent years there has been some indication that the durability of pine heartwood products has declined, such as, for example, high-temperature-dried pine poles in playgrounds that have become seriously decomposed after just a few years usage.[1] One hypothesis is that the drying process might negatively affect the natural durability of wood. In this study, the main issue is to clarify the impact of the drying process on the durability of Scots pine lumber in above-ground applications.

According to the European Standard,[2] pine heartwood is classified into class 3–4 (moderately to slightly durable) and pine sapwood into class 5 (not durable) in terms of natural durability in resistance to wood-destroying brown rot fungus. Mass loss, expressed as a percentage of the original dry weight, is commonly used in laboratory tests to assess the natural durability of wood.[3] However, the variation in durability between pine trees from growing stands has been shown to be large in decay tests with the brown rot fungus *Coniophora puteana*.[4] A large proportion of this variation is the result of genetic differences.[5] The variation in durability within a single tree in the radial direction is also shown to be large, with higher durability in outer heartwood, compared to inner heartwood, while tree height, crown limit, wood density, heartwood radius, and proportion of latewood do not explain the variation.[4] The amount of extractives in heartwood generally increases with distance from pith. The pattern of lower extractive content near the pith may reflect the degradation of extractives over time or an increase in extractive deposits with age. Thus, the age of the tree affects heartwood extractive content.[6]

Various heartwood extractives are known to contribute to decay resistance. The chemical characteristics that separate decay-resistant trees from decay-susceptible trees are resin acids, pinosylvins, acetone-soluble extractives, and total phenolics measured according to the Folin–Ciocalteau (FC) assay.[4] The spatial distribution of pinosylvin in pine heartwood was found to decline in inner heartwood, while the concentrations were highest in outer heartwood at the transition between sapwood and heartwood.[7] No seasonal trend in the distribution pattern or concentration of pinosylvins was found in pine heartwood.[8]

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Compared to heartwood, the extractive content in sapwood is considerably lower in Scots pine. According to different studies the extractive content in pine sapwood was found to be 2.2% of dry weight (petroleum ether soluble),[9] 4.5% (acetone soluble),[10] and 2.3%–3.0% (cyclohexane-acetone soluble)[11] and that in heartwood was 8.6% (ether soluble)[9] and 9.3% (acetone soluble).[10]

Sapwood, with its low natural durability, contains high amounts of carbohydrates as free sugars that play an important role as nutrients for, primarily, mold fungi. The concentration of soluble carbohydrates such as glucose, fructose, and sucrose in pine sapwood is greatest in the outer sapwood and decreases gradually toward the innermost sapwood.[12] The seasonal fluctuation of low molecular weight sugars is great, with the highest concentrations during autumn and winter months in pine sapwood[13] as well as in spruce sapwood.[14] The surfaces of dried, winter-felled pine sapwood were shown to be more susceptible to mold growth than spring-felled timber.[15]

In the early stage of the drying process when free water in sapwood moves toward the evaporation front beneath the surface, an enrichment of carbohydrates and nitrogen compounds takes place at the surface.[16] The drying rate has a significant effect on this redistribution, with a higher accumulation if the drying rate is high.[17] Thus, the nitrogen and carbohydrate gradients near the lumber surface in dried sapwood depend on the drying process. Air-dried sapwood surfaces were shown to have smaller gradients than kiln-dried lumber.[18]

In mold growth testing on dried sapwood surfaces, planing was shown to reduce mold growth on kiln-dried lumber whereas mold growth on planed, air-dried surfaces increased compared to unplaned surfaces.[19] For kiln-dried sapwood, the reduction of mold growth on planed surfaces was higher in fast drying schedules compared to slow drying schedules. Planing of kiln-dried sapwood removes the most enriched zone, while in air-dried sapwood, planing might expose wood with a higher nutrient concentration.

The natural durability of wood has been evaluated by a multitude of methods for many species.[6] In general, there are difficulties in transforming and comparing results from tests on one species to another. Furthermore, even if the same standardized decay test is performed at five European test institutes on the same species in a round-robin test, the mass loss varies considerably.[20]

Studies of the impact of different drying methods on the durability of pine and spruce have been done with various short- and long-term decay methods with varying results. No difference between different drying methods was found concerning mass loss in a 10-week rot test when comparing air-dried pine lumber with artificially dried pine lumber at temperature levels not exceeding 54°C,[21] temperature levels considered moderate by today's standards. In a long-term outdoor test above ground, air-dried pine and spruce lumber were compared with kiln-dried lumber of the same species.[22,23] Air-dried spruce showed higher mass loss after 9 years exposure compared to kiln-dried spruce,[22] but also significantly higher average moisture content (MC) during exposure time, which probably explains the higher mass loss because of more favorable conditions for wood-destroying fungi. However, the drying process in the study[22] is poorly described, merely stated as "kiln dried." For pine sapwood,[23] no difference in mass loss after 9 years exposure was found between air-dried and kiln-dried material dried at a maximum of 65°C.

