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Effect of fungal exposure on the strength of thermally modified Norway spruce and Scots pine

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ORIGINAL ARTICLE

Effect of fungal exposure on the strength of thermally modified Norway spruce and Scots pine

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Abstract
Thermal modification at elevated temperatures changes the chemical, biological and physical properties of wood. In this study, the effects of the level of thermal modification and the decay exposure (natural durability against soft-rot microfungi) on the modulus of elasticity (MOE) and modulus of rupture (MOR) of the sapwood and heartwood of Scots pine and Norway spruce were investigated with a static bending test using a central loading method in accordance with EN 408 (1995). The results were compared with four reference wood species: Siberian larch, bangkirai, merbau and western red cedar. In general, both the thermal modification and the decay exposure decreased the strength properties. On average, the higher the thermal modification temperature, the more MOE and MOR decreased with unexposed samples and increased with decayed samples, compared with the unmodified reference samples. The strength of bangkirai was least reduced in the group of the reference wood species. On average, untreated wood material will be stronger than thermally modified wood material until wood is exposed to decaying fungi. Thermal modification at high temperatures over 210°C very effectively prevents wood from decay; however, strength properties are then affected by thermal modification itself.

Keywords: *Bending strength, decay resistance, heartwood, modulus of elasticity, modulus of rupture, Norway spruce, sapwood, Scots pine, soft rot, thermal modification.*

Introduction

Thermal modification of wood is a process where the biological durability of wood is enhanced. In above-ground applications (use class 2 and 3 conditions), it is an alternative method for the traditional pressure impregnation of wood. Different methods for the thermal modification of wood have been developed in France, Finland, the Netherlands and Germany. One of these processes, developed in Finland, is referred to as the ThermoWood® process, which is environmental friendly with no toxic chemicals used. This method is based on heating the wood material for a few hours at high temperatures of over 180°C under normal pressure, using water vapour as a shielding gas.

Thermally modified wood is incorporated in many use class 2 and 3 applications, where enhanced dimensional stability and biological durability are needed, owing to high humidity exposure. In addition, the brown colour of thermally modified wood is seen as a benefit in indoor furnishing. There are plenty of good experiences of using thermally modified timber in many different applications, such as exterior cladding, covered decking, flooring, garden furniture, panelling, kitchen furnishing, and the interiors of bathrooms and sauna baths. However, some problems have also been detected in existing applications with high moisture exposure, e.g. the wood material may have reached very high moisture content (MC), the surface of wood may have become unaesthetic, or the strength of the material may have been weakened and a plank may have suddenly broken. This confirms that more research is needed for the further development of thermal modification processes and to find out more detailed properties and suitable end-use applications of thermally modified wood.

The effect of thermal modification on the mechanical properties of wood has been widely studied.

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The change in mechanical properties is a consequence of changes in the wood's chemical composition. As a result of thermal modification, the wood becomes more brittle, and bending and tension strength decrease in relation to the level of thermal modification (Viitaniemi & Jämsä, 1996; Santos, 2000; Kamdem *et al.*, 2002; Militz, 2002). In many studies, the bending strength [modulus of rupture (MOR)] was decreased significantly, whereas there was no or only a slight effect (decrease or increase) on the modulus of elasticity (MOE). For instance, Bekhta and Niemz (2003) heat-treated spruce wood at temperatures between 100 and 200°C, which decreased bending strength by 44–50%, while the modulus of elasticity was reduced by only 4–9%. In addition, Esteves *et al.* (2007*a*) found 40% and 50% decreases in bending strength for pine and eucalypt wood, respectively, while the MOE was little affected. Reduced strength properties have also been reported by Kubojima *et al.* (2000), Poncsák *et al.* (2006), Sundqvist *et al.* (2006), Boonstra *et al.* (2007*a*), Esteves *et al.* (2007*b*), Shi *et al.* (2007) and Korkut *et al.* (2008).

The improved fungal resistance of thermally modified wood has been reported by Viitanen *et al.* (1994), Sailer *et al.* (2000), Kamdem *et al.* (2002), Hakkou *et al.* (2006), Welzbacher and Rapp (2005, 2007), Jones *et al.* (2006), Mburu *et al.* (2006) and Boonstra *et al.* (2007*b*). However, depending on the level of the thermal modification, some degradation of wood components takes place in the event that thermally modified wood is exposed to fungal attack. Sivonen *et al.* (2003) studied the chemical properties of thermally modified Scots pine exposed to brown- and soft-rot fungi and found that, as with the untreated wood, brown-rot fungi degraded mainly hemicelluloses while soft-rot fungus attacked cellulose more extensively. Mass loss caused by fungal attack was dependent on the modification temperature. Weiland and Guyonnet (2003) also found that in spite of strong hemicellulose degradation by the thermal modification, the fungal attack still takes place. In addition, the degradation of wood components caused by decaying fungi decreases the mechanical properties of wood (Fengel & Wegener, 1989; Curling *et al.*, 2002).

