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ORIGINAL ARTICLE

Decay resistance of sapwood and heartwood of untreated and thermally modified Scots pine and Norway spruce compared with some other wood species

SINI METSÄ-KORTELAINEN & HANNU VIITANEN

VTT Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Finland

Abstract
Thermal modification has been developed for an industrial method to increase the biological durability and dimensional stability of wood. In this study the effects of thermal modification on resistance against soft- and brown-rot fungi of sapwood and heartwood of Scots pine and Norway spruce were investigated using laboratory test methods. Natural durability against soft-rot microfungi was determined according to CEN/TS 15083-2 (2005) by measuring the mass loss and modulus of elasticity (MOE) loss after an incubation period of 32 weeks. An agar block test was used to determine the resistance to two brown-rot fungi using two exposure periods. In particular, the effect of the temperature of the thermal modification was studied, and the results were compared with results from untreated pine and spruce samples. The decay resistance of reference untreated wood species (Siberian larch, bangkirai, merbau and western red cedar) was also studied in the soft-rot test. On average, the soft-rot and brown-rot tests gave quite similar results. In general, the untreated heartwood of pine was more resistant to decay than the sapwood of pine and the sapwood and heartwood of spruce. Thermal modification increased the biological durability of all samples. The effect of thermal modification seemed to be most effective within pine heartwood. However, very high thermal modification temperature over 230°C was needed to reach resistance against decay comparable with the durability classes of “durable” or “very durable” in the soft-rot test. The brown-rot test gave slightly better durability classes than the soft-rot test. The most durable untreated wood species was merbau, the durability of which could be evaluated as equal to the durability class “moderately durable”.

Keywords: *Biological durability, brown rot, decay, heartwood, high temperature, Norway spruce, sapwood, Scots pine, soft rot, thermal modification.*

Introduction

Thermal modification at high temperatures, above 180°C, changes the chemical, biological and physical properties of wood. The effects of thermal modification on wood have been widely studied. According to the published results, hemicelluloses and amorphous cellulose are partly degraded or modified, the structure of lignin is modified and a part of extractives, particularly resin acids, is evaporated or modified (Kotilainen, 2000; Viitaniemi *et al.*, 2002; Wikberg, 2004; Nuopponen, 2005; Boonstra & Tjeerdsma, 2006; Mburu *et al.*, 2006). As a consequence of chemical changes in the wood material, the appearance and the biological and physical properties of the wood are also changed. The colour turns to deep brown and the wood loses its weight (Viitaniemi & Jämsä, 1996; Viitaniemi, 1997*a*; Bekhta & Niemz, 2003). Thermal modification significantly improves the dimensional stability and reduces the equilibrium moisture content of wood, and, in most cases, water absorption is reduced, depending on the wood species (Viitaniemi, 1997*b*; Jämsä *et al.*, 2000; Kamdem *et al.*, 2002; Bekhta & Niemz, 2003; Pétrissans *et al.*, 2003; Hakkou *et al.*, 2005; Repellin & Guyonnet, 2005; Metsä-Kortelainen *et al.*, 2006). However, the wood becomes more brittle and bending and tension strength decrease in relation to the level of thermal modification (Viitaniemi & Jämsä, 1996; Kamdem *et al.*, 2002; Bekhta & Niemz, 2003).

Correspondence: S. Metsä-Kortelainen, VTT Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Finland. E-mail: sini.metsa-kortelainen@vtt.fi

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One of the main targets of thermal modification is to increase the biological durability of wood. Viitanen *et al.* (1994) reported that the decay resistance to brown-rot fungus *Coniophora puteana* according to EN 113 and soft-rot fungi according to prENV807 in thermally modified spruce was significantly improved, depending on the level of the thermal modification. Weiland and Guyonnet (2003) also used an EN 113 standard test and detected that resistance to fungal degradation in maritime pine and beech increased by 43% and 74%, respectively, compared with untreated wood. Hakkou *et al.* (2006) found an important correlation between the biological durability and temperature of thermal modification. Improved biological durability in different thermally modified wood species was also reported by Sailer *et al.* (2000), Kamdem *et al.* (2002), Edlund and Jermer (2004), Jones *et al.* (2006) and Mburu *et al.* (2006).

According to the published papers, there may be several reasons for the increased biological durability of thermally modified wood. During thermal modification the wood becomes more hydrophobic, which limits the absorption of water into the wood and may prevent fungal growth. Thermal modification changes the chemical composition of wood, making it more difficult for fungi to attack the wood material, and it may also generate new extractives, which may act as fungicides. Wood polymers may also be modified or degraded in thermal modification and for this reason the wood cannot be used as a nutritive source by decay fungi (Kotilainen, 2000; Weiland & Guynnoet, 2003).

It has long been known that the chemical composition and physical and biological properties of heartwood are different from those of the sapwood within many wood species. The sapwood of many softwoods, for instance, contains fewer extractives than the heartwood (Fengel & Wegener, 1984). A relatively high percentage of phenolic substances, pinosylvins and acetone-soluble extractives, particularly resin acids, protects the wood against microbiological attack (Sjöström, 1993; Harju *et al.*, 2003; Venäläinen *et al.*, 2003). The water permeability and hygroscopicity of heartwood are smaller than those of sapwood, and this may reduce the potential fungal growth and activity in wood (Kollmann & Côté, 1968).

