Dimensional Stabilization of Wood Originating from Small-diameter Trees through Heat Treatment

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Small-diameter wood resulting from thinning operations is an important secondary wood resource. Compared to wood originating from mature trees of the same species, it is less stable in shape and dimension when exposed to environmental humidity changes. To reduce its hygroscopicity and valorize this secondary wood resource in solid wood panels for outdoor use, wood samples cut from mature and small-diameter spruce, black pine, lime, and beech logs were heat-treated at 180 and 200 °C for 1 to 6 h in air at atmospheric pressure. Mass loss, swelling coefficients, and anti-swelling efficiency (ASE) were established for each wood type for a comparison between species. Mature and small-diameter wood was also compared under the influence of different temperature/time combinations. The heat treatment conditions that led to a mass loss of maximum 5% in each case were: 200 °C/3.5 h (mature spruce), 200 °C/5 h (thin spruce), 200 °C/3 h (mature pine), 200°C/3.7 h (thin pine), 200 °C/3.2 h (mature lime), 200 °C/2h (thin lime), 200°C/3 h (mature beech), and 200 °C/2.7 h (thin beech). Small-diameter spruce, pine, and lime (the soft species) recorded better dimensional stabilization than the mature wood of each species (ASE_{vol}=49.7% compared to 39.3% for spruce, 38.6% compared to 38% for pine, 52.3% compared to 44.4% for lime), while small-diameter beech behaved differently (with ASE_{vol}=43.5% compared to 48.5 for the mature wood).

Keywords: Small-diameter wood; Heat treatment; Dimensional stabilization

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INTRODUCTION

Small-diameter wood (Φ < 20 cm) resulting from thinning operations is an important secondary wood resource. Compared to wood originating from a mature tree of the same species, a small-diameter log mostly comprises juvenile wood, which has lower density, lower hardness, and lower mechanical strength (Gryc *et al.* 2011; Guler *et al.* 2007; Olarescu *et al.* 2011; Zobel and Sprague 1998) due to earlywood cells with thin walls. Small-diameter wood is also characterized by higher dimensional instability than mature wood. This is mostly because of the presence of spiral grain (Gapare *et al.* 2007; Watt *et al.* 2013), as well as to the peculiar inclination angle of the cellulose microfibrils in the cell walls of juvenile wood (Barnett and Bonham 2004). To valorize this secondary wood resource in solid wood panels for outdoor use (claddings, porch floors, garden furniture, *etc.*), it is possible to heat-treat the lamellas cut from small-diameter logs to increase their dimensional stability.

Heat treatment is known as the most environmentally friendly method of dimensional stabilization. It can make wood suitable for outdoor use by reducing its hygroscopicity without the addition of any chemical substances because it only utilizes the effect of high temperature, which changes the chemical composition of wood. The treatment temperature must be chosen to produce, as much as possible, only those modifications of the chemical structure that favor improvement (incipient decomposition of the hemicelluloses), but do not affect the cellulose structure, which is responsible for the mechanical strength of wood. Much experimental research regarding the effects of high temperature on the wood properties of different species has been performed, and a comprehensive literature review was published by Esteves and Pereira (2009).

Mass loss is considered one of the most important factors in heat treatment because it reflects the severity of degradation in the chemical composition of wood. The higher is the mass loss, the more efficient the heat treatment is in terms of dimensional stabilization. However, at the same time, the more efficient the heat treatment is in terms of dimensional stabilization, the weaker wood becomes. According to Viitaniemi *et al.* (1997), mass loss should not exceed 5% (with possible extension up to 6% for some species) to keep the strength losses at an acceptable level.

Several researchers have tried to establish correlations between mass loss and the physical, chemical, and mechanical properties that suffer during the heat treatment process. Allegretti *et al.* (2012) and Ferrari *et al.* (2013) published the results of comprehensive research conducted with no less than eight different European wood species: spruce (*Picea abies* Karst.), fir (*Abies alba* Mill.), larch (*Larix decidua* Mill.), oak (*Quercus petraea* Liebl.), ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.), cherry (*Prunus avium* L.), and black locust (*Robinia pseudoacacia* L.), heat-treated in vacuum using the Thermovuoto technology. For each of these species they found correlations between the mass loss and equilibrium moisture content (EMC), color change (ΔE), modulus of rupture (MOR), and modulus of elasticity (MOE). Tong *et al.* (2010) found a relationship between the mass loss and changes in hydroxyl and carbonyl peaks of acacia hybrid wood (*Acacia mangium*), heat-treated in boiling water. Gonzales-Pena and Hale (2009), as well as Todorovic *et al.* (2012), found correlations between the mass loss and color change of beech wood, heat-treated in superheated steam. Kocaefe *et al.* (2008) studied the correlation between the chemical transformations and mechanical properties (MOR, MOE, and hardness) of birch and aspen, heat-treated in a thermo-gravimetric furnace, using hot inert gas (80% nitrogen, 20% carbon dioxide). Bal and Bektas (2012) found regression equations between the mass loss and volumetric swelling for eucalyptus (*Eucalyptus grandis*) wood, heat-treated at atmospheric pressure, in the presence of air. Korkut *et al.* (2010) determined mass loss, swelling, MOR and MOE, compression strength parallel-to-grain, hardness, impact bending, tensile strength, and surface roughness of heat-treated sessile oak in air under atmospheric pressure.

However, since the mass loss values greatly depend on wood species and the heat-treating method applied, these correlations are strictly applicable to the conditions they were established for.

Most of these studies refer to heat-treated mature wood, but there are also a few references to the peculiarities of heat-treating juvenile wood (Bal 2014; Bal and Bektas 2012; Guler *et al.* 2007).

The main objective of the present study was to determine the mass loss, swelling coefficients, and dimensional and shape stabilization obtained after the heat treatment of wood originating from small-diameter trees (Φ < 20 cm), compared to mature wood originating from the same forest parcel. Four European wood species were employed in this study: spruce (*Picea abies*), black pine (*Pinus nigra*), lime (*Tilia cordata*), and beech (*Fagus sylvatica*). The results of this study can be used for the manufacture of valueadded products: solid wood panels for outdoor use, as the ones obtained from the semi-products heat-treated within the present research (Fig. 1).

Fig. 1. Solid wood panels obtained from small-diameter spruce wood semi-products, heat-treated within the present research

EXPERIMENTAL

Materials

The wooden materials used in these experiments consisted of eighteen 620 × 85 × 30 mm defect-free boards, cut from small-diameter logs (Φ = 15 to 16 cm) and mature logs (Φ = 30 to 32 cm), for each of the selected wood species: spruce (*Picea abies*), black pine (*Pinus nigra*), lime (*Tilia cordata*), and beech (*Fagus sylvatica*), all originating from the same forest parcel, located in the southern part of Romania (Stroesti - Arges: 45° 8' 0'' North, 24° 47' 0'' East). The average oven-dry densities of the tested material are given in Table 1.