In previous studies, the water absorption and the fungal resistance of sapwood and heartwood of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) thermally modified at four different temperatures were studied (Metsä-Kortelainen *et al.*, 2006; Metsä-Kortelainen & Viitanen, 2009). In general, thermal modification reduced the water absorption and increased the fungal resistance of wood in relation to the level of the thermal modification. However, highly significant water absorption and mass loss differences between sapwood and heartwood of Scots pine and Norway spruce were detected in these studies. The differences between sapwood and heartwood of spruce were significantly smaller than with pine. According to these studies, it can be concluded that the effect of the wood part (sapwood/heartwood) has an important effect on the properties of wood, whether it is thermally modified or not.

It is known that both the thermal modification itself and the degradation of wood components in fungal exposure reduce the mechanical properties of wood. The strength of decayed thermally modified wood is a combination of these two parameters. The aim of this study was to determine the bending strength (MOR) and (MOE) of unexposed and soft-rotted sapwood and heartwood of Scots pine and Norway spruce thermally modified at several temperatures. The results of the bending test are compared with the results of water absorption test and decay test with soft-rot fungi using principal component analysis (PCA).

Materials and methods

Materials

For the decay exposure in the laboratory and the bending strength test, pure sapwood and heartwood without juvenile wood of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) were selected from the Finnish sawmill industry. The target was to have research material with good quality and small variation in the width of year-rings. The selected wood material was industrially kiln-dried at an approximate temperature of 70°C to a MC of 11–15% before it was thermally modified at VTT using the ThermoWood® method. Thermal modifications were carried out at four different temperatures (170°C, 190°C, 210°C, 230°C) under a steam atmosphere. A detailed description of the selection of the research material and the thermal modification procedures is reported in another publication (Metsä-Kortelainen *et al.*, 2006). In addition, industrially kiln-dried Siberian larch, merbau, bangkirai and western red cedar (WRC) were selected for the experiments as untreated reference material since these wood species are partly used in the same, mainly exterior, applications. The origin of this reference wood material is not known in more detail because it was delivered by a Finnish timber company.

Decay exposure and bending strength test

To determine the bending strength of the wood material, small specimens ($5 \times 10 \times 100\ mm^3$) were used. The longitudinal faces of the specimens were parallel to the direction of the grain. Half of the specimens chosen for the bending strength test were unexposed reference material conditioned at 65% relative humidity (RH) and 20°C to constant mass and weighed. The other half of the specimens for the strength test were selected from the material that had been exposed for 32 weeks to fungal attack in unsterile compost-based soil in accordance with CEN/TS 15083-2 (2005). This kind of soil and water content of the soil will expose wood mainly to soft-rotting fungi and bacteria. The presence of soft rot was confirmed under light microscopy after the exposure. Special visual signs of brown rot and white rot were not found in the studied samples or in the decay chambers. However, the eventual effects of these rot types are not critical for the evaluation of the results, since the potential effects of all types of decay on the strength properties of samples after different treatments are taken into consideration. After the natural durability test against the soft-rotting micro-fungi, these decayed specimens were also conditioned at 65% RH and 20°C to constant mass and weighed. Ten replicate specimens were taken from each wood material and the total number of test specimens was approximately 240. The original results of the decay test are reported in another publication (Metsä-Kortelainen & Viitanen, 2009).

The MOE and bending strength (MOR) were determined with a static bending test using a central loading method in accordance with EN 408 (1995). The bending test was carried out using a span of 80 mm and a loading speed of $1\ mm\ min^{-1}$. The bending stress was directed to the middle of the upper face of the sample in a tangential direction. The slope of the decayed and reference material was calculated, in almost every case, between the flexure load differences of 10–40 N and 40–80 N on the straight-line portion of the deformation curve, respectively. Some of the specimens were very fragile and were less durable than the upper limit, and in these cases the slope was calculated manually. The MOE and MOR were calculated according to eqs (1) and (2):

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

$$\text{MOR}\ (\text{N mm}^{-2}) = \frac{3 \times F \times l}{2 \times b \times h^2} \qquad (2)$$

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), h is the height (thickness) of the specimen (mm), and F is the peak load (N).

After the bending strength test, the specimens were dried at 103°C for 24 h and weighed. The MC was calculated by expressing the mass of water ($w_u - w_{dry}$) as a percentage of the oven-dry mass (w_{dry}).