Viitanen *et al.* (2006) studied the fungal resistance to *C. puteana* in the sapwood and heartwood of uncoated and coated Scots pine and Norway spruce. Significant differences were observed between the decay resistance of sapwood and heartwood, particularly within pine. The origin of the wood also strongly affected the decay resistance. Nuopponen (2005) discovered that thermal modification at high temperatures (>200°C) removes extractives, particularly resin acids, from wood. Therefore, the amount of resin acids may not be the most critical factor for the decay resistance of thermally modified wood. The decay resistance of thermally modified heartwood has been less studied. The aim of this study was to determine the differences in decay resistance of sapwood and heartwood of Scots pine and Norway spruce thermally modified at different temperatures. The results were compared with the results for other wood species, such as Siberian larch, bangkirai, merbau and western red cedar (WRC).

Materials and methods

Materials

Test planks of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were selected from Finnish sawmills. The planks were industrially kiln-dried at a temperature of approximately 70°C to a moisture content of 11–15%. Half of the planks were sawn from the sapwood part of the logs and half from the heartwood. The selection criteria were the cleanness of the sapwood or heartwood, small variation in the year rings' width and density and good quality of the sawn timber. The test material was made from pure sapwood and heartwood and were thermally modified using the ThermoWood® method at VTT (Finland). A detailed description of the thermal modification method is reported in another publication (Metsä-Kortelainen *et al.*, 2006). Thermal modifications were carried out at four different temperatures (170°C, 190°C, 210°C and 230°C) under a steam atmosphere. The time of thermal modification at the target temperature was 3 h in every test run. Specimens used in the decay tests were sawn out from 1.2 m long planks, but not until the thermal modifications were carried out. In addition, untreated wood material from four different wood species (Siberian larch, merbau, bangkirai and WRC) was used as reference material in the soft-rot test. These wood materials were industrial kiln dried and delivered by a Finnish timber company.

Decay test against soft-rot fungi

The natural durability against the soft-rot microfungi of untreated and thermally modified sapwood and heartwood of Scots pine and Norway spruce and reference wood species (Siberian larch, merbau, bangkirai and WRC) was determined according to CEN/TS 15083-2 (2005). Small specimens ($5 \times 10 \times 100$ mm^3) were inserted into containers with unsterile soil. The incubation time was 32 weeks.

The test specimens of sapwood and heartwood of Scots pine and Norway spruce were sawn from eight different 1.2 m long test planks of each wood material thermally modified at VTT; 40 replicate specimens from each wood material were used, of which 30 were used in the decay test and 10 were used in determination of moisture content. In addition, 30 reference specimens of Scots pine sapwood were prepared. Specimens of other reference wood species were sawn from one to three replicate planks. The total number of test specimens was 720 and the number of moisture content specimens was 240.

All the specimens were conditioned at 65% relative humidity (RH) and 20°C to constant mass and weighed. The moisture content specimens and reference specimens were dried at 103°C for 24 h and weighed. The moisture content was calculated by expressing the mass of water ($w_u - w_{dry}$) as a percentage of the oven-dry mass (w_{dry}). The mean moisture content of the moisture content specimens was calculated and used in the calculation of the initial dry mass of each test timber specimen according to CEN/TS 15083-2 (2005).

The test timber specimens and the reference timber specimens were impregnated with water and left in the vessels for 2 h. The modulus of elasticity (MOE) was determined with a static bending test using a central loading method according to EN 408 (1995). The bending test was carried out very carefully without breaking the specimens using a span of 80 mm, a loading speed of 1 mm min^{-1} and maximal deformation of 0.5–1 mm, and the slope was calculated between the flexure load difference of 10–40 N on the straight line portion of the deformation curve. The MOE was calculated according to eq. (1). After the bending test the specimens were conditioned to approximately 50% moisture content based on their initial dry mass and dipped 80 mm vertically in containers with unsterile soil. The soil was compost based and its water-holding capacity was 51.7%.

$$\text{MOE (Nmm}^{-2}) = \frac{(F_2 - F_1) \times l^3}{4 \times (w_2 - w_1) \times b \times h^3} \quad (1)$$

where $F_2 - F_1$ is the increment of load on the straight-line portion of the deformation curve (N), l is the span (mm), $w_2 - w_1$ is the increment of deformation corresponding to $F_2 - F_1$ (mm), b is the width of the specimen (mm), and h is the height (thickness) of the specimen (mm).

The containers were incubated in a conditioning chamber at 27°C and 70% RH. After 32 weeks of incubation the specimens were cleaned of adhering soil particles and weighed. The MOE was determined in a similar way to before the incubation and the specimens were then dried at 103°C for 24 h and weighed. The moisture content after the test, and the mass and MOE loss were calculated and expressed as a percentage of their initial values.

The results of the soft-rot test were classified into durability classes based on the calculated X value (eq. 2). The durability classes are shown in Table I.

$$X = \frac{\text{Median value of MOE loss for test timber specimens}}{\text{Median value of MOE loss for reference timber specimens}} \quad (2)$$

Table I. Durability rating scale according to CEN/TS 15083-2 (2005).