Table 1. Oven-dry Density (kg/m^3) of Experimental Material

Spruce mature	Spruce small-diam	Pine mature	Pine small-diam	Lime mature	Lime small-diam	Beech mature	Beech small-diam
376±14.1	371±10.0	547±21.1	544±23.6	458±18.2	428±17.8	688±7.4	684±13.6

Note: The values after ± represent the mean standard deviations.

Methods

The boards were first air-dried to 12% moisture content and then conditioned for 2 weeks at 20 °C and 65% relative humidity in a Feutron KPK200 climate chamber (Germany). Afterwards, 20 × 20 × 30 mm strictly radial-tangential samples were cut to determine the swelling coefficients and mass loss.

Before being heat-treatment, the samples were oven-dried in a Binder electric oven with natural convection and PID controller (Germany) at a constant temperature of 103 °C. The oven-dry mass and all three dimensions of each sample were measured before heat-treatment by means of a Kern electronic scale by (Germany), with 0.001-g accuracy and an electronic sliding gauge with 0.01-mm precision.

Heat treatment was carried out at two different temperatures: 180 and 200 °C, combined with four treatment durations: 1, 2, 3, and 4 h for spruce, pine, and lime, and 2, 3, 4, and 6 h for beech. The treatment conditions were chosen considering the structural peculiarities of the chosen species and previous experience with their behavior under heat treatment at atmospheric pressure, in the presence of air. For each experimental heat treatment condition, as well as for the controls (oven-dry untreated wood), a set of 10 samples was employed.

Each set of samples was heat-treated in the Binder dry oven, in air, under atmospheric pressure, by increasing the temperature to the pre-set value (180 or 200 °C) and maintaining it at this value for the chosen time. After each hour of treatment, a set of samples was taken from the oven and cooled down in a desiccator, and the mass and dimensions of the samples were measured.

Based on the experimental data obtained, regarding the samples' mass before and after the heat-treatment (both masses being determined in an oven-dry state and ambient temperature), the mass loss (ML) was calculated according to Eq. 1,

$$ML = \frac{m_0 - m_{tr}}{m_0} \cdot 100\,[\%] \tag{1}$$

where m_0 is the oven-dry mass before heat treatment (g) and m_{tr} is the oven-dry mass after the heat-treatment (g).

Both the treated and untreated samples were then immersed in distilled water until they reached the fiber saturation point (until the tangential dimension stopped growing). In this state, all three dimensions were measured again. The total swelling coefficients in the radial (α_r) and tangential directions (α_{tg}) were calculated according to ISO 4859:1982, and the total volumetric swelling (α_v) was determined according to ISO 4860:1982.

Based on these values, the shape and dimensional stabilization effects of the heat treatment were assessed:

- The ratio between tangential and radial swelling (α_{tg}/α_r) reflects the warping tendency of wood; therefore, it can be considered a good indicator of shape stability. The higher its value is, the higher the deformation risk is.
- The dimensional stability is best quantified by the anti-swelling efficiency (ASE), calculated according to Eq. 2:

$$ASE = \frac{\alpha_{untreated} - \alpha_{treated}}{\alpha_{untreated}} \cdot 100\ [\%] \tag{2}$$

The statistical interpretation of the results was performed according to ISO 2602-2 (1980), by calculating the mean $\bar{x}$ and the standard deviation *s*.

RESULTS AND DISCUSSION

Mass Loss (ML)

Tables 2 through 9 present the results regarding the mass losses suffered by the eight tested wood types as a consequence of heat treatment at different temperatures and exposure times.

The values obtained for mature wood were in accordance with those obtained by other researchers using the same species under similar conditions (Bekhta and Niemz 2003 - spruce; Guller 2012 - pine; Barboutis *et al*. 2011 - lime).

Table 2. Mass Loss and Swelling of Heat-treated and Untreated Mature Spruce Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	4.1	0.8	9.2	1.4	14.1	1.6
180	1	0.822	0.227	3.8	0.6	8.6	1.3	13.2	1.6
	2	1.437	0.212	3.6	0.7	8.7	0.8	13.1	1.2
	3	1.856	0.245	3.1	0.3	7.5	1.0	11.3	1.2
	4	2.184	0.439	2.9	0.4	6.9	0.4	10.4	0.8
200	1	2.006	0.142	3.2	0.3	7.4	0.9	11.2	1.2
	2	3.066	0.487	2.7	0.5	6.5	0.8	9.7	1.2
	3	4.519	0.352	2.6	0.2	6.4	0.8	9.5	0.9
	4	5.778	0.495	1.9	0.9	5.5	0.7	7.6	1.7

Table 3. Mass Loss and Swelling of Heat-treated and Untreated Small-Diameter Spruce Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	4.3	0.6	8.8	0.9	13.7	1.1
180	1	0.932	0.099	4.1	0.5	7.2	1.2	12.0	0.9
	2	1.434	0.132	3.9	0.8	7.0	1.0	11.7	1.1
	3	1.630	0.180	3.5	0.3	6.9	0.80	10.9	0.9
	4	1.699	0.129	3.4	0.4	6.5	0.5	10.6	0.7
200	1	1.856	0.253	3.0	0.3	6.9	0.3	10.3	0.3
	2	2.939	0.194	3.0	0.4	6.1	0.9	9.5	0.6
	3	4.210	0.396	2.5	0.2	5.2	0.5	7.9	0.8
	4	4.500	0.284	2.1	0.5	4.3	1.0	7.4	0.8

Table 4. Mass Loss and Swelling of Heat-treated and Untreated Mature Black Pine Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	5.8	0.6	9.9	0.5	16.6	1.1
180	1	1.024	0.169	5.6	1.1	9.3	0.4	15.8	1.3
	2	1.454	0.191	5.2	0.6	8.6	0.7	14.8	1.1
	3	1.954	0.258	4.2	1.2	7.4	1.4	12.5	2.6
	4	2.319	0.457	4.1	0.7	6.5	1.9	11.6	1.5
200	1	2.097	0.223	4.3	0.6	7.6	0.4	12.5	0.9
	2	3.790	0.701	3.5	0.5	6.6	0.9	10.7	1.3
	3	4.923	0.140	3.5	0.2	6.3	0.2	10.3	0.5
	4	5.815	0.683	3.5	0.3	6.2	0.8	10.3	1.3

