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Effect of Drying Technology on Aspen Wood Properties

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This article reports the impacts of three different drying treatments on selected physical and mechanical properties of European (*Populus tremula* L.) and hybrid (*P. tremula* × *tremuloides*) aspen wood. The material originates from 5 European aspen stands and 7 hybrid aspen stands in southern and central Finland. After processing the logs at a saw mill, sawn timber samples were dried using 1) conventional warm air drying, 2) press drying, or 3) heat treatment into Thermo-S grade by the Finnish Thermowood® method. Finally, small clearwood specimens were manufactured from different within-stem positions for the measurements of physical and mechanical properties. Both press dried and heat treated specimens absorbed water at significantly slower pace than the conventionally dried specimens. In normal climate, the conventionally dried, press dried and heat treated specimens conditioned at equilibrium moisture contents of 12.2, 8.7, and 8.9 per cent, respectively. It appears that the butt logs between 2–6 metres contain the lightest and, thus, weakest wood in aspen stems. Radial compression strength was at its highest in heat treated specimens, whereas conventionally and press dried specimens did not differ from each other. Press dried specimens had the highest longitudinal compression strength, also heat treated specimens showed higher values than the conventionally dried ones. Radial Brinell hardness of press dried specimens was higher than that of conventionally dried or heat treated specimens. Both modulus of elasticity and modulus of rupture were at their highest in press dried specimens. Irrespective of the drying treatment, the tangential shear strength of European aspen specimens was approximately 5% higher than that of hybrid aspen. Heat treated specimens indicated significantly lower tangential shear strength values than the conventionally dried ones. In case of both aspen species, the longitudinal tensile strengths of heat treated specimens were significantly lower than those of conventionally and press dried specimens. Heat treated specimens had the highest variability among the results. The inherent flaws in aspen wood material, e.g., wetwood and density fluctuations, increase especially the property variability of heat treated wood.

Keywords heat treatment, modification, press drying, stability, strength
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1 Introduction

Wood properties can be modified by tree breeding, resulting in improvements of characteristics such as annual ring width, branchiness, and wood density (e.g., Zobel and van Bujtenen 1989). Modifying the properties of the currently available wood, however, requires technical means that are related to the processing stages from round timber to wood products. Technical modifications aim at improving, e.g., weather resistance, decay resistance, dimensional stability in changing humidity conditions, colour, paintability or mechanical performance of wood (e.g., Hill 2006). In other words, the range of wood's usability is broadened by improving its properties by technical means. Often, the modifications are related to wood drying. There are a range of wood modification methods available: chemical, thermal, impregnation, polymerisation and enzymatic treatments (Hill 2006). Some of the commercialised processes, such as the Thermowood® process, have been based on the findings of pioneering wood scientist over the past decades. However, some of the newer modification methods apply the technologies adopted from non-wood systems. One already commercialised example of is the Belmadur® treatment of wood with 1,3-dimethylol-4,5-dihydroxyethylenurea (DMDHEU). Here, the treatment, per se, has been adopted from the fabric and textile industries producing wrinkle-free fabrics (Jones 2007).

Generally, some tree species are more in keeping with certain modification technologies than the others. A good example is pressure impregnation that can be applied only for species with proper anatomical structure resulting in sufficient transfer of fluids. Also high wood density renders many modification methods. Hence, ideal raw material has intermediate or relatively low density, high porosity, and uniform structure both considering the micro (within ring) and macro (within stem) structure of wood. Aspen species fulfil these anatomical requirements (e.g. Perng 1985, Bjurhager 2008).

Aspen (*Populus* sp.) wood is light-coloured, almost odourless, tasteless, and uniform of its visual texture. In North Europe, its principal end uses are pulping and energy production. Aspen fibres provide high quality magazine papers with good opacity and printability. However, due to its lightness, uniform appearance and low heat conductivity aspen is also valued material for interior uses, such as panelling, cabinets and sauna benches (e.g., Verkasalo 1999, Heräjärvi et al. 2006). In North America, local poplar species have been successfully used as a raw material of OSB (oriented strand board) and LVL (laminated veneer lumber) for decades already (Hoover et al. 1984, Bao et al. 2001, Lee et al. 2001, Wang and Dai 2005). In addition, poplars are occasionally used as construction lumber (e.g., Bailey 1973, Robichaud et al. 1974, Beauregard et al. 1992, Kretschmann et al. 1999, Serrano and Cassens 2001), surface veneers and plywood (Söyrilä 1992, Vadla 1999), as well as engineered wood products such as parallel strand lumber PSL (Liu and Lee 2003).