Durability class	Description	X value
1	Very durable	≤0.10
2	Durable	>0.10 to ≤0.20
3	Moderately durable	>0.20 to ≤0.45
4	Slightly durable	>0.45 to ≤0.80
5	Not durable	>0.80

Decay test against brown-rot fungi

Thermally modified sapwood and heartwood of Scots pine and Norway spruce were exposed to brown-rot fungi *C. puteana* and *Poria placenta* essentially according to a mini-decay test (Bravery, 1979). The sample size was smaller and incubation time shorter than normally is used in the standardized tests [EN 350-1 (1994), EN 113 (1996) and CEN/TS 15083-1 (2005)]. In the previous studies on resistance of pine heartwood, similar tests with smaller specimens and shorter incubation times have been performed by VTT and published by Harju *et al.* (2003), Venäläinen *et al.* (2003) and Viitanen *et al.* (2006). A relevant dependence between mass loss and incubation time used in these studies has been detected.

The size of the test specimens was 5 × 20 × 35 mm^3 and incubation times were 6 and 10 weeks. Four replicates for every wood material were used in the test with *P. placenta* (FPRL 280) and eight with

C. puteana (BAM, Ebw 15). The total number of specimens was 640. The specimens were conditioned at 65% RH and 20°C to constant mass and then dried at 60°C for 48 h, after which they were cooled in a desiccator and weighed to an accuracy of 1 mg. The specimens were sterilized under steam as mentioned in the standard EN 113 (1996) and CEN/TS 15083-1 (2005), and subjected to a mini-decay test on agar using rubber underlay between the agar and wood sample. After the decay test the specimens were weighed and then dried at 103°C for 24 h and weighed again for the calculation of mass loss and moisture content according to CEN/TS 15083-1 (2005).

The results of the brown-rot test were classified into durability classes based on the median mass losses according to CEN/TS 15083-1 (2005). The durability classes are shown in Table II.

Table II. Durability rating scale according to CEN/TS 15083-1 (2005).

Durability class	Description	% loss in mass
1	Very durable	≤5
2	Durable	>5 to ≤10
3	Moderately durable	>10 to ≤15
4	Slightly durable	>15 to ≤30
5	Not durable	>30

Results and discussion

Soft-rot test

The density of the soft-rot test specimens (at 65% RH and 20°C, nominal dimensions), moisture content before and after the soft-rot test, median MOE loss, calculated X value and durability class of the soft-rot decay test samples are presented in Table III. Each value is the mean of 30 replicate specimens. The median MOE loss of the reference specimens of pine sapwood was 64.8% (this value was used in calculation of the X values) and the mean MOE loss of the same samples was 64.9%, which exceeds the minimum validity limit (40%) of the decay test according to the standard CEN/TS 15083-2 (2005). In addition, the presence of soft rot was confirmed under light microscopy.

The mass and MOE losses in the soft-rot test are presented in Figures 1–5. Each column or point represents the average value and standard deviation of 30 replicates. The correlation between the two different evaluation methods, mass loss and MOE loss, is shown in Figure 6.

Table III shows that the density of the spruce and pine was reduced as a consequence of the weight loss taking place during the thermal modification. In addition, the reduction in the equilibrium moisture content (65% RH and 20°C) strongly depends on the thermal modification temperature. The moisture content of the thermally modified samples after the test was slightly lower than that of the untreated ones. This dependence of equilibrium moisture content on the level of thermal modification was first shown by Viitaniemi and Jämsä (1996).

In general, the thermal modification increased the decay resistance of the wood material (Figures 1–4). The mass loss and MOE loss differences between the sapwood and the heartwood were more evident with pine than with spruce. The differences between sapwood and heartwood of spruce were not significant. It seems that a sufficiently high thermal modification temperature of 210–230°C reduces the differences between different wood materials and gives clearly better decay resistance.

According to the present results from the soft-rot test in soil contact, the untreated heartwood of pine is also classified in the lowest durability class 5, as are the untreated pine sapwood and both spruce materials (Table III). In general, only bangkirai and merbau were more durable than heartwood of pine (Figure 5). A very interesting observation is that the mass loss of larch was at the same level as the values of untreated pine sapwood and spruce. However, the MOE loss of larch was even better than that of untreated pine heartwood and therefore larch was classified in durability class 4 (Table III).

Thermal modification very significantly affects the biological durability. The durability classes 2 and 3 in the soft-rot test can be reached with both spruce materials and sapwood of pine, respectively, by means of thermal modification at high enough temperatures, over 230°C. Pine heartwood thermally modified at this very high temperature can be classified into the best durability class 1. Thermal modification at the lower temperatures of 190°C and 210°C, which are commonly used in Finnish industry, increases the biological durability of pine sapwood and spruce (Figures 1–3), but the wood material is still classified into the durability classes "not durable" or "slightly durable" (Table III).