Table 5. Mass Loss and Swelling of Heat-treated and Untreated Small-Diameter Black Pine Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	6.3	1.3	8.2	1.5	15.6	2.7
180	1	0.963	0.154	6.0	0.3	7.6	1.5	14.8	1.4
	2	1.453	0.173	5.1	1.6	6.9	1.2	13.3	2.5
	3	1.839	0.286	5.0	1.1	6.8	1.3	12.7	2.3
	4	1.976	0.298	4.3	0.5	6.5	2.3	11.7	2.6
200	1	2.137	0.267	4.7	0.3	6.0	1.3	11.5	1.1
	2	3.240	0.400	4.3	1.9	5.7	1.2	10.9	3.1
	3	4.212	0.307	4.3	2.0	5.2	1.1	10.0	2.1
	4	5.506	0.690	3.7	0.7	5.1	1.3	9.4	1.9

Table 6. Mass Loss and Swelling of Heat-treated and Untreated Mature Lime Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	4.3	0.8	6.9	1.4	11.8	1.1
180	1	1.117	0.617	3.7	0.3	6.2	0.6	10.3	0.7
	2	1.365	0.125	3.5	0.2	5.8	0.5	9.9	0.6
	3	1.823	0.106	3.0	0.1	5.7	0.6	9.1	0.7
	4	1.977	0.095	2.9	0.8	5.7	1.4	9.8	1.0
200	1	3.109	0.684	3.4	0.6	4.2	0.7	7.9	0.8
	2	3.644	0.335	3.0	0.7	3.6	1.5	6.8	1.8
	3	4.515	0.729	3.0	0.3	3.3	0.4	6.6	0.4
	4	7.967	0.088	2.5	0.3	2.4	0.3	5.2	0.5

Table 7. Mass Loss and Swelling of Heat-treated and Untreated Small-Diameter Lime Wood

Temp (ºC)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	6.1	0.6	10.4	0.5	17.2	0.6
180	1	1.342	0.223	5.4	0.4	8.7	0.4	15.8	0.6
	2	1.752	0.133	5.3	1.3	7.8	0.4	14.9	0.8
	3	2.131	0.169	5.0	0.4	6.9	0.6	13.9	1.3
	4	2.371	0.282	4.9	0.5	6.8	0.3	12.6	0.9
200	1	4.274	1.104	3.4	0.2	4.5	0.8	12.6	0.3
	2	4.960	0.382	3.2	0.1	4.4	0.3	8.2	0.8
	3	6.755	0.387	2.6	0.3	4.2	0.2	8.0	0.4
	4	9.308	0.662	2.1	0.6	3.5	1.3	7.0	0.5

The mass losses obtained for the resinous species (spruce and pine) were lower than for the hardwood species (lime and beech). The different behavior of the two wood types during the heat-treatment is mainly due to the different chemical composition: since the amount of hemicelluloses in hardwood species is higher and more unstable than in softwood species, degrading is also easier in hardwoods than softwoods (ThermoWood Handbook 2003, Kamden *et al.* 2002). This statement is sustained by Ferrari *et al.*

(2013), who obtained mass losses of 5.8 to 7.3% for the resinous species and 9.5 to 15% for the hardwood species, under the same heat treatment conditions (220 °C/3 h/210 mbar), using the Thermovuoto technology.

Table 8. Mass Loss and Swelling of Heat-treated and Untreated Mature Beech Wood

Temp (°C)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	7.3	3.8	12.4	3.5	20.6	1.0
180	2	0.874	0.095	6.7	3.0	11.3	3.1	18.9	0.8
	3	1.194	0.125	6.5	2.7	11.2	3.4	17.1	1.0
	4	1.374	0.095	5.8	0.4	11.2	0.3	17.9	0.8
	6	1.626	0.125	5.3	0.3	11.1	0.2	17.4	0.6
200	2	3.201	0.239	3.5	0.4	7.9	0.5	11.9	0.5
	3	5.051	0.564	3.4	0.3	7.1	0.3	10.6	0.4
	4	6.782	0.555	3.3	1.2	5.8	1.235	9.8	0.4
	6	9.809	1.799	2.8	0.1	5.3	0.373	8.5	0.3

Table 9. Mass Loss and Swelling of Heat-treated and Untreated Small-Diameter Beech Wood

Temp (°C)	Time (h)	ML (%)		α_r (%)		α_{tg} (%)		α_v (%)	
		x	s	x	s	x	s	x	s
Control		-	-	7.4	1.8	13.9	2.2	22.6	1.6
180	2	1.100	0.070	7.0	1.2	12.3	2.5	20.6	1.8
	3	1.365	0.103	6.3	1.3	12.0	2.8	20.5	0.5
	4	1.563	0.098	6.3	1.0	11.8	0.9	20.1	0.7
	6	1.967	0.137	6.2	1.5	11.6	1.3	18.6	0.9
200	2	4.035	0.536	4.2	0.8	8.2	1.1	13.1	1.2
	3	5.385	0.629	4.0	1.6	8.1	0.6	12.6	1.4
	4	8.592	2.989	3.0	0.6	7.8	0.8	11.3	1.3
	6	9.905	0.846	3.0	0.3	7.1	0.4	10.6	0.5

Referring to the mass losses of the small-diameter wood compared to the ones obtained from the mature wood, it was established that they were lower in the case of the two resinous species and higher in the case of the two hardwood species. The explanation is also given by the different chemical composition: juvenile wood in hardwoods contains a higher amount of hemicelluloses, which makes it more susceptible to degradation than mature wood. This statement is sustained by Nazerian *et al.* (2011), who tested the chemical composition of heat-treated (at 180 °C) and untreated veneers, originating from three mature and juvenile hardwood species: beech (*Fagus orientalis*), maple (*Acer insigne*), and poplar (*Populus nigra*). The authors reported a higher decrease of the glucose, xylose, mannose, galactose, and arabinose amount in the juvenile veneers compared to the ones originating from mature wood, which also resulted in an up to 50% lower swelling of the mature veneers compared to the juvenile ones. The opposite behavior concerning mature *vs.* juvenile wood was established for resinous wood (*Pinus nigra*) by Guler *et al.* (2007). In this case, the authors established that the swelling and shrinkage properties of juvenile wood are lower. Using the same species but heat-treated, Bal (2014) established that the heat treatment at 140 °C, 170 °C, and 200 °C for 3 h had greater impact on the mechanical properties of mature black pine wood than upon the juvenile wood. All these results are in accordance with the results obtained within the present study (Tables 2 to 9), namely: lower mass loss and lower swelling in small-diameter resinous woods compared to mature wood of the same species; higher mass loss and higher swelling in small-diameter hardwoods compared to mature wood of the same species.