Principal component analysis

The effects of wood properties [wood species, sapwood/heartwood, density, equilibrium moisture content (EMC), at 65% RH] and thermal modification (modification temperature, weight loss) on the durability (weight and MOE loss), strength (MOE, MOR) and water absorption (MC after 71 h floating) were analysed using PCA. PCA were carried out by Simca software. PCA is a multivariate projection method that is very useful for obtaining an overview of the dominant patterns and major trends in a large data group.

Results and discussion

Initial data

The initial data of the test material are shown in Table I. The density (at 65% RH and 20°C, nominal dimensions) and weight loss caused by the thermal modification are presented therein. These values are average values of all specimens (reference and decay test specimens) before the decay test. In the same table, the EMCs at 65% RH of reference and decayed specimens, the results of water absorption test after 71 h floating and the results of the decay test against soft-rotting microfungi (weight and MOE loss) are also presented. These results are compared with the findings of the strength test presented later, using PCA.

In brief, Table I shows that the density of all spruce and pine samples was decreased as a consequence of reduced EMC and weight loss taking place during the thermal modification. Reduction in the EMC at 65% RH and 20°C after the thermal modification can be seen very clearly. However, the difference between the MCs of reference and decayed specimens is not very significant. More detailed information on the water absorption and decay test is presented in other publications

Table I. Initial data of the test material.

	Thermal modification (°C)	Density (kg m^{-3}) Average	Weight loss (%) After thermal modification Average	MC (%) RH 65% Reference	MC (%) RH 65% Decayed	MC (%) After 71 h floating Reference	Mass loss (%) After soft-rot test Decayed	MOE loss (%) After soft-rot test Decayed
Spruce, sapwood	Untreated	444.6	0.0	11.0	10.2	19.0	20.2	72.6
	170°C	431.0	1.7	9.8	9.8	14.9	19.8	72.5
	190°C	426.5	3.5	8.9	8.9	14.0	13.4	58.7
	210°C	410.5	6.5	7.8	8.4	12.2	8.3	35.4
	230°C	387.2	10.1	6.2	7.1	10.1	2.9	5.6
Spruce, heartwood	Untreated	432.1	0.0	11.1	10.3	17.0	18.8	69.5
	170°C	441.8	3.4	8.6	9.7	12.8	16.3	64.6
	190°C	432.9	5.2	8.7	8.6	12.0	12.2	52.3
	210°C	421.9	6.7	6.9	8.3	9.8	8.2	36.3
	230°C	379.6	11.0	6.6	6.9	7.9	3.6	10.4
Pine, sapwood	Untreated	506.3	0.0	10.9	10.1	30.9	20.3	68.2
	170°C	493.1	2.0	9.2	9.7	42.5	18.3	66.3
	190°C	482.7	4.0	8.3	8.8	43.2	16.4	66.5
	210°C	490.2	6.6	7.2	8.4	37.2	8.8	38.0
	230°C	485.4	11.8	6.3	7.4	27.5	4.6	17.3
Pine, heartwood	Untreated	550.2	0.0	10.3	9.8	14.8	15.4	56.5
	170°C	540.2	5.2	8.2	8.8	9.6	13.9	55.6
	190°C	516.3	6.1	7.7	8.5	10.0	9.8	44.2
	210°C	512.3	7.1	7.0	7.8	10.2	6.4	23.9
	230°C	463.1	10.8	6.0	6.5	7.8	2.3	5.5
Larch	Untreated	634.3	–	10.3	10.1	–	19.3	49.9
Bangkirai	Untreated	915.3	–	8.7	8.9	–	11.6	29.9
Merbau	Untreated	1107.3	–	7.9	8.1	–	8.2	18.1
WRC	Untreated	372.3	–	7.8	9.5	–	16.6	50.6

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

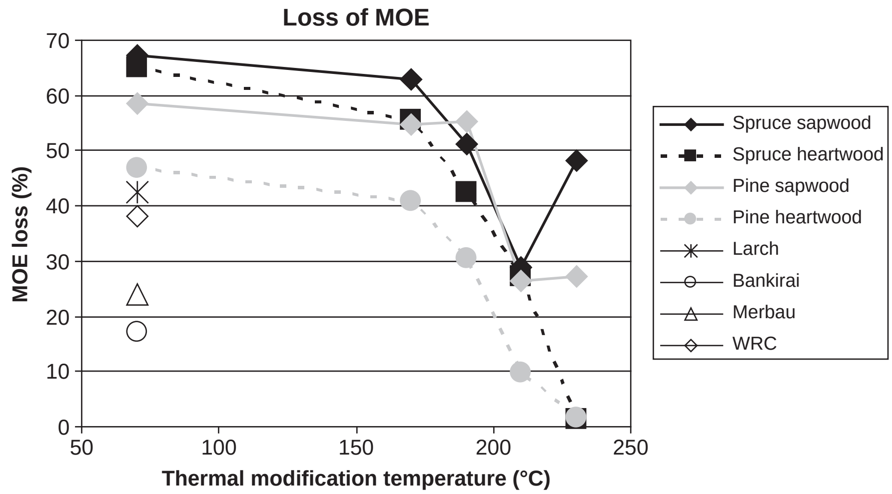

Figure 1. Modulus of elasticity (MOE) loss after fungal exposure. WRC = western red cedar.