According to the standard EN 350, parts 1 and 2 (1994), untreated pine, spruce, larch, merbau, WRC and bangkirai are classified into the natural durability classes 3–4, 4, 3–4, 1–2, 2–3 and 2, respectively. The results of the soft-rot test seem to give worse durability classes than is determined for these wood species in the standard EN 350. The soft-rot test seems to be a very hard test because it was originally intended to measure the resistance of wood preservatives against soft-rot fungi. The test may even be too hard for wood species from durability class 3 or lower (4 and 5) to measure the natural durability.

Table III. Density, moisture content before and after decay test, median MOE loss, calculated *X* value and durability class of the soft-rot samples.

	Thermal modification (°C)	Density (kg/m^3)	Moisture content (%) RH 65%	Moisture content (%) After test	Median MOE loss (%) Test timber	*X* value	Durability class
Spruce, sapwood	Untreated	445.9	11.5	273.9	72.0	1.11	5
	170°C	430.5	9.8	266.0	71.4	1.10	5
	190°C	423.4	9.1	247.9	59.5	0.92	5
	210°C	412.6	7.4	231.3	36.9	0.57	4
	230°C	384.2	6.7	221.8	7.7	0.12	2
Spruce, heartwood	Untreated	434.3	11.6	276.4	69.8	1.08	5
	170°C	448.9	8.8	241.1	63.8	0.98	5
	190°C	429.1	9.0	235.3	52.8	0.81	5
	210°C	414.1	7.4	224.8	34.3	0.53	4
	230°C	381.4	5.8	221.1	7.3	0.11	2
Pine, sapwood	Untreated	501.3	11.4	247.0	69.6	1.07	5
	170°C	489.8	9.9	238.7	69.0	1.06	5
	190°C	478.6	8.5	229.2	65.8	1.01	5
	210°C	488.6	7.4	192.5	39.0	0.60	4
	230°C	475.8	6.3	181.9	19.9	0.31	3
Pine, heartwood	Untreated	554.1	11.0	192.4	53.6	0.83	5
	170°C	551.4	8.1	183.9	55.7	0.86	5
	190°C	524.4	7.9	182.3	43.5	0.67	4
	210°C	519.5	6.9	166.8	22.9	0.35	3
	230°C	466.7	5.7	175.3	6.6	0.10	1
Larch	Untreated	647.3	11.7	176.1	49.0	0.76	4
Bangkirai	Untreated	943.4	10.4	87.2	35.2	0.54	4
Merbau	Untreated	1119.1	10.3	61.2	21.0	0.32	3
WRC	Untreated	379.2	8.8	300.6	53.6	0.83	5

Note: MOE = modulus of elasticity; RH = relative humidity; WRC = western red cedar.

According to this research, differences between mass and MOE losses were, however, detected with untreated and thermally modified wood materials. Despite this, there were not equally important differences between durability classes of these wood materials rated with the scale determined in the standard, except for the results for thermally modified heartwood of pine.

The correlation between loss of mass and MOE is very high (Figure 6). This confirms the view that it is possible to measure MOE loss many times during the incubation of the soft-rot test to measure the durability and resistance of the test samples.

Brown-rot test

The mass losses in the brown-rot tests with *C. puteana* and *P. placenta* are presented in Figures 7–10. Each value is the mean of four (*P. placenta*) or eight (*C. puteana*) replicates. The median mass losses and

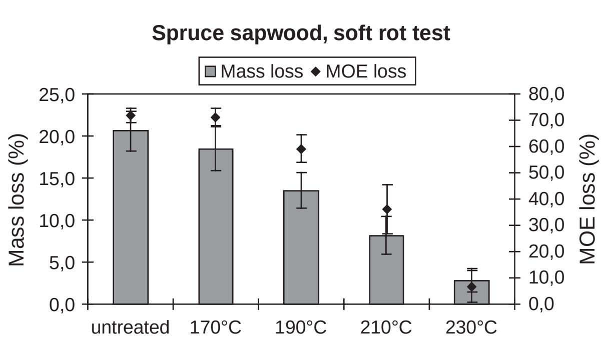

Figure 1. Mass and modulus of elasticity (MOE) losses of spruce sapwood after 32 weeks' incubation, soft-rot test.

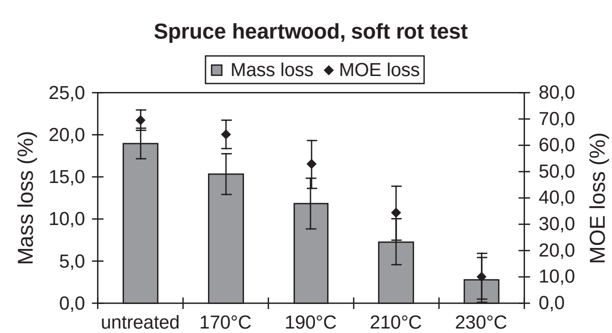

Figure 2. Mass and modulus of elasticity (MOE) losses of spruce heartwood after 32 weeks' incubation, soft-rot test.

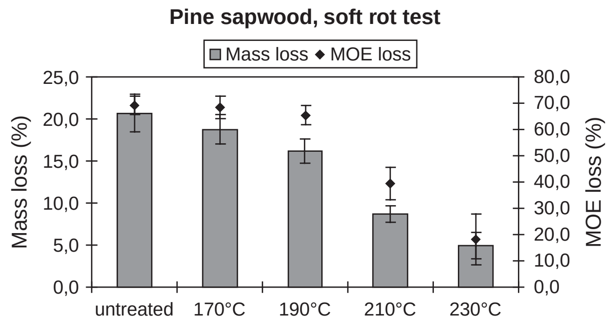

Figure 3. Mass and modulus of elasticity (MOE) losses of pine sapwood after 32 weeks' incubation, soft-rot test.