The main challenges related to aspen in wood product manufacturing processes in Finland are: 1) raw material availability, 2) quality of logs and further products (colour defects, wetwood, large branches, internal stresses, 3) drying of sawn wood (twisting, non-uniform final moisture content, end-checks, collapse of cellular structure) (e.g., Kemp 1959, Mackay 1975ab, Maeglin et al. 1985, De Boever et al. 2005, Heräjärvi et al. 2006). Tangential swelling can be even 10% in sapwood, which causes severe twisting problems especially in pieces that contain both heartwood and sapwood.

Cross-breeding experiments made between European aspen (*Populus tremula* L.) and North American trembling aspen (*P. tremuloides* Michx.) in the 1950's resulted in a hybrid (*P. tremula* × *tremuloides*) that grows exceptionally fast in boreal conditions. The yield studies have indicated almost 300 m^3/ha yields during a 25-year rotation (e.g., Hynynen et al. 2004). As a result of the active aspen planting campaign in the late 1990's and early 2000's, there are now approximately 1000 hectares of hybrid aspen plantations in Finland (Holm 2004). Their primary use is intended to be pulp and paper, but also a considerable volume of saw or veneer logs appears to be available from those stands in twenty–thirty years (see: Heräjärvi et al. 2006). Only fragmented information has been available on the differences of European and hybrid aspen wood from the viewpoint of woodworking and processing.

The objective of this paper is to compare some relevant physical properties of European and hybrid aspen clearwood specimens after three different drying treatments (conventional warm air drying, press drying and heat treatment) and conditioning in a normal climate.

Table 1. Conventional warm air drying schedule used for aspen sawn timber.

Time, h	Dry temperature, °C	Wet bulb temperature, °C
0	50	43
24	60	56
48	60	54
96	60	50
144	60	40
168	45	35

2 Materials and Methods

The material originated from five mature *P. tremula* and seven *P. tremula* × *tremuloides* stands in southern Finland. The stands were selected based on the following criteria: large enough area (ca. 0.5 ha minimum), proper age (max. 40 years for *P. tremula* × *tremuloides*, 60 years for *P. tremula*), and sufficient technical quality of trees to provide saw logs. The *P. tremula* stands were of natural origin, whereas the *P. tremula* × *tremuloides* stands were planted. A total of 75 trees were felled from the stands for further analyses. The sample trees were randomly selected from all aspen trees that fulfilled the requirements for saw logs in that particular stand.

Each felled stem was cross-cut into 2-metre-long logs, which were transported to a saw mill and sawn into 35-mm-thick boards. A sawn timber sample of approximately 1 m^3 of both aspen species was chosen for three drying treatments resulting, thus, six strata to compare. Detailed description of the initial stand measurements, selection of sample trees, sample tree measurements and processing of the specimens is given in Heräjärvi et al. (2006).

Conventional warm-air drying is the most commonly utilised method for drying aspen lumber. The warm-air drying schedule used in this study (Table 1) is commonly used schedule for aspen wood drying in Finland.

Press drying is a developing technology, where physical compression is used to reduce the drying induced deformations (twisting and warping), and if wanted, to increase the density of the dried wood. In case of this study, the materials were press dried using the kiln by Arboreo Ltd. In this system, green lumber is set between porous aluminium plates that are heated up to maximum temperature of 130 °C. During the drying process, the plates are hydraulically pressed with a force of 0.15 MPa (heating phase) to 0.3 MPa (drying phase) (equal to 1.5–3 kg/cm^2) in order to prevent distortion and slightly increase the density of wood. As a result of heating the plates, moisture moves towards the surface of lumber, and finally evaporates through the pores in the plates. The total drying time in this case was 36 hours. Heating increases wood's viscosity, thus enabling larger elastic and plastic deformations in the cells.