(Metsä-Kortelainen *et al.*, 2006; Metsä-Kortelainen & Viitanen, 2009).

Strength test

The effect of fungal exposure on the MOE and MOR of the research material in a static bending test is presented in Figures 1 and 2. In general, both the MOE and MOR were reduced as a consequence of fungal exposure. The decrease in strength was greater with untreated wood (with the exception of the reference wood species) than with thermally modified samples. The higher the thermal modification temperature, the less the strength properties decreased as a consequence of fungal exposure.

The differences in MOE and MOR losses between sapwood and heartwood of spruce were quite small, except for sapwood samples thermally modified at 230°C (Figures 1 and 2). These samples had exceptionally high MOE and MOR losses. This may partially be a consequence of contingency, because many of these samples suddenly broke at the early stages of the bending test. However, there is some congruence between both sapwood materials thermally modified at 230°C. Also, the strength loss of sapwood of pine modified at this very high temperature was only slightly changed compared with the results of samples modified at 210°C. On average, the losses of MOE and MOR were smaller with pine than with spruce. In addition, the differences between sapwood and heartwood of pine were more evident than with spruce. The loss of MOE of heartwood samples thermally modified at 230°C was negligible, and the bending strength, MOR, was only slightly affected. The MOE and MOR were moderately reduced with reference wood species. The strength was reduced least with bangkirai and merbau, which were approximately at the same level

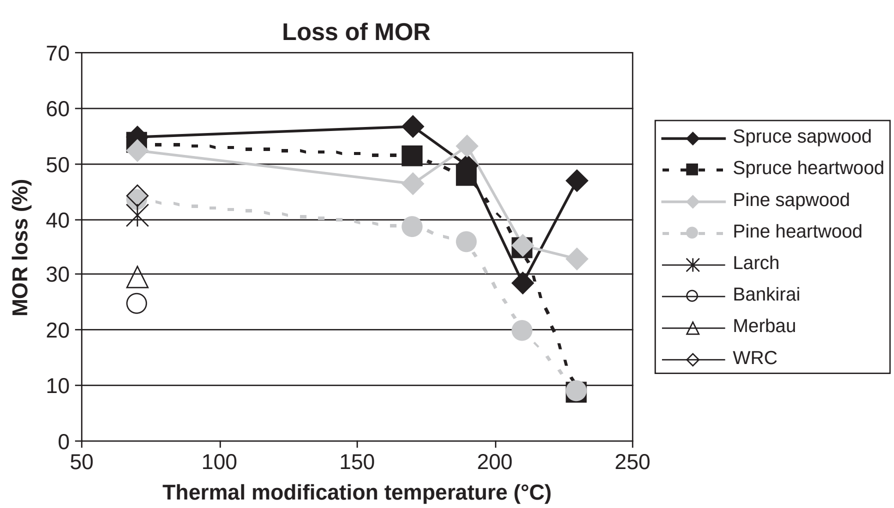

Figure 2. Modulus of rupture (MOR) loss after fungal exposure. WRC = western red cedar.

Table II. Modulus of elasticity (MOE), standard deviation (SD) and effect of thermal modification (change) on unexposed and decayed wood material.