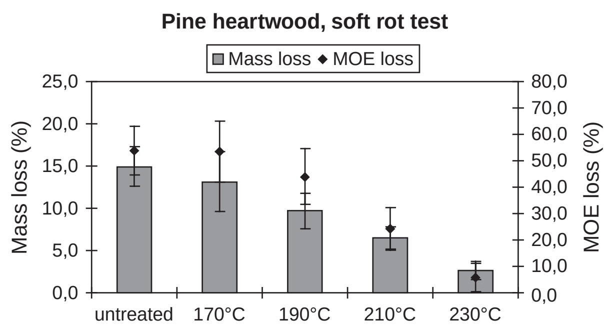

Figure 4. Mass and modulus of elasticity (MOE) losses of pine heartwood after 32 weeks' incubation, soft-rot test.

the durability classes according to CEN/TS 15083-1 (2005) are presented in Table IV.

In general, the heartwood of pine was also the most durable wood material in the brown-rot test. There was no significant difference between the decay resistance of sapwood and heartwood of spruce and sapwood of untreated pine. Thermal modification clearly increased the decay resistance to brown-rot fungi in all pine and spruce materials. The higher the thermal modification temperature, the more the biological durability was increased. This confirm the previous results on the positive effect of heat treatment on the decay resistance against brown rot (Viitanen *et al.*, 1994).

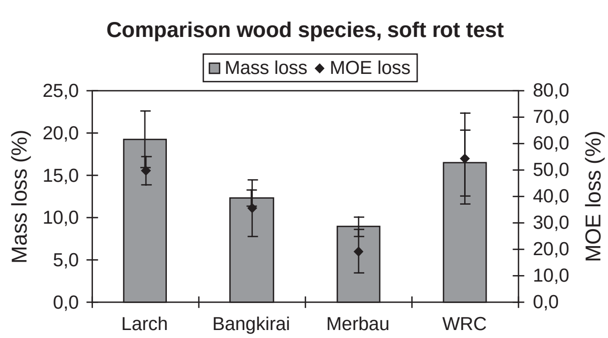

Figure 5. Mass and modulus of elasticity (MOE) losses of comparison wood species (Siberian larch, bangkirai, merbau and western red cedar) after 32 weeks' incubation, soft-rot test.

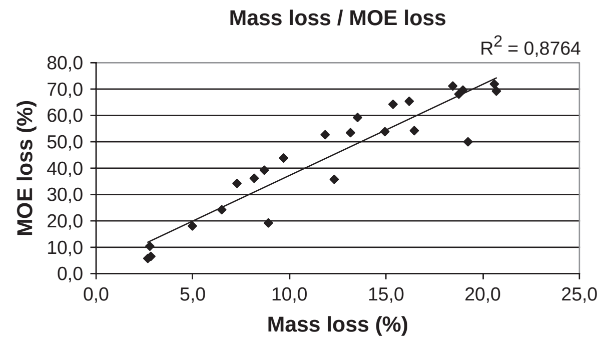

Figure 6. Correlation between mass loss and modulus of elasticity (MOE) loss, soft-rot test.

Poria placenta fungus was more aggressive than *C. puteana* against thermally modified wood, but after 10 weeks' exposure *C. puteana* caused mass losses in untreated wood the same as or higher than *P. placenta*. The differences between two brown-rot fungi were evident with spruce material when the thermal modification temperature was 210°C and the incubation time 10 weeks. The thermal modification of pine sapwood and heartwood at 210–230°C outstandingly improved the resistance to brown-rot fungi. The mass losses of all wood materials were near to 0 when the samples were modified at 230°C, and the decay resistance was comparable with the durability class "very durable" (Table IV).

The exposure time also significantly affected the mass losses and decay resistance (Figures 7–10). After 6 weeks' exposure the mass losses of different wood material were clearly smaller than after a longer incubation time. The exposure time may be used for the measurement of environmental severity during use of wooden products. In this study different exposure times were used for evaluating the biological resistance, and the results indicated that in the lower exposure situation of use class 3 (fences, façades) the durability of wood thermally modified at lower temperatures may be sufficient for acceptable requirements during its service life.

General remarks on the results

On average, the biological durability of pine heartwood is better than that of pine sapwood and spruce, especially in use class 3 conditions, e.g. aboveground contact, but wide variation may exist (Viitanen *et al.*, 2006). In very severe exposure conditions, such as ground contact, the difference between the resistance of pine heartwood and that of pine sapwood and spruce is clearly smaller (Augusta & Rapp, 2003).

The intended use should be taken into account when determining the required biological durability.