Mold growth with *Cladosporium cladosporioides* and *Penicillium commune* has been studied on spruce sapwood and heartwood dried at temperatures between 20° and 170°C, together with spruce commercially heat treated at 190° and 210°C.[24] Mold growth was more pronounced on the original surfaces than on resawn surfaces, and heavier on sapwood than on heartwood. All kiln-dried material exhibited higher mold growth than air-dried material after 20 weeks of exposure, whereas heat-treated spruce showed very low mold growth levels. An inhibiting effect of higher drying temperatures on mold growth after 8 weeks of exposure with *Penicillium brevicompactum* was found for pine sapwood.[25] In an 8-week rot test with the brown-rot fungus *Fomitopsis palustris* on high-temperature-treated Japanese cedar blocks, results show that durability was improved at treatment temperatures higher than 135°C and that longer treatment time resulted in stronger decay resistance.[26]

The drying process can in fact be seen as a hygrothermal treatment of wood, and the performance of the drying process can be varied infinitely. The main issue with this study is to investigate if and how the drying processes commonly used at Swedish sawmills affect the durability of pine sapwood and heartwood. The focus is on the performance of the drying process with regard to temperature levels, material temperatures at different stages of drying, and the impact of conditioning at the end of the drying process. A short-term in vitro test with the brown rot fungus *Coniophora puteana* was chosen as a measure of the durability of sapwood and inner and outer heartwood from winter-felled lumber with a high concentration of nutrients in the sapwood.

Materials and methods

Lumber

Center-sawn boards 50 × 125 mm from Scots pine (*Pinus sylvestris* L.) butt logs felled in January 2007 from a stand in Norrbotten in northern Sweden were used in the tests. Each green board was cut into four 1-m samples (numbered 1 to 4 from butt to top end) that were end sealed with Sikaflex polyurethane sealant and kept in a climate chamber at 0°C and 95% relative humidity (RH) until the start of drying. Slices from all samples were cut for measurement of moisture content (MC), density, and heartwood content. All samples were sorted into six similar series with regard to heartwood content, visually estimated resin content, and position along the board. After each drying series, slices for MC control (oven-dry method) were cut from each sample. The samples were then kept in a freezer at −25°C until further cutting of test material.

Drying and conditioning

Drying was performed in six different series. Series A, considered similar to outdoor air-drying, was, due to the time of year, done indoors at the laboratory on stickers at 20°–25°C, 38%–45% RH for slightly less than 9 weeks. Series B–F were dried in a small-scale laboratory air-circulation kiln at maximum temperature levels of 70°, 90°, and 110°C. For the 70°C and 90°C series B–E, two different regulation principles were used after the initial preheating:

I. Dry-bulb temperature (T_{db}) gradually rising to maximum temperature level and wet-bulb temperature (T_{wb}) at one or two constant levels.

II. Constant T_{db} at maximum level with initial T_{wb} dropping to a constant level.

Both these principles correspond to kiln-drying schedules used at Swedish sawmills.

Series F was dried with a high-temperature schedule at a maximum temperature of 110°C. During series F, kiln regulation was unfortunately interrupted for 9 h because of activation of an alarm, which resulted in a temporary temperature drop. The appraisal is, however, that this disturbance had a finite influence on the results in the decay test. The drying series are summarized in Table 1 and Fig. 1. Schedules for series B–F are presented in detail.