With respect to temperature (Fig. 2), it should be noted that all ML values recorded at 180 °C were below 2.5%, suggesting low efficiency of the heat treatment at this temperature for all eight wood types. Nevertheless, the ML values obtained at 200 °C were significantly higher, ranging up to 4.5% for small-diameter spruce, 5.5% for pine, 9.3% for lime, and 8.6% for beech when heat-treated for 4 h, which was the largest time of experimental lineation, and therefore, the difference between the mass loss values for the two temperatures was best put into evidence.

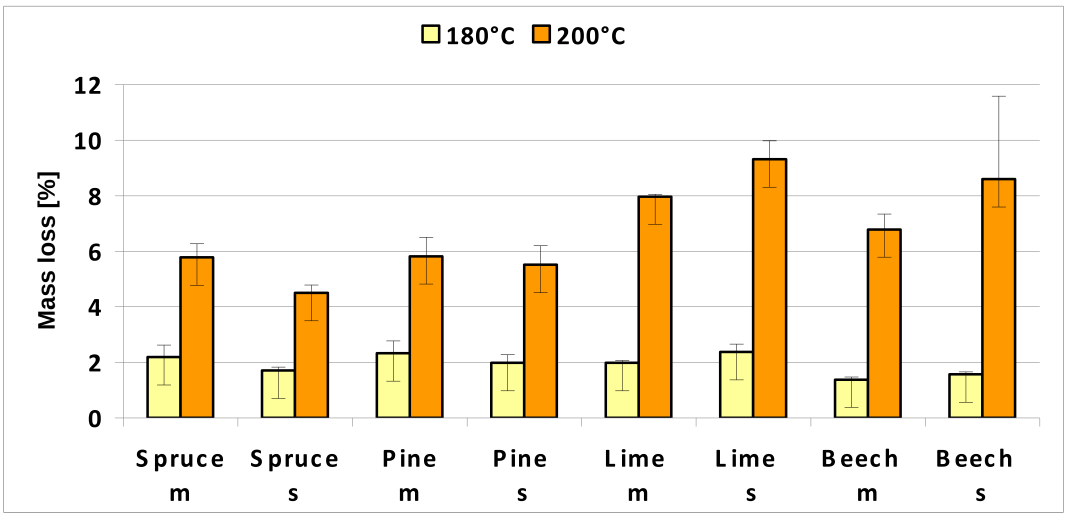


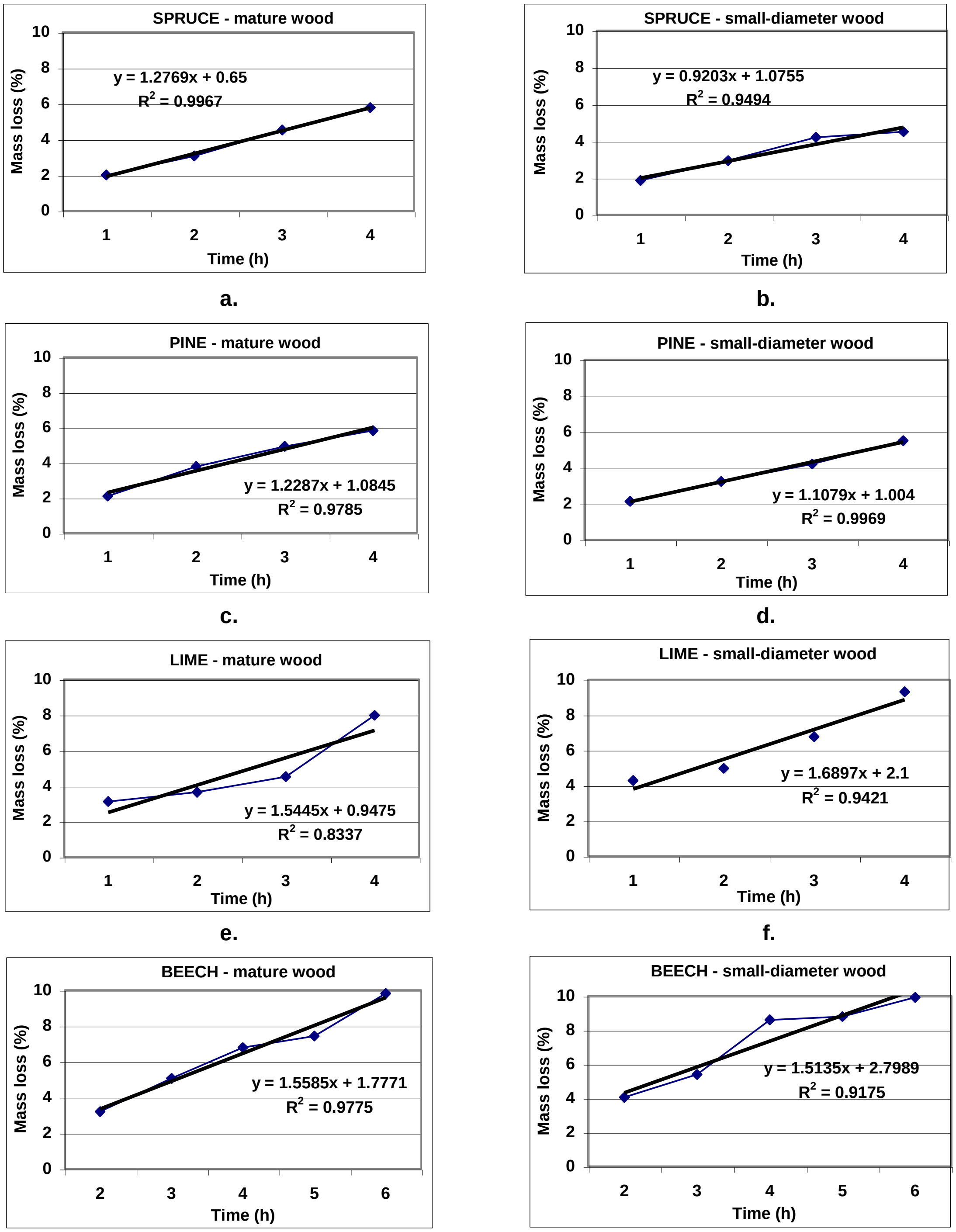
Fig. 2. Effect of treatment temperature on mass loss (treatment time = 4 h); m = mature wood; s = small-diameter wood

The regression equations obtained for all species, both mature and small-diameter wood, regarding the correlation between the mass loss and the treatment duration are ascending linear functions of the type: ML= a · Time + b (Fig. 3), with coefficients of determination (R^2) ranging between 0.83 and 0.99.