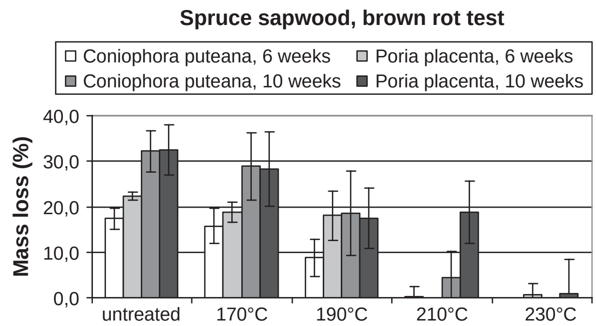

Figure 7. Mass loss of spruce sapwood after 6 and 10 weeks' brown-rot test with *Coniophora puteana* and *Poria placenta*.

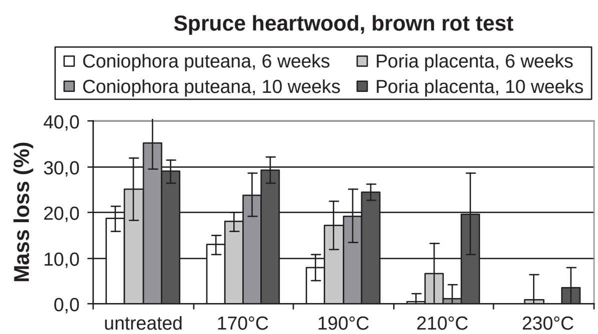

Figure 8. Mass loss of spruce heartwood after 6 and 10 weeks' brown-rot test with *Coniophora puteana* and *Poria placenta*.

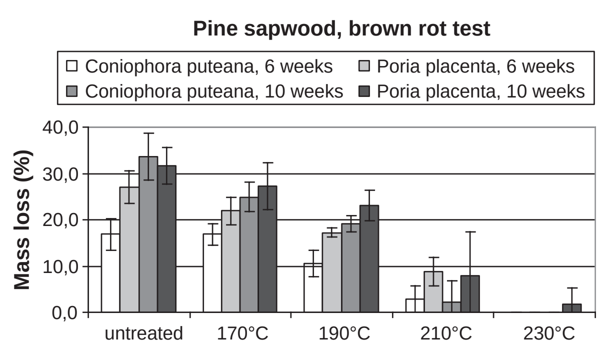

Figure 9. Mass loss of pine sapwood after 6 and 10 weeks' brown-rot test with *Coniophora puteana* and *Poria placenta*.

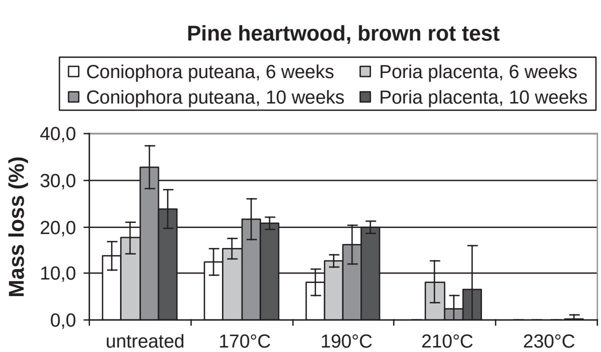

Figure 10. Mass loss of pine heartwood after 6 and 10 weeks' brown-rot test with *Coniophora puteana* and *Poria placenta*.

EN 335-1 (2006) presents the use classes representing different service situations to which wood and wood-based products can be exposed. It also indicates the biological agents relevant to each situation and use condition (1–5). The use condition in ground contact is ranked a high exposure condition (class 4) and the soft-rot test has been proposed to represent the biological exposure conditions under this use condition. The use class 3, wood above ground, is much wider and there are varied and very different use conditions. The test method using brown-rot fungi is proposed to represent partly this use condition, especially in the most exposed conditions such as terraces and jetties. However, in use class 3, the required resistance to decay is most often linked to the moisture damage conditions (decay damage) or high exposure situations. For these aspects, new opportunities to use the present test methods should be found and the results of different exposure times used during the tests should be taken into account more often for evaluating the durability needed in different intended use conditions. The coating may also have an important role in the resistance of wood against decay (Viitanen *et al.*, 2006). The coating will decrease the water absorption and weathering effect, but in damage cases, the coating may also accelerate the decay if water is accumulated into the wood.

Thermal modification at very high temperatures (over 230°C) also has an effect on the other properties of wood. For instance, the strength properties are reduced, the wood becomes more brittle and the colour turns dark (Viitaniemi & Jämsä, 1996). Even though the biological durability of wood increases and water absorption decreases a great deal with thermal modification at high temperatures, the other properties may have an unfavourable effect on the usability of the wood material. The selection of the thermal modification temperature is a compromise between improved durability and reduced other properties. It can be concluded that thermal modification at 210°C does not reduce the strength properties significantly (Finnish ThermoWood Association, 2003), but it does improve the biological durability of Scots pine and Norway spruce to the level of merbau in the soft-rot test. Thermally modified pine heartwood in particular may be a potential material for applications where improved biological durability is needed.

Conclusions

In general, both decay tests, soft-rot and brown-rot tests gave quite similar results. The untreated heartwood of Scots pine was more durable against decay organisms than the sapwood of Scots pine and the

Table IV. Median mass losses and the durability classes of the brown-rot test samples.