Heat treatment according to the Finnish Thermowood® process (see: Thermowood® handbook 2003) is nowadays an industrial modification method providing improved visual and technical quality for wood. The wood material is heated at, at least 180 °C and protected from burning by using water vapour as a shield gas. The heat treatment schedule used in this material is presented in Table 2.

The following specimens were prepared from the dried wood:

- Moisture swelling and drying shrinkage: 20×20×30 mm (according to Kučera 1992): 488 specimens.
- Water absorption: 32×100×100 mm, 12 specimens per species and drying treatment: 72 specimens.
- Modulus of elasticity (MOE) and modulus of rupture (MOR) in radial three-point static bending (Kučera 1992): 485 specimens.
- Compression strength in longitudinal and radial directions (Kučera 1992): 20×20×60 mm: 972 specimens.
- Brinell hardness: 100×100×25 mm (EN 1534 (2000), slightly altered): 494 specimens.
- Tensile strength in longitudinal direction (Kučera 1992): 133 specimens (Fig. 1).

Table 2. Heat treatment schedule used for aspen sawn timber.

Stage	Procedure		
Pre-heating	Temperature raised to 95°C using steam at 150°C; heating rate 35°C/h		
Drying	Time, h	Dry temperature, °C	Wet temperature, °C
(steam feed	0	90	85
ca. 3 kg/m^3/h)	15	130	98
Heat treatment	Time, h	Dry temperature, °C	
	15	130	
	17	160	
	19	180	
	21	180	
Cooling	Final temperature 90°C, cooling rate 15°C/h		
Conditioning	Conditioning time 15 h, dry temperature 90°C, ambient humidity 85%		
Final moisture content of wood 7%, total process time 44 h			

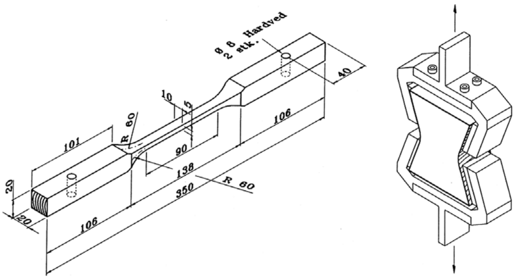

Fig. 1. Tensile strength test specimen in the parallel to the grain direction (left). Tensile strength test specimen in the radial direction (right). Original drawings: Kučera (1992).

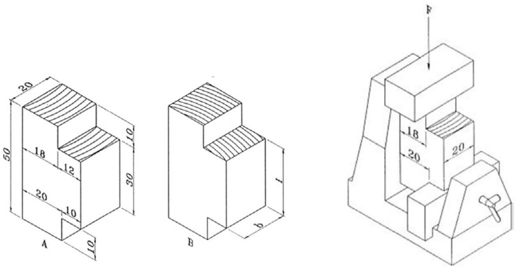

Fig. 2. Specimen shapes and dimensions in the radial (left) and tangential (middle) shear strength tests and the apparatus to measure the shear strength (right). Original drawings: Kučera (1992).

- Tensile strength in radial direction (Kučera 1992, slightly altered): 167 specimens (Fig. 1).
- Shear strength in radial and tangential directions (Kučera 1992): 143 and 147 specimens, respectively (Fig. 2).

The specimens were prepared so that a representative series was obtained from a single tree, taking into account the within-stem location both in vertical and horizontal directions. The heights, from which the specimens originated, were 1–2 m, 3–4 m, 7–8 m, and 15–16 m. However, a representative horizontal series of specimens could not be prepared for the tensile strength and shear strength tests. Therefore, only species and treatment wise results are shown.