Preheating was performed with saturated steam in series C, E, and F and with high-pressure water spray in series B

Fig. 1. Drying schedules with two regulation principles at maximum dry-bulb temperature 70°C (series B and C), 90°C (series D and E), and 110°C (series F). In series F, a 9-h interruption occurred because of activation of an alarm. T_{db}, dry-bulb temperature; T_{wb}, wet-bulb temperature

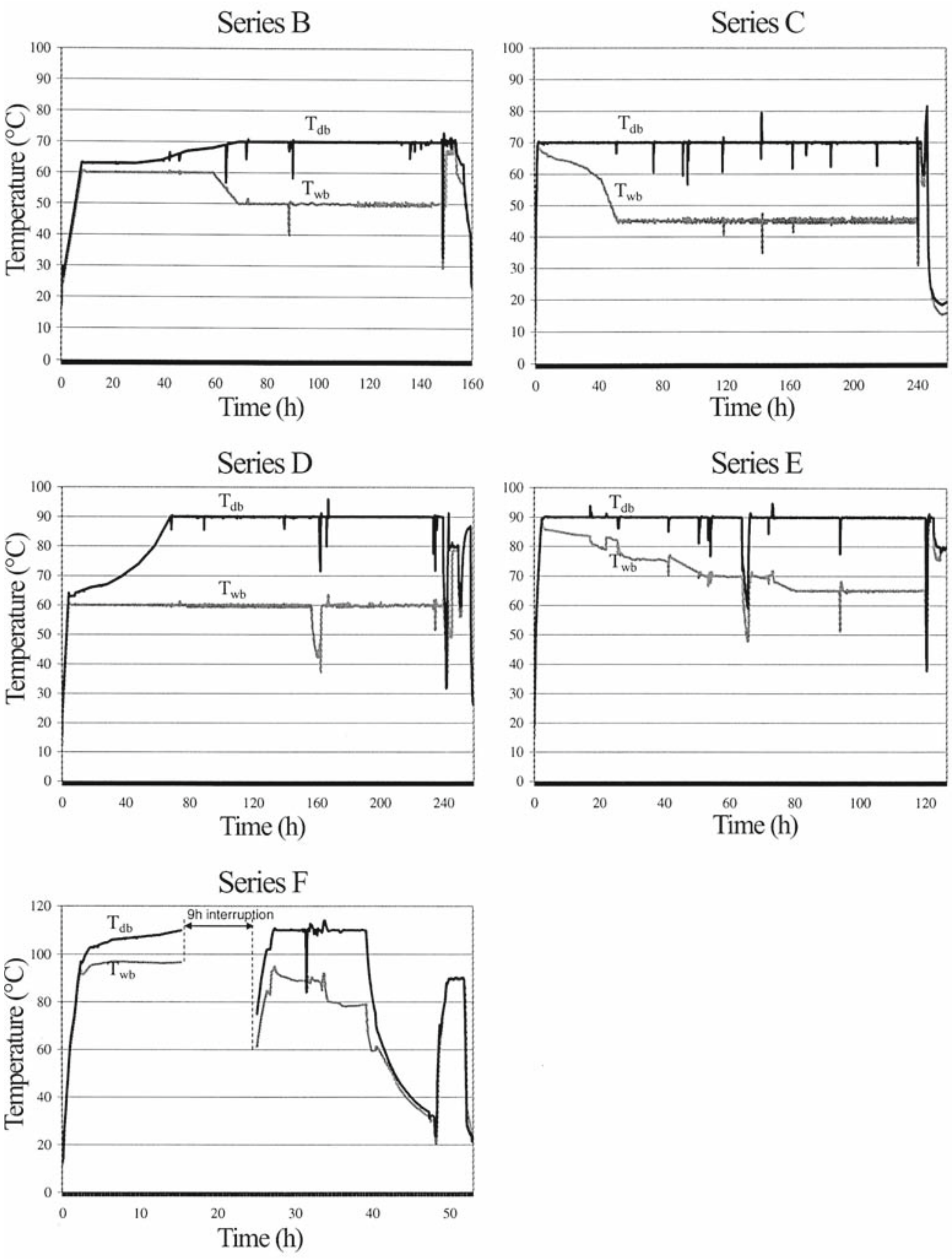

Table 1. Description of drying series A–F

Series	Maximum temperature	Preheating	Regulation principle	Number of samples	Steam conditioning
A	25°C	–	–	10	–
B	70°C	Water spray	I	10	Half batch, 4 h
C	70°C	Steam	II	10	Half batch, 5.5 h
D	90°C	Water spray	I	10	Half batch, 9.7 h[a]
E	90°C	Steam	II	10	Half batch, 3.7 h
F	110°C	Steam	–	19	Half batch, 3.5 h

[a] Extended conditioning to adjust the low final moisture content (MC) after drying

Table 2. Moisture content (MC) before and after drying and conditioning in series A–F