		Coniophora puteana, 6 weeks		*Poria placenta*, 6 weeks		*Coniophora puteana*, 10 weeks		*Poria placenta*, 10 weeks	
	Thermal modification (°C)	Median mass loss (%)	Durability class	Median mass loss (%)	Durability class	Median mass loss (%)	Durability class	Median mass loss (%)	Durability class
Spruce, sapwood	Untreated	17.4	4	22.0	4	31.3	5	32.6	5
	170°C	16.1	4	18.5	4	28.7	4	26.6	4
	190°C	9.6	2	18.0	4	20.8	4	14.9	3
	210°C	0.1	1	0.0	1	3.4	1	21.4	4
	230°C	0.0	1	0.0	1	0.0	1	4.6	1
Spruce, heartwood	Untreated	17.9	4	27.6	4	34.7	5	28.6	4
	170°C	13.3	3	17.2	4	24.2	4	28.3	4
	190°C	8.7	2	18.1	4	21.1	4	24.6	4
	210°C	0.0	1	7.5	2	0.2	1	22.1	4
	230°C	0.0	1	0.0	1	0.0	1	2.5	1
Pine, sapwood	Untreated	16.9	4	28.1	4	34.1	5	31.3	5
	170°C	15.7	4	22.3	4	24.8	4	27.6	4
	190°C	11.5	3	17.1	4	18.7	4	23.1	4
	210°C	2.1	1	9.0	2	0.3	1	8.1	2
	230°C	0.0	1	0.0	1	0.0	1	0.3	1
Pine, heartwood	Untreated	14.3	3	17.0	4	32.7	5	24.6	4
	170°C	13.9	3	16.3	4	21.9	4	21.2	4
	190°C	7.4	2	12.6	3	14.9	3	19.9	4
	210°C	0.0	1	8.8	2	1.9	1	3.5	1
	230°C	0.0	1	0.0	1	0.0	1	0.2	1

sapwood or heartwood of Norway spruce. The differences between sapwood and heartwood were more significant within pine than within spruce material. The thermal modification significantly increased the decay resistance of all pine and spruce samples. The higher the level of thermal modification, in other words the modification temperature, the better the biological durability. However, a very high thermal modification temperature, over 230°C, was needed to reach resistance equal to durability class 1 or 2 (durable or very durable) in the soft-rot test. Merbau was the most durable of the group of reference wood species and was classified into durability class 3 (moderately durable). The other reference wood species were classified into durability class 4 or 5 (slightly durable or not durable). The brown-rot test gave slightly better durability classes than the soft-rot test. Thermal modification at 210°C was enough to increase the durability of pine and spruce into durability classes 1 and 2 in almost every case.

The intended use should be taken into account in the evaluation of the test results and biological durability needed. One optional solution to evaluate the resistance level of different wooden products may be to use the test results after different exposure times during the accelerated tests.

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References

Augusta, U. & Rapp, A. O. (2003). *The natural durability of wood in different use classes* (Doc. No. IRG/WP/03-10457). International Research Group on Wood Preservation.

Bekhta, P. & Niemz, P. (2003). Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. *Holzforschung*, *57*, 539–546.

Boonstra, M. J. & Tjeerdsma, B. (2006). Chemical analysis of heat treated softwoods. *Holz als Roh- und Werkstoff*, *64*, 204–211.

Bravery, A. F. (1979). *A miniaturised wood-block test for rapid evaluation of wood preservative fungicides* (Doc. No. IRG/WP 2113). International Research Group on Wood Preservation.

CEN/TS 15083-1 (2005). *Durability of wood and wood-based products—Determination of the natural durability of solid wood against wood-destroying fungi, test methods. Part 1: Basidiomycetes*. Brussels: European Committee for Standardization.

CEN/TS 15083-2 (2005). *Durability of wood and wood-based products—Determination of the natural durability of solid wood against wood-destroying fungi, test methods. Part 2: Soft-rotting micro-fungi*. Brussels: European Committee for Standardization.

Edlund, M.-L. & Jermer, J. (2004). Durability of heat-treated wood. *COST Action E22 Environmental Optimisation of Wood Protection*, Lisbon, Portugal, March 22–23, 2004.

EN 113 (1996). *Wood preservatives—Test method for determining the protective effectiveness against wood destroying basidiomycetes—Determination of the toxic values*. Brussels: European Committee for Standardization.

EN 335-1 (2006). *Durability of wood and wood-based products—Definition of use classes. Part 1: General*. Brussels: European Committee for Standardization.

EN 350-1 (1994). *Durability of wood and wood-based products—Natural durability of solid wood. Part 1: Guide to the principles of testing and classification of the natural durability of wood*. Brussels: European Committee for Standardization.

EN 350-2 (1994). *Durability of wood and wood-based products—Natural durability of solid wood. Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe*. Brussels: European Committee for Standardization.

EN 408 (1995). *Timber structures—Structural timber and glued laminated timber—Determination of some physical and mechanical properties*. Brussels: European Committee for Standardization.

Fengel, D. & Wegener, G. (1984). *Wood: Chemistry, ultrastructure, reactions*. Berlin: Walter de Gruyter & Co.