Shrinkage and swelling characteristics were measured in laboratory by determining the dimensions (digital calliper, 0.01 mm accuracy), weights (digital scale, 0.01 g accuracy) and volumes (either gravimetricly (wet specimens) or based on dimensions (specimens with moisture content (MC) below the fibre saturation point (FSP)) of the specimens at different moisture contents. The measurements were done in four different stages:

- Stage 1: specimens conditioned in normal climate (T: 20 ± 2 °C, RH: 65 ± 3%).
- Stage 2: specimens moisturised above the FSP.
- Stage 3: specimens dried down to zero per cent MC.
- Stage 4: specimens moisturised for the second time above the FSP.

The water absorption experiments were not based on any standards. The specimens were simply oven dried down to zero moisture content, weighed and sunk into water. Then they were weighed again after 1, 2, 3, 4, 7, 11, 18 and 30 days of sinking.

Prior to the tests of the mechanical properties, all specimens were conditioned in normal climate (temperature T: 20 ± 2 °C, relative humidity RH: 65 ± 3%) as long as their mass did not change anymore. Mechanical properties were measured using a Matertest FMT-MEC 100 material testing device. In radial compression tests, the compressive stress increases, in theory, infinitely, as the cellular structure of wood flattens. Hence, modulus of rupture cannot be determined. Stress at proportional limit was used instead.

Standard EN 1534 (2000) reports the method for determining the Brinell hardness of wood. There, the diameter of an indentation caused by a steel ball pressed on the surface of the specimen using a constant force of 1.0 kN is measured in two directions perpendicular to each other. Brinell hardness is then calculated based on the area of the indentation. However, especially in case of hard surfaces (e.g., press dried wood), the diameter of the indentation is difficult to measure objectively in parallel to the grain direction, since the specimen's surface also deforms aside the steel ball. Therefore, in this study, the depth of the indentation was used as a variable based on which the area of the indentation was calculated. The depth could be measured exactly and objectively by the testing machine, and by this means the differences in the Brinell hardness could be detected more detailed. This method does not take into account either the anisotropy of wood or the elastic reverse of the indentation after load removal.

The differences in the mean values of study variables between the strata were compared by using t-test for variables that were normally distributed, and Mann-Whitney U-test for variables that were not normally distributed.

3 Results

3.1 Shrinkage and Swelling

Table 3 and Fig. 3 show the shrinkage and swelling behaviour of European and hybrid aspen wood in longitudinal (L), tangential (T) and radial (R) directions. Tangential swelling of conventionally dried hybrid aspen was significantly larger than that of European aspen (t-test: p = 0.027). After conditioning, heat treated and press dried specimens had approximately 2.5 unit % lower equilibrium moisture content (EMC) than the conventionally dried ones. Swellings in T, R and L directions did not differ between the specimens

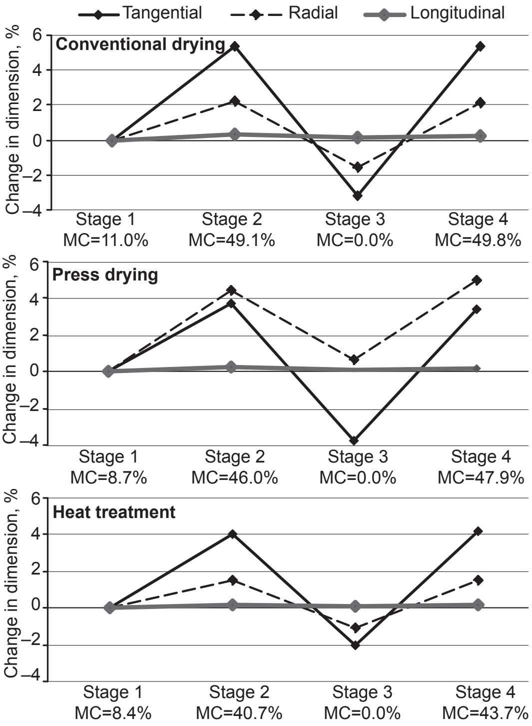

Fig. 3. Moisture swelling and drying shrinkage of specimens dried by different methods. Stage 1: specimens conditioned in normal climate (T: 20 ± 2 ºC, RH: 65 ± 3%). Stage 2: specimens moisturised above the FSP. Stage 3: specimens dried down to zero per cent MC. Stage 4: specimens moisturised for the second time above the FSP.