Considering ML = 5% a threshold value to keep the mechanical strength of wood at an acceptable level, the following treatment conditions were established as optimal for each wood type (Table 10). All involve the temperature level 200 °C, considering that the mass losses at 180 °C were all below 2.3%.

Table 10. Heat Treatment Conditions for 20-mm-thick Samples to Reach ML = 5%

Spruce (m)	Spruce (s)	Black pine (m)	Black pine (s)	Lime (m)	Lime (s)	Beech (m)	Beech (s)
200 ºC / 3.5 h	200 ºC / 5 h	200 ºC / 3 h	200 ºC / 3.7 h	200 ºC / 3.2 h	200 ºC / 2 h	200 ºC / 3 h	200 ºC / 2.7 h



g. h.

Fig. 3. Mass loss *vs.* heat treatment duration (t = 200 °C). a. spruce (m); b. spruce (s); c. black pine (m); d. black pine (s); e. lime (m); f. lime (s); g. beech (m); h. beech (s)

Swelling

The values of the total radial, tangential, and volumetric swelling coefficients of treated and untreated wood of the eight wood species are given in Tables 2 to 9. The values of volumetric swelling of untreated small-diameter wood were quite close to the ones for mature wood of resinous species (difference < 1%). The values for small-diameter wood were significantly higher in the case of lime and beech (difference = 2 to 5.4%). Heat treatment reduced the swelling differently for the four wood species considered, depending on grain direction, treatment temperature, and time. It was found that small-diameter resinous wood swells more in radial direction and less in tangential direction than mature wood. Therefore, the values of volumetric swelling were similar for both wood types (juvenile and mature) and both species (spruce and pine).

Spruce swelling

The volumetric swelling of spruce wood was reduced by up to 27% for mature wood and by up to 13% for small-diameter wood at 180 °C and by up to 47% for mature wood and up to 39% for small-diameter wood at 200 °C when the treatment time was raised from 1 h to 4 h. The minimum swelling was recorded at 200 °C and 4 h, with α_r = 2.1%, α_{tg} = 4.3%, and α_v = 7.4% for small-diameter spruce wood heat-treated at 200 °C for 4 h, compared to α_r = 4.3%, α_{tg} = 8.8%, and α_{vol} = 13.7% for untreated small-diameter spruce. The swelling was practically reduced by half through these heat treatment conditions.

Black pine swelling

The volumetric swelling of pine wood was reduced by up to 36% for mature wood and by up to 26% for small-diameter wood at 180 °C and by up to 21% for mature wood and up to 22% for small-diameter wood at 200 °C when raising the treatment time from 1 h to 4 h. The percent reduction was thus lower than with spruce wood, which reveals a lower efficiency of the heat treatment in the case of pine wood.

Lime swelling

The volumetric swelling of lime wood was reduced by up to 51% at 180 °C and by up to 80% at 200 °C for small-diameter wood when increasing the treatment time from 1 h to 4 h. These were the highest reduction values recorded among the eight wood species. For the mature lime wood, the reduction was less spectacular (maximum 25%). The minimum swelling was recorded at 200 °C after 4 h, with α_r = 2.1%, α_{tg} = 3.5%, and α_v = 7.0% for small-diameter lime wood heat-treated at 200 °C for 4 h, compared to α_r = 6.1%, α_{tg} = 10.4%, and α_v = 17.2% for untreated small-diameter lime, the swelling was practically reduced to one-third through these heat treatment conditions.

Beech swelling

The volumetric swelling of beech wood was insignificantly reduced by heat treatment at 180 °C (by 8% for the mature wood and by 11% for the small-diameter wood). However, at 200 °C, the volumetric swelling was reduced by up to 40% (for mature wood) and by up to 23% (for small-diameter wood) when the treatment time was increased from 2 h to 6 h. The minimum swelling was recorded at 200 °C for 6 h, with α_r = 3.0%, α_{tg} = 7.1%, and α_v = 10.6% for small-diameter beech heat-treated at 200 °C for 6 h, compared to α_r = 7.4%, α_{tg} = 13.9%, and α_v = 22.6% for untreated small-diameter beech. The swelling was practically reduced to 40% through these heat treatment conditions.

Swelling *vs.* Mass Loss

The dependency between the volumetric swelling (α_v) and the mass loss (ML) of heat-treated wood is illustrated in Fig. 4.