Finnish ThermoWood Association (2003). *ThermoWood handbook*. Retrieved from http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

Hakkou, M., Pétrissans, M., Zoulalian, A. & Gérardin, P. (2005). Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. *Polymer Degradation and Stability*, *89*, 1–5.

Hakkou, M., Pétrissans, M., Gérardin, P. & Zoulalian, A. (2006). Investigations of the reasons for fungal durability of heat-treated beech wood. *Polymer Degradation and Stability*, *91*, 393–397.

Harju, AM., Venäläinen, M., Anttonen, S., Viitanen, H., Kainulainen, P., Saranpää, P. & Vapaavuori, E. (2003). Chemical factors affecting the brown-rot decay resistance of Scots pine heartwood. *Trees*, *17*, 263–268.

Jones, D., Suttie, E., Ala-Viikari, J., Bergstrom, N. & Mayes, D. (2006). *The commercialisation of ThermoWood® products* (Doc. No. IRG/WP 06-40339). International Research Group on Wood Preservation.

Jämsä, S., Ahola, P. & Viitaniemi, P. (2000). Long-term natural weathering of coated ThermoWood. *Pigment & Resin Technology*, *29*, 68–74.

Kamdem, D. P., Pizzi, A. & Jermannaud, A. (2002). Durability of heat-treated wood. *Holz als Roh- und Werkstoff*, *60*, 1–6.

Kollmann, F. F. & Côté, W. A. (1968). *Principles of wood science and technology. I: Solid wood*. Berlin: Springer.

Kotilainen, R. (2000). *Chemical changes in wood during heating at 150–260°C*. Doctoral thesis, University of Jyväskylä, Finland.

Mburu, F., Dumarcay, S., Huber, F., Petrissans, M. & Gérardin, P. (2006). *Improvement of Grevillea robusta durability using heat treatment* (Doc. No. IRG/WP 06-40333). International Research Group on Wood Preservation.

Metsä-Kortelainen, S., Antikainen, T. & Viitaniemi, P. (2006). The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170°C, 190°C, 210°C and 230°C. *Holz als Roh- und Werkstoff*, *64*, 192–197.

Nuopponen, M. (2005). *FT-IR and UV Raman spectroscopic studies on thermal modification of Scots pine wood and its extractable compounds*. Doctoral thesis, Helsinki University of Technology, Finland.

Pétrissans, M., Gérardin, P., El bakali, I. & Serraj, M. (2003). Wettability of heat-treated wood. *Holzforschung*, *57*, 301–307.

Repellin, V. & Guyonnet, R. (2005). Evaluation of heat-treated wood swelling by differential scanning calorimetry in relation to chemical composition. *Holzforschung*, *59*, 28–34.

Sailer, M., Rapp, A. O., Leithoff, H. & Peek, R.-D. (2000). Vergütung von Holz durch Anwendung einer Öl-Hitzebehandlung. *Holz als Roh- und Werkstoff*, *58*, 15–22.

Sjöström, E. (1993). *Wood chemistry, fundamentals and applications*. San Diego, CA: Academic Press.

Venäläinen, M., Harju, A. M., Kainulainen, P., Viitanen, H. & Nikulainen, H. (2003). Variation in the decay resistance and its relationship with other wood characteristics in old Scots pines. *Annals of Forest Science*, *60*, 409–417.

Viitanen, H., Jämsä, S., Paajanen, L., Nurmi, A. & Viitaniemi, P. (1994). *The effect of heat treatment on the properties of spruce* (Doc. No. IRG/WP 94-40032). International Research Group on Wood Preservation.

Viitanen, H., Metsä-Kortelainen, S. & Laakso, T. (2006). *Resistance of pine and spruce against decay—The effect of wood chemical composition and coating with water-borne wood oil product* (Doc. No. IRG/WP 06-10597). International Research Group on Wood Preservation.

Viitaniemi, P. (1997*a*). ThermoWood—Modified wood for improved performance. In *Proceedings of the 4th Eurowood Symposium, Wood—The Ecological Material*, Stockholm, Sweden (Trätek Rapp. No. P9709084, pp. 67–69).

Viitaniemi, P. (1997*b*). Decay-resistant wood created in a heating process—A heat-treatment process of wood developed by VTT Building Technology yields timber products with enhanced properties. *Industrial Horizons*, (December), 22–23.

Viitaniemi, P. & Jämsä, S. (1996). *Puun modifiointi lämpökäsittelyllä* [Modification of wood with heat treatment]. Espoo: VTT Publications, 814. (In Finnish with English abstract.)

Viitaniemi, P., Jämsä, S., Vuorinen T., Sundholm F., Paakkari T. & Paajanen L. (2002). Reaction mechanisms of modified wood. In Paavilainen, L. (Ed.) & Marttila, S. (Assistant Ed.), *Final Report, Finnish Forest Cluster Research Programme WOOD WISDOM (1998–2001)*, Helsinki, 2002 (Rep. 3, pp. 185–192).

Weiland, J. J. & Guyonnet, R. (2003). Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. *Holz als Roh- und Werkstoff*, *61*, 216–220.

Wikberg, H. (2004). *Advanced solid state NMR spectroscopic techniques in the study of thermally modified wood*. Doctoral thesis, University of Helsinki, Finland.