Table 3. Swelling of specimens from 7–12% MC to the fibre saturation point FSP as a function of distance from the pith. E = European aspen, H = hybrid aspen.

Swelling, %	Distance from the pith, mm 0–35 E	 H	 All	39–74 E	 H	 All	78–113 E	 H	 All
Conventionally dried specimens									
Tangential	4.5	5.0	4.7	5.3	5.6	5.5	5.6	6.0	5.8
Radial	2.4	2.3	2.3	2.0	2.3	2.1	2.0	2.2	2.1
Longitudinal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Volumetric	12.9	13.0	12.9	13.1	13.1	13.1	13.2	13.1	13.1
Press dried specimens									
Tangential	3.6	3.2	3.4	3.7	3.7	3.7	3.9	4.1	4.0
Radial	4.0	4.6	4.3	4.5	4.1	4.3	5.4	4.0	4.7
Longitudinal	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.3	0.2
Volumetric	12.9	12.9	12.9	13.0	12.9	13.0	13.2	13.0	13.1
Heat treated specimens									
Tangential	2.5	2.9	2.7	4.3	4.0	4.2	4.9	4.6	4.7
Radial	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.6
Longitudinal	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Volumetric	12.3	12.4	12.4	12.6	12.5	12.5	12.7	12.7	12.7

prepared from the base and from the top of trees (t-tests: $p=0.074$–0.822). On the other hand, tangential swelling was the higher the closer to the stem surface the specimen originated. Although the differences in dimensional changes between the drying treatments were small, they were significant in T and R directions. Tangential swelling from stage 1 to stage 2 was the biggest in conventionally dried specimens (5.4%), the difference being significant both compared to press dried (3.7%) and heat treated specimens (4.0%). Conventionally dried specimens also shrank more than the others from stage 2 to stage 3, as much as 8.6% on average. Press dried specimens swelled most (4.4%) from stage 1 to stage 2. The structure of press dried specimens reversed from the compressed state as a result moisturising, which could be seen from the radial thickness swelling. Also Pearson correlation coefficient showed negative (–0.390) and significant ($p<0.001$) dependence between T and R swellings for press dried specimens. Thus, press drying not only reduced the thickness of sawn timber but also increased its width, both of which appeared to spring back after moisturising. According to the Mann-Whitney U-test, heat treated specimens swelled less than the other specimens from measurement stage 1 to stage 2 in L direction ($p<0.001$).

3.2 Water Absorption

Hybrid aspen absorbed water slightly faster than European aspen, the difference being proportional to the average difference between the densities of the two aspen species. Heat treated specimens absorbed water most slowly, and absorption velocity of press dried specimens was closer to heat treated than conventionally dried specimens. Fig. 4 shows the water absorption for the 100 × 100 × 32 mm specimens in 30 days.

3.3 Bending

Table 4 shows the average MOE, MOR, air-dry densities and numbers of annual rings as a function of specimen's distance from the tree pith. The average MOR of press dried specimens (79.9 MPa) was higher than that of conventionally dried and heat treated specimens (Mann-Whitney U-tests: $p<0.001$). MOR of heat treated specimens was lower but MOE significantly (Mann-Whitney U-test: $p=0.011$) higher than in case of the conventionally dried specimens. MOE of press dried and heat treated specimens did not differ. Press dried specimens had also more narrow annual rings than the other specimens, the dif-