Series	Average MC before drying (%)	Drying time (h)	Steam conditioning	Final average MC (%)
A	70	1480	Unconditioned	9.0
B	63	141	Unconditioned	10.3
			Conditioned	11.4
C	64	238	Unconditioned	7.9
			Conditioned	9.9
D	62	235	Unconditioned	6.2
			Conditioned	10.9[a]
E	66	117	Unconditioned	8.9
			Conditioned	10.6
F	47[b]	37	Unconditioned	9.7
			Conditioned	11.9

[a] Low MC after drying was adjusted with an extended conditioning

[b] The low average MC before drying in series F is explained by a high fraction of heartwood content

and D. Conditioning after drying was done on half of each batch in series B, C, D, E, and F, whereas the other half was removed from the kiln at the end of drying. Conditioning was performed with saturated steam at 100°C injected from an external steam boiler for a range of hours according to Table 1. No conditioning was done on series A.

Wood temperature during drying

The wood temperature in one chosen sample per drying series B–F was registered using a PT100 sensor inserted in a hole drilled from the board edge to half board width at a depth of 5 mm below sapwood surface. No temperature measurements were done in the lumber dried indoors in series A.

Decay test

The decay test with the brown rot fungus *Coniophora puteana* (BAM Ebw.15) was performed according to the standardized EN113 decay test, but modified with respect to sample size and incubation time in the same way as described by Harju and Venäläinen.[27] The mass loss of the samples after an incubation time of 7 weeks, expressed as percent of dry mass of wood before decay test, was used as a measure of durability.

Sampling for decay test

Specimens cut into 5 × 15 × 30 mm blocks were sawn from dried and planed samples in all six series at three positions: inner heartwood, outer heartwood, and sapwood (Fig. 2). Thus, only planed surfaces were used in the study, with a planing depth of 2–3 mm. For outer heartwood specimens, the distance from pith side was measured. In total, 194 specimens were made: 2 × 66 heartwood specimens and 62 sapwood specimens.

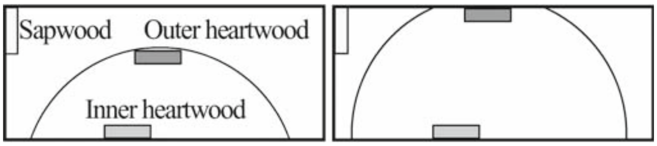

Fig. 2. Sampling of specimen for decay test from dried and planed samples in positions of inner heartwood, outer heartwood, and sapwood. For inner heartwood, the pith was avoided. *Left:* Position of outer heartwood specimen in lumber with low heartwood content. *Right:* With high heartwood content

Results and discussion

MC and density

The average density, $\rho_{0,\mathrm{raw}}$, of all dried boards before drying was 418 kg/m^3 with a standard deviation of 40 kg/m^3. Average MC before and after drying and conditioning (half batches in series B–F) in each series is shown in Table 2. In series D, the low final MC after drying was adjusted with an extended two-step conditioning for half the batch.