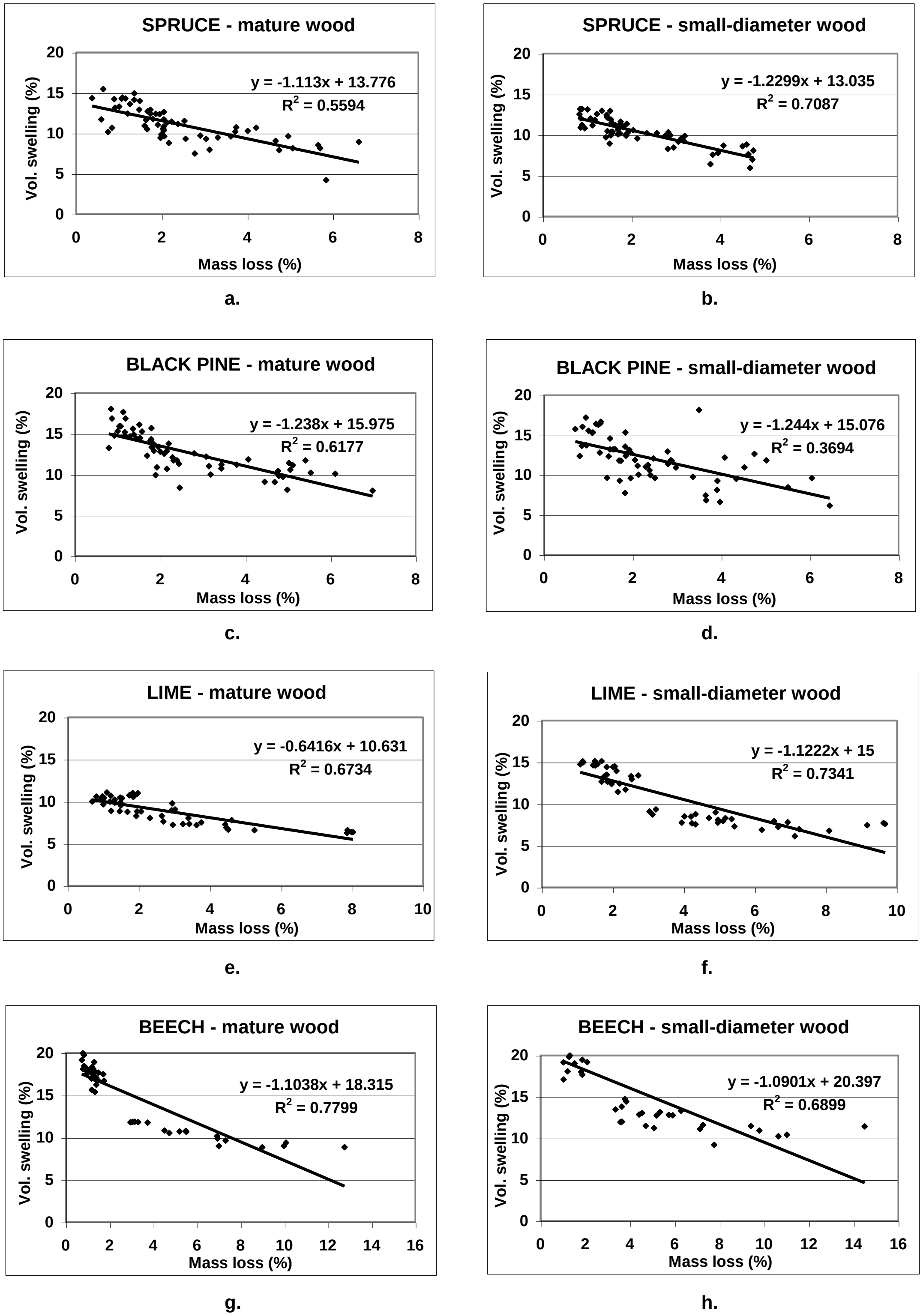


Fig. 4. Volumetric swelling *vs.* mass loss following heat-treatment. Comparison between the values obtained for mature wood *vs.* small-diameter wood. a. spruce (m); b. spruce (s); c. black pine (m); d. black pine (s); e. lime (m); f. lime (s); g. beech (m); h. beech (s)

For all eight wood species considered, the graphs show a linear decrease of the volumetric swelling with increasing mass loss, and coefficients of determination (R^2) ranging between 0.56 and 0.78, with higher values for the small-diameter spruce and lime wood (homogenous species) and lower values for the mature pine and beech wood (species with higher internal stresses). The greatest variability (R^2=0.37) was recorded for the small-diameter black pine and it must be attributed to the fact that these samples were the only ones which contained 50% heartwood, and this considerably disturbed the swelling values.

As already stated, the graphs in Fig. 4 show that the mass losses of the small-diameter wood were lower than that for the mature wood of resinous species, but higher with lime and beech wood.

Swelling Anisotropy

According to the values measured in this study, the ratio α_{tg}/α_r for untreated wood ranged between 2.0 and 2.3 for spruce, 1.3 and 1.7 for pine, 1.6 and 1.7 for lime, and 1.7 and 1.9 for beech. After heat treatment, this ratio tended to remain steady or grow for most species, except for lime, where a clear reduction of this indicator could be seen, both in mature and small-diameter wood (Fig. 5). This means that heat-treated lime wood has better shape stability than untreated lime.

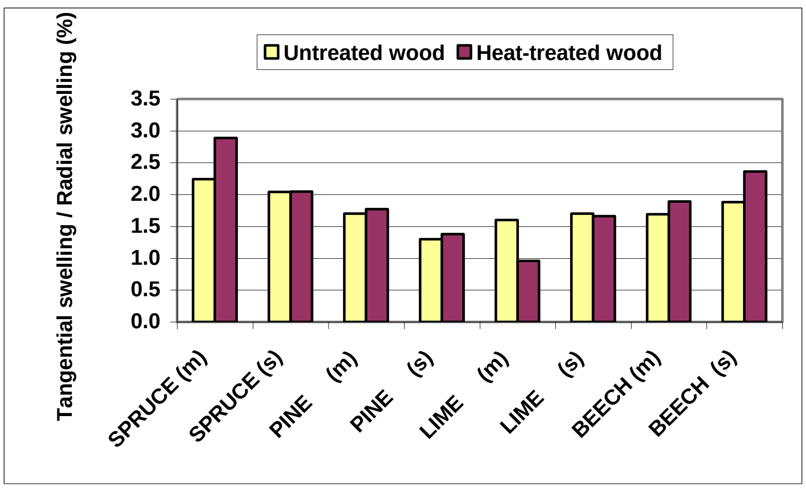


Fig. 5. Influence of the heat treatment on the anisotropy of wood expressed by the ratio between tangential and radial swelling. m = mature wood; s = small-diameter wood

Dimensional Stabilization

The ASE values calculated by means of Eq. 2 in radial and tangential directions, as well as the whole volume, are given in Tables 11 to 14. In all species, the ASE increased with more severe heat treatment conditions (higher temperature, longer time).

Spruce dimensional stabilization

The highest ASE values were obtained at 200 °C after 4 h, both from mature and small-diameter spruce wood. The radial ASE was slightly higher than tangential ASE for the mature spruce, while for small-diameter spruce, the two values were very close (51%). The volumetric ASE amounted to 46% for both wood types.

Table 11. Spruce (*Picea abies L.*) - ASE Mature Wood *vs*. Small-diameter Wood

Temp (ºC)	Time (h)	Mature wood			Small-diameter wood		
		ASE tg	ASE rad	ASE vol	ASE tg	ASE rad	ASE vol
180	1	6.5	7.3	6.4	18.2	4.7	12.4
	2	5.4	12.2	7.1	20.5	9.3	14.6
	3	18.5	24.4	19.9	21.6	18.6	20.4
	4	25.0	29.3	26.2	26.1	20.9	22.6
200	1	19.6	22.0	20.6	21.6	30.2	24.8
	2	29.3	34.1	31.2	30.7	30.2	30.7
	3	30.4	36.6	32.6	40.9	41.9	42.3
	4	40.2	53.7	46.1	51.1	51.2	46.0

Black pine dimensional stabilization

With maximum 38% in volume for mature wood and maximum 40% for small-diameter wood, the ASE values for pine wood were significantly lower than for spruce, confirming a fact already suggested by the mass loss values: heat treatment is much less efficient in case of this species.