		Reference			Decayed		
	Thermal modification (°C)	MOE (N mm^{-2})	SD (N mm^{-2})	Change (%)	MOE (N mm^{-2})	SD (N mm^{-2})	Change (%)
Spruce, sapwood	Untreated	11,294.8	1,056.4	0.0	3,708.9	507.5	0.0
	170°C	10,104.3	1,150.4	−10.5	3,741.7	607.5	0.9
	190°C	10,328.8	1,121.0	−8.6	5,030.2	485.0	35.6
	210°C	9,573.4	762.0	−15.2	6,814.9	1,555.3	83.7
	230°C	9,224.6	1,057.3	−18.3	4,779.4	2,160.0	28.9
Spruce, heartwood	Untreated	10,647.8	910.3	0.0	3,723.4	554.8	0.0
	170°C	10,901.7	1,578.6	2.4	4,836.3	904.2	29.9
	190°C	10,607.2	1,151.5	−0.4	6,093.7	1,289.0	63.7
	210°C	10,150.4	1,165.2	−4.7	7,380.2	1,175.2	98.2
	230°C	8,156.3	1,530.8	−23.4	8,048.5	1,287.4	116.2
Pine, sapwood	Untreated	10,587.2	1,299.3	0.0	4,378.9	603.8	0.0
	170°C	10,729.7	1,498.1	1.3	4,858.6	1,109.3	11.0
	190°C	10,790.1	1,025.0	1.9	4,833.4	565.0	10.4
	210°C	10,888.1	943.4	2.8	8,007.4	1,150.2	82.9
	230°C	10,699.3	1,076.9	1.1	7,775.0	3,248.0	77.6
Pine, heartwood	Untreated	11,339.2	2,096.0	0.0	6,022.4	1,724.7	0.0
	170°C	11,168.5	2,217.1	−1.5	6,599.2	2,282.4	9.6
	190°C	10,977.0	1,333.0	−3.2	7,636.9	1,709.1	26.8
	210°C	11,099.4	1,764.5	−2.1	10,023.5	1,849.1	66.4
	230°C	10,086.6	1,369.6	−11.0	9,932.0	1,267.3	64.9
Larch	Untreated	12,521.0	1,535.2	–	7,208.8	1,475.2	–
Bangkirai	Untreated	15,896.0	1,695.0	–	13,154.9	3,451.0	–
Merbau	Untreated	16,542.1	1,558.9	–	12,579.0	934.4	–
WRC	Untreated	7,665.5	1,176.1	–	4,739.4	1,521.1	–

Note: WRC = western red cedar.

as heartwood of spruce and pine thermally modified at the minimum at 210°C.

The average and standard deviation (SD) values of the MOE and MOR of the test material in the static bending test are presented in Tables II and III. The change values in the tables describe the effect of thermal modification on the strength properties. The strength values of thermally modified samples are compared with strength values of samples without thermal modification.

The MOE and the MOR of reference wood samples were decreased depending on the level of the thermal modification and wood species (Tables II and III). Both strength values were reduced more with spruce than with pine. The MOE and MOR of pine sapwood were only slightly affected (0–5%), depending on the modification temperature, and the changes in the strength values were very small with pine and spruce heartwood thermally modified at temperatures between 170 and 210°C. Thermal modification at 230°C decreased the MOE and MOR of spruce and pine heartwood by approximately 20% and 11–15%, respectively. The strength of spruce sapwood was most affected: thermal modification at 210°C reduced MOE and MOR 15%, and with samples thermally modified at 230°C MOR was reduced nearly 30%. Bangkirai and merbau were the strongest reference wood species, while the MOE and MOR of WRC reached the lowest values of untreated wood in the whole study.

In general, MOE was reduced slightly less than MOR (Tables II and III). This is in agreement with Esteves *et al.* (2007*a*) and Bekhta and Niemz (2003). Viitaniemi and Jämsä (1996) also studied the effect of thermal modification on the bending strength of pine and spruce, and reported that MOR was lowered by 16% in spruce and by 12% in pine when the weight loss of wood material after thermal modification was approximately 11%. This is in quite good accordance with the results presented in this paper, where the weight losses of wood material after thermal modification at 230°C were approximately 11% (Table I). However, there may be some differences between the results of this paper and those of other publications, because the bending test was performed using smaller specimens than are usually used in strength tests.

Thermal modification increased the MOE and MOR of decayed wood material in almost every case (Tables II and III). The higher the modification temperature, the higher the MOE and MOR values. Thermal modification at least at 210°C increased the

Table III. Modulus of rupture (MOR), standard deviation (SD) and effect of thermal modification (change) on unexposed and decayed wood material.

		Reference			Decayed		
	Thermal modification (°C)	MOR (N mm^{-2})	SD (N mm^{-2})	Change (%)	MOR (N mm^{-2})	SD (N mm^{-2})	Change (%)
Spruce, sapwood	Untreated	88.1	5.3	0.0	39.9	4.9	0.0
	170°C	88.7	10.3	0.6	38.4	7.4	−3.8
	190°C	85.7	16.8	−2.8	43.0	7.4	7.9
	210°C	74.3	17.8	−15.7	53.2	17.2	33.3
	230°C	64.2	18.1	−27.2	34.1	22.2	−14.6
Spruce, heartwood	Untreated	87.3	4.8	0.0	40.4	6.0	0.0
	170°C	93.1	10.6	6.6	45.3	9.9	12.1
	190°C	95.5	9.7	9.4	50.0	10.0	23.9
	210°C	86.3	19.1	−1.2	56.2	11.3	39.1
	230°C	68.5	10.1	−21.5	62.6	11.6	55.1
Pine, sapwood	Untreated	97.7	4.8	0.0	46.4	3.9	0.0
	170°C	96.0	15.0	−1.7	51.4	10.1	10.9
	190°C	94.7	13.2	−3.0	44.4	7.9	−4.3
	210°C	93.7	18.0	−4.0	60.6	12.5	30.7
	230°C	92.6	19.6	−5.1	62.3	29.4	34.2
Pine, heartwood	Untreated	112.9	23.3	0.0	63.9	16.7	0.0
	170°C	112.9	26.3	0.1	69.6	26.7	8.8
	190°C	111.9	18.0	−0.8	72.0	17.7	12.6
	210°C	109.1	18.9	−3.3	87.5	16.4	36.9
	230°C	95.5	12.1	−15.3	87.1	14.5	36.2
Larch	Untreated	135.3	24.1	–	80.2	18.2	–
Bangkirai	Untreated	200.0	26.9	–	150.8	28.8	–
Merbau	Untreated	234.9	33.8	–	165.5	14.5	–
WRC	Untreated	79.0	13.6	–	44.0	14.7	–