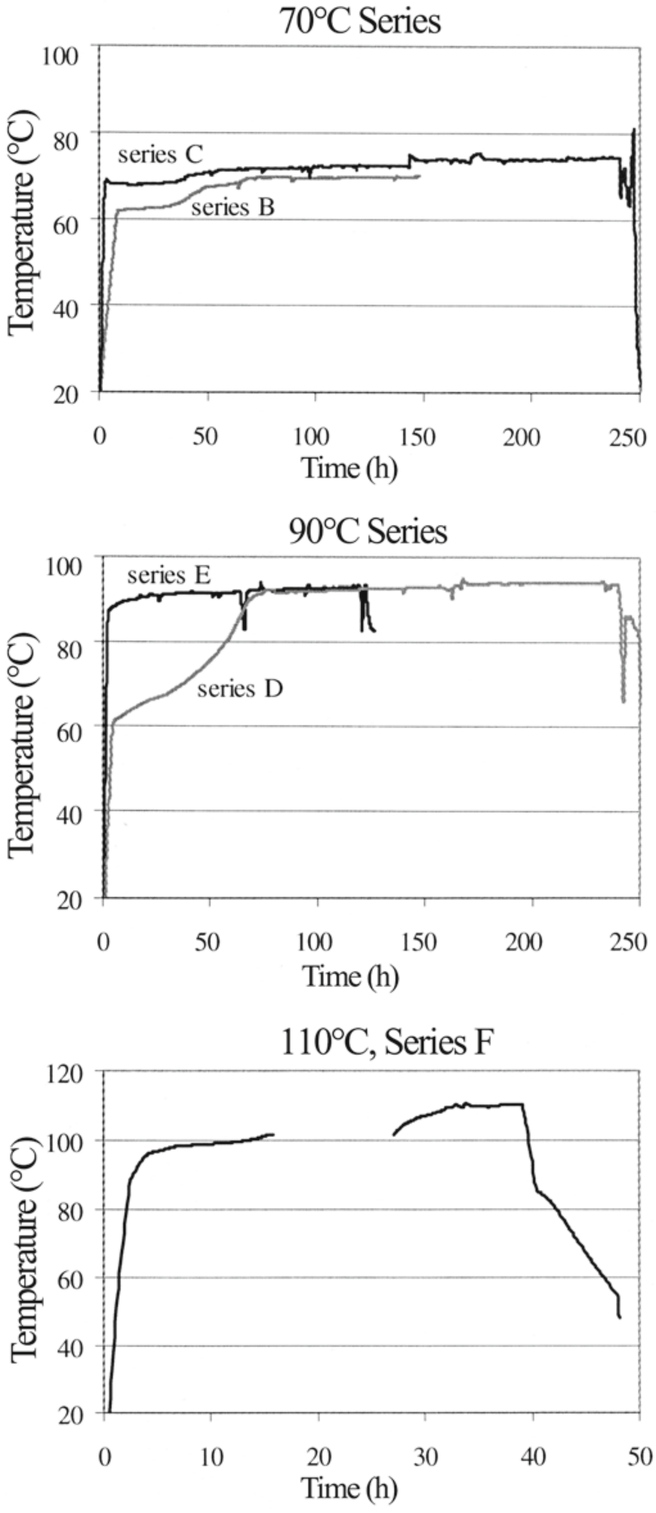

Fig. 3. Material temperature during drying in series B and C (*top*), in series D and E (*middle*), and in series F (*bottom*)

Wood temperature during drying

Measurements of the temperature development in the wood material during drying are shown in Fig. 3 for series B–F. A pronounced difference between the two regulation principles, I and II, is found in the early stages of drying after the preheating phase. In series C and E with regulation principle II, the wood temperature reaches close to maximum temperature 70°C or 90°C early in drying when the MC is high with free capillary water present in sapwood and with MC in heartwood close to fiber saturation point. In series B and D with regulation principle I, however, maximum temperature is reached considerably later in the drying process when the MC is substantially lower. Less temperature difference early in drying between regulation principles I and II can be seen in the 70°C series compared to the 90°C series.

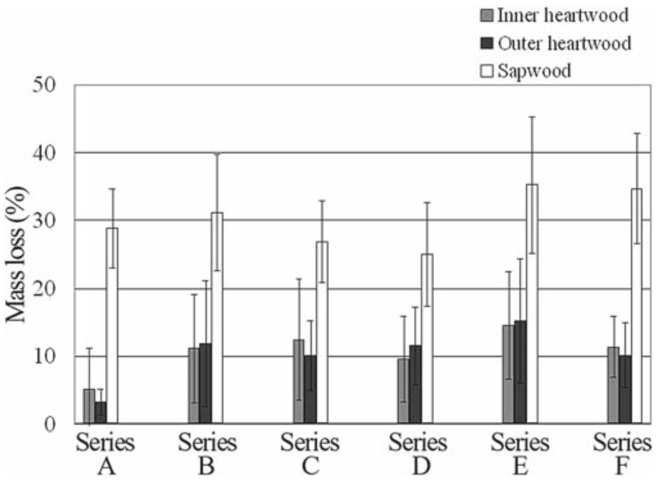

Fig. 4. Mass losses after 7 weeks incubation with brown-rot fungus *Coniophora puteana* for pine lumber dried in series A–F. Data are given as average values with 95% confidence intervals (n = from 10 to 16 in each bar). Average values comprise conditioned and unconditioned specimens

Mass loss in decay test

The mass losses after 7 weeks incubation time in each series are shown in Fig. 4 for the three wood type positions: inner heartwood, outer heartwood, and sapwood. A large variation in mass loss is seen for all positions in all series, judging from the confidence intervals. As expected, the mass loss in sapwood in all series is significantly higher (at 5% significance level) than in inner heartwood and outer heartwood.