Table 12. Black Pine (*Pinus nigra L.*) – ASE Mature Wood *vs*. Small-diameter Wood

Temp (ºC)	Time (h)	Mature wood			Small-diameter wood		
		ASE tg	ASE rad	ASE vol	ASE tg	ASE rad	ASE vol
180	1	6.1	3.4	4.8	7.3	4.8	5.1
	2	13.1	10.3	10.8	15.9	19.0	14.7
	3	25.3	27.6	24.7	17.1	20.6	18.6
	4	34.3	29.3	30.1	20.7	31.7	25.0
200	1	23.2	25.9	24.7	26.8	25.4	26.3
	2	33.3	39.7	35.5	30.5	31.7	30.1
	3	36.4	39.7	38.0	36.6	31.7	35.9
	4	37.4	39.7	38.0	37.8	41.3	39.7

Lime dimensional stabilization

According to the very good results obtained in swelling reduction, small-diameter lime was characterized by record ASE values at 200 °C after 4 h: ASE_{rad} = 66.3%, ASE_{tg} = 65.6, and ASE_{vol} = 59.3%. However, these values were recorded at mass losses higher than 5%. In order to have a fair result, the compared ASE values should be considered at the same ML value.

Table 13. Lime (*Tilia cordata* Mill.) - ASE Mature Wood *vs*. Small-diameter Wood

Temp (ºC)	Time (h)	Mature wood			Small-diameter wood		
		ASE tg	ASE rad	ASE vol	ASE tg	ASE rad	ASE vol
180	1	10.1	14.0	12.7	16.3	11.5	8.1
	2	15.9	18.6	16.1	25.0	13.1	13.4
	3	17.4	30.2	22.9	33.7	18.0	19.2
	4	17.4	32.6	16.9	34.6	19.7	26.7
200	1	39.1	20.9	33.1	56.7	44.3	26.7
	2	47.8	30.2	42.4	57.7	47.5	52.3
	3	52.2	30.2	44.1	59.6	57.4	53.5
	4	65.2	41.9	55.9	66.3	65.6	59.3

Considering ML = 5% as the reference value, the heat-treatment conditions considered shall be 200 °C for 3.2 h for mature wood and 200 °C for 2 h for small-diameter wood (see Table 10). In this situation, the volumetric ASE was 47% for mature lime - very close to the volumetric ASE obtained for spruce wood - and 52.3% for small-diameter lime, which was the highest value among all analyzed situations.

Beech dimensional stabilization

Both mature beech and small-diameter beech recorded strong swelling reduction through heat treatment at 200 °C for 6 h. Accordingly, the ASE values were also high after this treatment, with values above 50%.

However, as in the case of lime, this treatment led to mass losses above 5% and in order to relate to a common ML value (5%), the conditions to be taken into consideration should be: 200 °C and 3 h for mature wood and 200 °C and 2.7 h for small-diameter wood. In this situation, the volumetric ASE would be 48.5% for mature beech and 43.5% for small-diameter beech.

Table 14. Beech (*Fagus sylvatica* L.) - ASE Mature Wood *vs*. Small-diameter Wood

Temp (ºC)	Time (h)	Mature wood			Small-diameter wood		
		ASE tg	ASE rad	ASE vol	ASE tg	ASE rad	ASE vol
180	2	8.9	8.2	8.3	11.5	5.4	8.8
	3	9.3	11.0	17.0	13.7	14.9	9.3
	4	9.7	20.5	13.1	15.1	14.9	11.1
	6	10.5	27.4	15.5	16.5	16.2	17.7
200	2	36.3	52.1	42.2	41.0	43.2	42.0
	3	42.7	52.7	48.5	41.7	45.9	44.2
	4	53.2	54.8	52.4	43.9	58.8	50.0
	6	57.3	61.6	58.7	48.9	59.5	53.1

ASE *vs*. Mass Loss

The relationship between the volumetric anti-shrinking efficiency (ASE) and the mass loss (ML) is illustrated in Fig. 6. The regression analysis shows that the relationship ASE_{vol} = f(ML) is a linear, positive function (increasing mass loss leads to ASE increase). The coefficients of determination were slightly higher in small-diameter wood (R^2 = 0.84-0.97).

The ASE values were also calculated considering the heat treatment conditions presented in Table 10 as the optimum for each species to obtain ML = 5%. The results are presented in Fig. 7. The graph clearly shows that:

- the best radial ASE was obtained with lime wood;
- high tangential ASE values were obtained with spruce, small-diameter lime, and mature beech wood;
- the best results in terms of volumetric ASE were obtained with lime wood, followed by mature beech, and then spruce;
- better ASE in small-diameter wood was clearly visible with lime; slightly better results were also obtained with black pine and spruce.

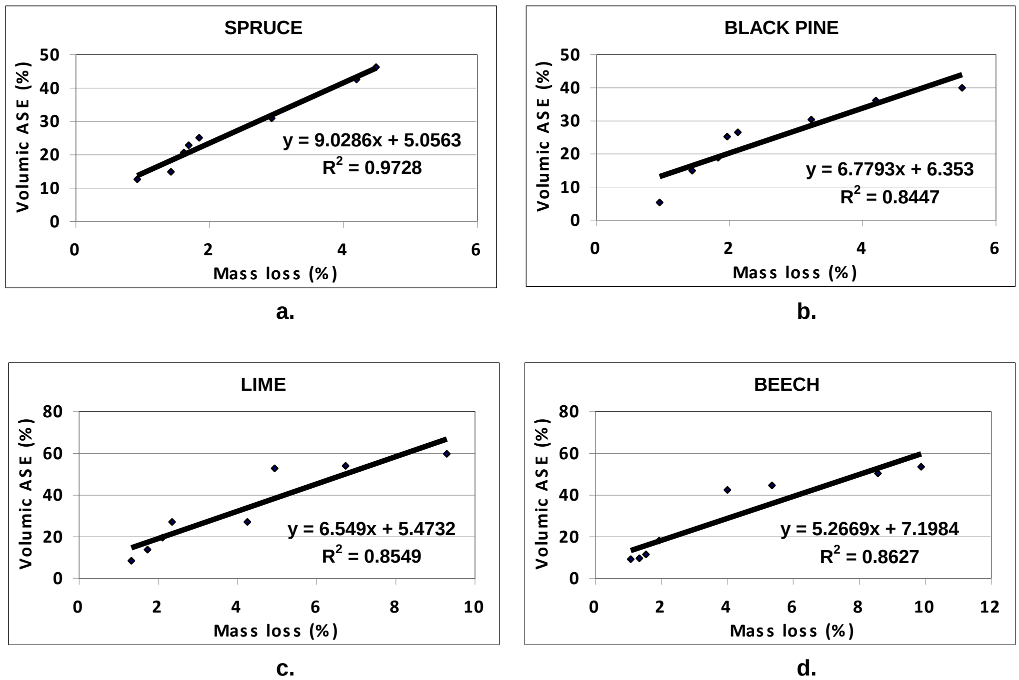


Fig. 6. Volumetric ASE *vs.* mass loss for heat-treated small-diameter wood. a. spruce; b. black pine; c. lime; d. beech