Note: WRC = western red cedar.

MOE by 65–116%, depending on the wood species, with the exception of spruce sapwood thermally modified at 230°C. The MOR of decayed wood material was increased by up to 55% as a consequence of thermal modification, although once again the sapwood of spruce underwent thermal modification at 230°C. There were also quite high SD values; in particular, the SD of spruce and pine sapwood thermally modified at 230°C was high in almost every case.

It can be seen from these results that both the thermal modification itself and fungal exposure affect the strength properties of wood. Untreated wood material will be stronger than thermally modified wood material until wood is exposed to decay fungi. Thermal modification at high temperatures over 210°C very effectively prevents wood from decaying, although the strength properties are affected by thermal modification itself. Edlund and Jermer (2004) studied the durability of heat-treated wood in the field according to EN 252 and observed that thermally modified stakes showed a high rate of failure after 2 years' exposure, but a microscopic analysis revealed no indication of decay. The authors concluded that the high rate of failure was a possible consequence of the strength loss caused by the thermal modification, enhanced by wetting in the ground and further chemical degradation. In general, the same kind of behaviour can be detected from the results of this study (Table I). MOE loss was at a higher level than mass loss in the soft-rot test.

Data analysis

The data on pine and spruce were classified using PCA. There were several variables in the PCA: the MOE, bending strength (MOR), density, weight loss caused by thermal modification, EMC, mass and MOE losses of the soft-rot test and the water absorption test results after floating for 71 h. The results of the data analysis are presented in score plots in which the information from loading plots is marked in text boxes. The score plot shows the sample distribution while the loading gives information about the distribution of the variables.

The data on spruce and pine were clustered differently (Figures 3 and 4). The data are ringed according to the thermal modification temperature. With spruce (Figure 3), the first principal component in the score plot sorted the samples out very clearly in accordance with their weight loss,