Series E shows, on average, the largest mass loss compared to all other series for all three wood types. In sapwood, the mass loss in series E is significantly higher only in comparison to sapwood in series D at 10% significance level.

In heartwood, the mass loss, on average, is lowest in series A and highest in series E. Mass loss in outer heartwood in series A is significantly lower than in outer heartwood in all other series (at significance levels between 1% and 10%). Mass loss in inner heartwood in series A is significantly lower compared to series E and F at 10% significance levels.

In contradiction to other studies, no significant difference between mass loss in inner heartwood and mass loss in outer heartwood was found, either in any series or in overall average values. Also, the mass loss in outer heartwood specimens did not show any dependence on measured distance from pith side.

Among the various drying strategies, series A, considered equivalent to outdoor air-drying, shows the best decay resistance in heartwood. The average mass loss for heartwood (inner and outer grouped together) in series A is significantly lower compared to all other series (at 5% significance level compared to series B, C, D, and F and at 1% compared to series E). Drying with high wood material temperature early in the drying process, such as in series E at 90°C maximum temperature, shows the lowest decay resistance in sapwood and heartwood. The difference for heartwood (inner and outer grouped together) is, however, significantly higher only in comparison to series A.

High material temperature when MC is high, such as in series E, is an unsuitable combination for decay resistance in pine heartwood. In fact, these are also the conditions in the high-temperature drying in series F, but because the drying time is short, this combination of high material temperature and high MC does not lead to any pronounced decrease in decay resistance compared to the other series.

When comparing the drying time for the two series with maximum temperature 90°C, the total time for material temperature at maximum level is much longer in series D than in series E. Even though this is the case, mass loss is higher in series E. The interpretation of these results is that the duration of high material temperature early in drying when MC is high with presence of free, liquid water seems to be the critical combination for decay resistance in heartwood. At higher temperatures reactivity and solubility of compounds are normally increased, and it is possible that more of fungicides such as resin acids or pinosylvins in heartwood are inactivated when drying at higher temperatures and high MC. Duration of high material temperature later in drying when MC is lower, such as in series D, does not show any deterioration of decay resistance compared to series at 70°C.

Effect of conditioning on mass loss

At the end of each drying series, except series A, steam conditioning was performed on half of each batch. A comparison between mass loss in unconditioned and conditioned sapwood and heartwood is shown in Fig. 5. No significant effect of conditioning in heartwood is found, but in sapwood, steam-conditioning increases mass loss. The increase is significant at the 10% significance level.

In Fig. 6, the mass loss in conditioned/unconditioned planed sapwood in series B–F is shown. Conditioning has increased mass loss in all series apart from series C.

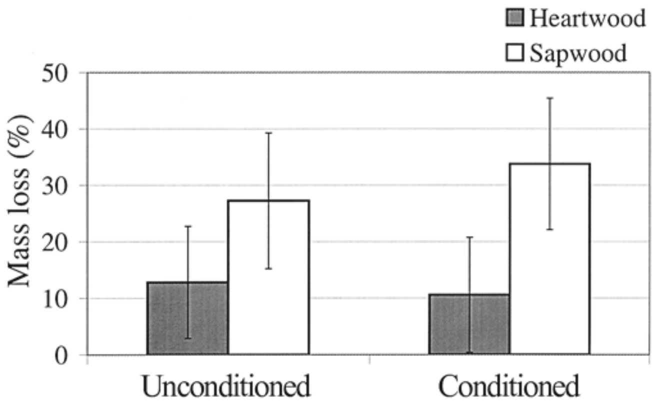

Fig. 5. Mass losses in pine sapwood and heartwood after 7 weeks incubation with brown-rot fungus *Coniophora puteana* for unconditioned and conditioned pine lumber in all series except series A. Data are given as average values with 95% confidence intervals ($n = 112$ for heartwood; $n = 52$ for sapwood)

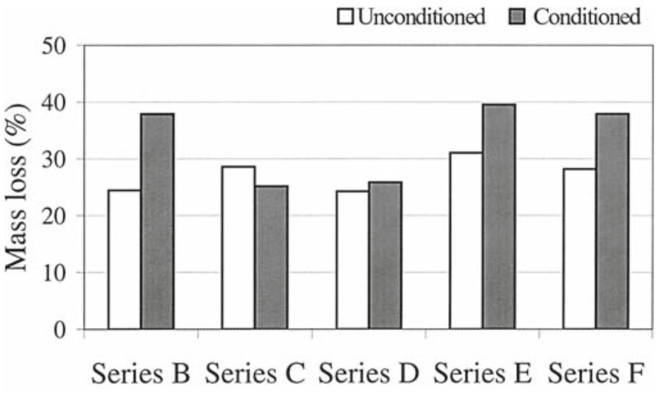

Fig. 6. Effect of conditioning on mass loss in pine sapwood in series B–F. Data are given as average values (n = from 5 to 8 for each bar)