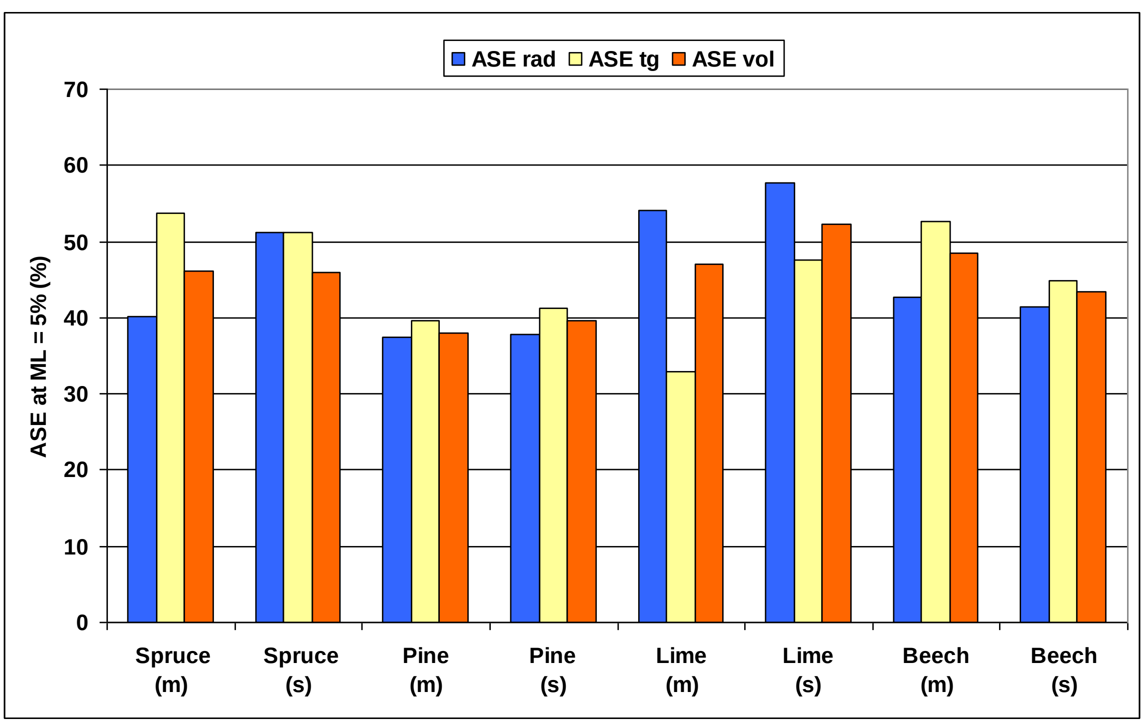


Fig. 7. Radial, tangential, and volumetric ASE of spruce, pine, lime, and beech wood, heat-treated until a mass loss of 5% was reached: m = mature wood; s = small-diameter wood

CONCLUSIONS

This study focused on the differences between heat-treated small-diameter wood and mature wood of four European species. The results obtained in this study led to the following conclusions:

1. The mass loss increased with increasing severity of the heat treatment conditions. The heat treatment at 200 °C/4 h led to 2.6 (for spruce), and to 5.5 (for beech) higher mass losses than at 180 °C/4 h. Significant difference between mature and juvenile wood concerning the influence of the temperature level upon the mass loss was noticed only for beech. As far as the influence of the time level is concerned, the heat treatment at 200 °C/4 h led to 2.17 (for lime), and to 3.06 (for beech) higher mass losses than at 200 °C/1 h. Juvenile wood samples were less affected than mature wood samples by the time level.
2. The heat treatment conditions which led to a mass loss of maximum 5% in each case were: 200 °C/3.5 h (mature spruce), 200 °C/5 h (thin spruce), 200 °C/3 h (mature pine), 200 °C/3.7 h (thin pine), 200 °C/3.2 h (mature lime), 200 °C/2 h (thin lime), 200 °C/3 h (mature beech), and 200 °C/2.7 h (thin beech).
3. The maximum ASE value among all wood species was obtained for small-diameter lime wood at 200 °C after 4 h (ASE_{rad} = 66.3%).
4. Compared to mature spruce, small-diameter spruce wood had higher radial ASE, but lower tangential ASE, so the volumetric ASE resulted similar. No significant improvement in the behavior of small-diameter wood compared to mature wood could be established. Both were well suited for heat treatment. The best results were obtained at 200 °C after 4 h; the expected volumetric ASE was 46%. The volumetric swelling was reduced by half, from a range of 13.7 to 14.1% to a range of 7.4 to 7.6%.
5. Black pine wood was less suited to heat treatment than spruce. It was more prone to checking and the ASE values were much lower than in the case of spruce at similar mass losses. The higher density, the presence of heartwood and resin channels are considered responsible for this behavior.
6. The results obtained from lime wood showed that this species is well suited for heat treatment. Better results in terms of shape and dimensional stabilization were obtained from small-diameter wood. The heat treatment conditions recommended for 20-mm-thick wood samples were as follows: 200 °C and 3.2 h if they originate from mature trees, and 200 °C and 2 h if they originate from thinning operations. The expected volumetric ASE under these conditions is 50% and the volumetric swelling was reduced by half, from a range of 11.8 to 17.2% to a range of 6.6 to 8.2%. An interesting aspect noticed with lime wood was that the ratio between the tangential and radial swelling decreased significantly with increasing severity of the heat treatment conditions. This means that heat-treated lime has better shape stability and is less prone to warp than untreated lime wood.
7. The results obtained from beech wood were also quite good. However, the mature wood behaved better under heat treatment than small-diameter wood. The volumetric ASE results at 200 °C after 6 h exceeded 55%, but they were correlated with a mass loss of 9.8 to 9.9%. Therefore, the heat treatment conditions recommended for 20-

mm-thick beech wood are as follows: 200 °C and 3 h for boards originating from mature trees, and 200 °C and 2.7 h if they originate from thinning operations. The expected volumetric ASE under these conditions is 45%, and the volumetric swelling is reduced by half, from a range of 20.6 to 22.6% to a range of 10.6 to 12.6%.

8. The main finding of this research refers to the comparative effect of heat-treatment upon juvenile and mature wood, respectively. It was found that the dimensional stabilization is better for small-diameter spruce, pine and lime (the soft species) than for the mature wood of these species (ASE_{vol}=49.7% compared to 39.3% for spruce, 38.6% compared to 38% for pine, 52.3% compared to 44.4% for lime), while for the hardwoods (beech), the dimensional stabilization is better for mature wood (with ASE_{vol}=48.5 compared to 43.5% for the small-diameter wood).

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