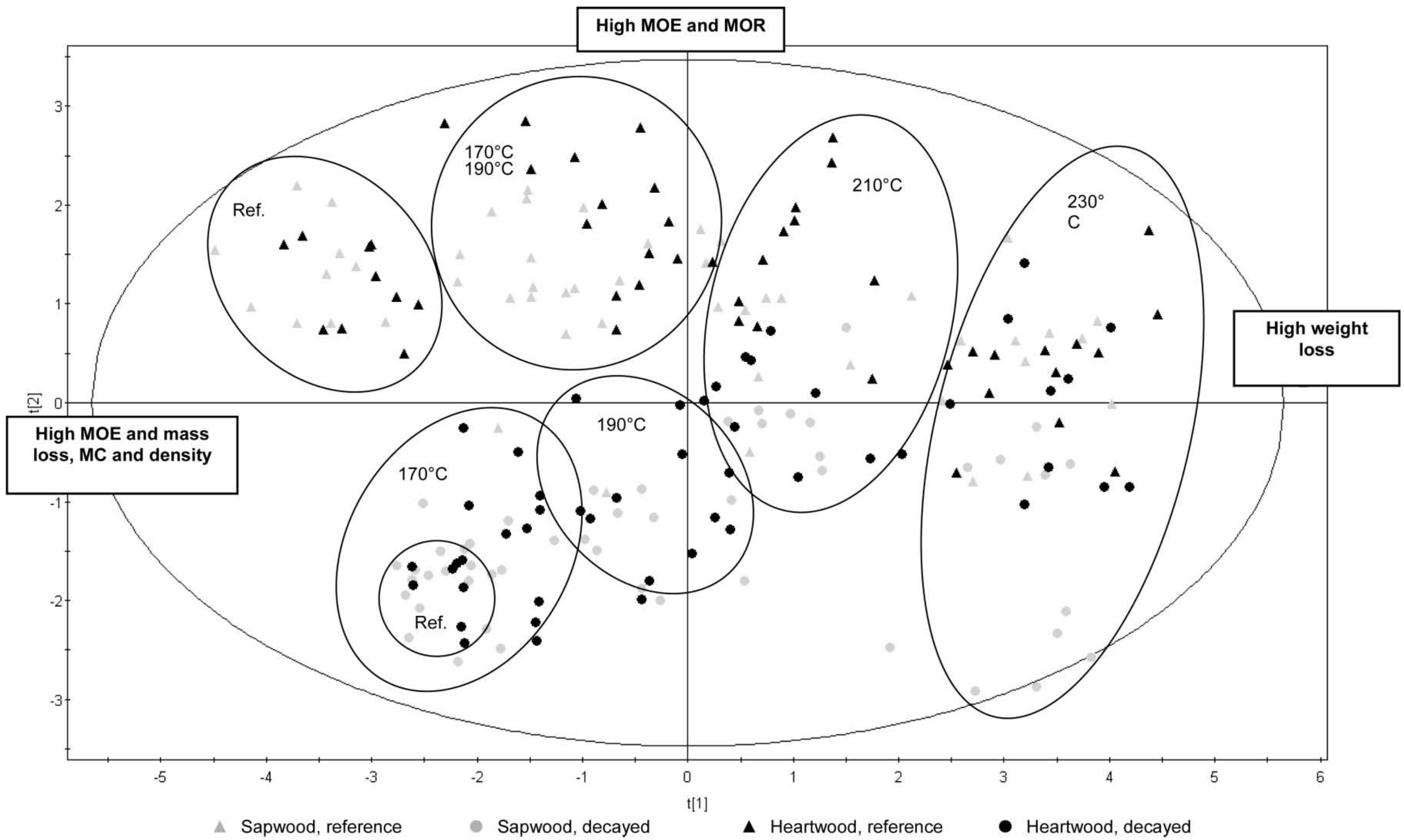

Figure 3. Principal component analysis (PCA) score plot (components 1 and 2) of the data of strength, decay exposure and water absorption tests with spruce. MOE = modulus of elasticity; MOR = modulus of rupture; MC = moisture content.