A hypothesis is that this increase of mass loss in conditioned sapwood depends on redistribution of nutrition during moistening of the dry lumber surface with free condensation water during injection of saturated steam. During this substantial moistening of the outermost thin dry layer, which forms early during drying[28,29] down to a depth of seven to ten cell rows beneath the surface,[28] a redistribution toward the surface of migrating nutrients through this thin dry layer is conceivable. These nutrients have been accumulated just beneath the thin dry layer early during drying and has a typically position of 0.5 mm below the surface down to a depth of 1.5–5 mm.[30] Such redistribution of nutrients at the surface might facilitate and initiate a more rapid decay of conditioned sapwood. In heartwood, it is likely that no such accumulation of soluble nutrients takes place during drying.

Effect of raw material properties on mass loss

The variation in decay resistance is large among different boards, as revealed in Figs. 4, 5, and 6, but also within single boards. Investigation of the impact of position along the board shown in Fig. 7 showed no dependence on positions 1–4.

One probable explanation to the large variation in mass loss is the natural variability of extractive content between and within individual boards. However, extractive content was not measured in this study.

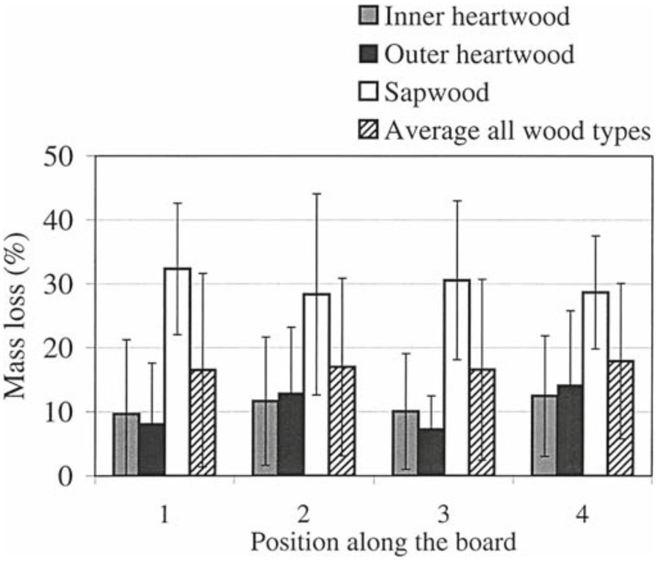

Fig. 7. Mass loss in different wood types at positions 1 through 4 along the boards from butt to top end. Data are given as average values and standard deviation ($n = 74, 41, 39$, and 40 for positions 1–4, respectively, in average values for all wood types)

Conclusions

The impact of different drying processes on the durability of Scots pine lumber has been evaluated with mass loss in a 7-week decay test with the brown rot fungus *Coniophora puteana* as a measure of decay resistance. The results are summarized as follows:

- The variation in decay resistance is large between different boards, but also within single boards.
- Sapwood shows considerably lower durability than heartwood. Mass loss after the 7 weeks rot test as average values for all drying series was 30% in sapwood compared to 11% in heartwood.
- In contrast to other studies, no difference was found between the durability of inner heartwood and that of outer heartwood.
- Air-dried heartwood shows the highest durability compared to the other drying series. Mass loss after the 7 weeks rot test as average values for inner and outer heartwood was 4.2% in air-dried lumber compared to 14.9% in the kiln-dried series, which showed the highest mass loss.
- Steam conditioning after drying lessens the durability of sapwood. Mass loss after the 7 weeks rot test as average values of all kiln-dried series was 27.3% in unconditioned sapwood compared to 33.8% in conditioned sapwood. The difference is significant at the 10% significance level.
- Steam conditioning after drying did not affect the durability of heartwood.
- Drying at 90°C maximum temperature with high material temperature early in drying when MC is high shows the lowest durability for both sapwood and heartwood. The interpretation is that the duration of high material temperature at high MC is the critical combination for decay resistance in heartwood.

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