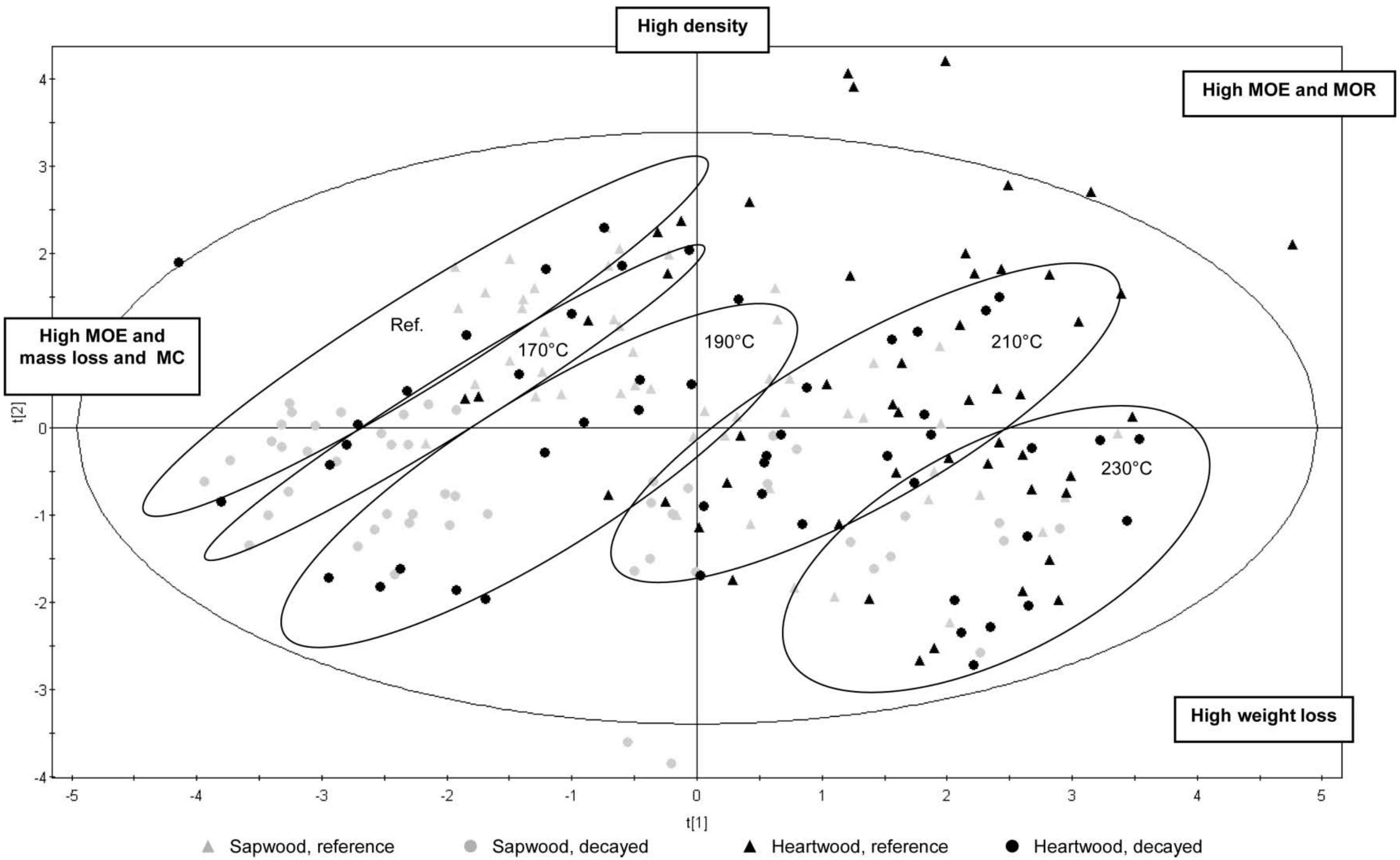

Figure 4. Principal component analysis (PCA) score plot (components 1 and 2) of the data of strength, decay exposure and water absorption tests with pine. MOE = modulus of elasticity; MOR = modulus of rupture; MC = moisture content.

durability, MCs and density. The samples with high weight loss in thermal modification are located on the right of Figure 3, while the samples with high mass and MOE loss values in the soft-rot test are located on the left. Samples with high moisture values (EMC and results of the floating test) are also located on the left. The strength values were clustered in accordance with the second principal component. The samples with high MOE and MOR are at the top of Figure 3. The sapwood and heartwood samples are dotted around the score plot, while the reference and decayed samples are located systematically: the decayed samples are at the bottom and the reference samples at the top of Figure 3.

The difference between sapwood and heartwood of pine was more distinguishable than for spruce (Figure 4). Most of the sapwood samples are located on the left of Figure 4, while the heartwood samples are on the right. The first principal component sorted the data according to the weight loss, strength, durability, MC and water absorption. The samples with high mass and MOE loss in the soft-rot test and high MCs are located on the left of Figure 4, while the samples with high weight loss in thermal modification and high MOE and MOR values are located on the right. The second principal component categorized the data in accordance with density. The samples with high density are at the top of Figure 4. The untreated and decayed samples of pine were not clustered as clearly as with spruce. The samples of both wood species were clustered in accordance with the thermal modification temperature. It is advantageous to note that the material properties and the effect of thermal modification of pine and spruce are different, not to mention every other wood species. A comprehensive understanding is needed to optimize the wood properties according to the circumstances and requirements of the application.

Conclusions

The strength of the untreated and decayed thermally modified sapwood and heartwood of pine and spruce was examined. The results were compared with strength values of reference wood species (Siberian larch, merbau, bangkirai and WRC). Thermal modification decreased the MOE and the bending strength (MOR) of the unexposed reference samples depending on the level of thermal modification. The situation was reversed with decayed samples: the higher the thermal modification temperature was, the higher the MOE and MOR values were compared with values of unmodified samples. The strength differences between sapwood and heartwood of pine were more evident than with spruce. Bangkirai and merbau were the strongest reference wood species.

On average, both the thermal modification itself and the fungal exposure reduced the strength of the wood. In general, the decrease in strength was approximately 0–30% and 0–65% as a consequence of thermal modification and fungal exposure, respectively. The fluctuation in strength loss was quite considerable as a consequence of the level of the thermal modification. However, the effect of decay exposure on the strength loss was more significant. Thus, it can be concluded that untreated wood material will be stronger than thermally modified wood material until wood is exposed to decaying fungi. Thermal modification at high temperatures of over 210°C quite effectively prevents wood from decay; however, the strength properties are then impacted to some extent by thermal modification itself. Other factors, e.g. high MC and defects in the wood material (knots, etc.), may also weaken the wood material in certain applications. The effect of moisture stress and wood defects may be more considerable in the case of thermally modified wood than with untreated wood. These impacts reflect the reasons why thermally modified wood is not recommended for use in load-bearing applications and why it should not replace pressure-treated wood.

In many applications, adequate wood strength is required. The prevailing circumstances must be taken into account when choosing the wood material for a certain application. Structural wood protection has an important role, as do various kinds of surface treatments. Selection of the wood material in accordance with the demands of the application should always be based on knowledge and understanding of the material used.

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