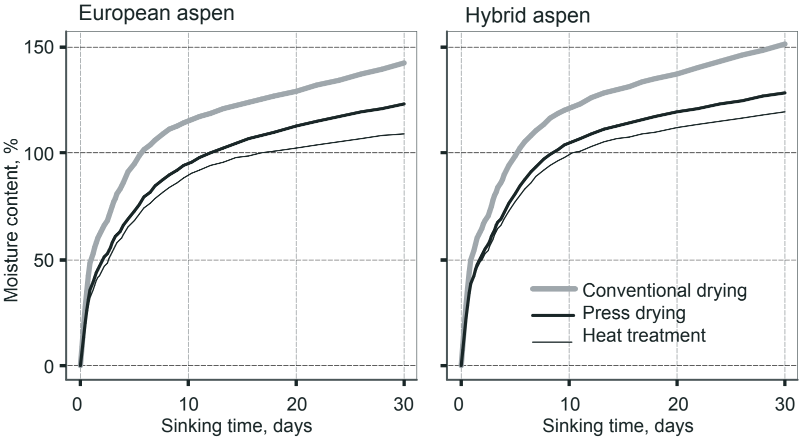

Fig. 4. Water absorption of the 100×100×32 mm aspen wood specimens as a function of time. The curves are drawn based on the raw measurement data.

ference being significant (Mann-Whitney U-tests: p=0.016–0.019). Specimens vertical position in stem did not have any influence on its MOE or MOR (t-tests: p=0.277–0.926). On the other hand, MOR increased 19% for conventionally dried, 28% for press dried, and as much as 85% for heat treated specimens from the pith towards the tree surface. Similarly, MOE increased 25%, 23% and 20% for conventionally dried, press dried and heat treated specimens, respectively. Both MOE and MOR of European aspen were higher than those of hybrid aspen.

3.4 Compression

Table 4 shows the compression strengths, air-dry densities and numbers of annual rings in 20×20 mm cross cuts of the specimens. Compression times in radial and longitudinal tests were 15.5–20.6 and 49.1–91.8 seconds, respectively. Radial compression strength was the highest in heat treated specimens (Mann-Whitney U-test: p<0.001). On the other hand, the limit of proportionality was reached within the shortest time in case of heat treated wood. Press dried specimens lasted the highest longitudinal compression stress prior to the failure, 43.9 MPa, on average. The time required to crush the specimen was the shortest in press dried specimens. Longitudinal compression strength was the lowest in conventionally dried specimens (t-tests: p<0.001). However, the density of conventionally dried European aspen specimens was clearly lower than that of other specimens. Heat treated specimens had the highest radial compression strength. Specimen's radial compression strength increased 20–30% from the pith to 75-mm-distance from the pith. The increment was the highest for heat treated specimens and the lowest for conventionally dried ones. Similarly, longitudinal compression strength increased only 12–13% from the tree pith towards the surface. The respective increments in density and number of annual rings per cm were 8–11% and 33–75%. Differences in the radial compression strengths between the two aspen species were insignificant irrespective of the drying treatment (t-tests: p=0.144–0.336). Longitudinal compression strength, on the other hand, was higher in European aspen (t-tests: p<0.028) that also had more annual rings than the hybrid aspen (t-test: p<0.001).

3.5 Brinell Hardness

Brinell hardnesses of the specimens are presented in Table 4 as a function of the measurement point (35, 74 and 113-mm distance from the tree pith). Average hardness of press dried specimens was 16.81 MPa which is approximately 2.5 MPa more than the hardness of the other specimens, the

Table 4. MOR, MOE, radial (R) and longitudinal (L) compression strengths, Brinell hardness as well as the air-dry densities and numbers of annual rings in 20 × 20 mm cross cut surface of the bending and compression test specimens as a function of distance from the tree pith. E = European aspen, H = hybrid aspen.

	Distance from the pith, mm											
	0–35			39–74			78–113			All		
	E	H	All	E	H	All	E	H	All	E	H	All
CONVENTIONALLY DRIED SPECIMENS												
Bending												
MOR, MPa	60.3	62.9	62.2	71.2	67.1	68.9	75.3	72.9	74.0	71.5	68.0	69.4
MOE, GPa	9.86	10.8	10.6	12.3	12.2	12.2	13.9	12.7	13.2	12.6	12.0	12.3
Density, kg/m^3	388	413	406	415	416	416	436	441	439	420	423	422
Annual rings	4.8	3.2	3.6	4.9	3.6	4.2	6.8	4.5	5.5	5.6	3.8	4.5
Compression												
R, MPa	3.9	4.2	4.1	4.9	4.6	4.7	5.2	4.9	5.0	4.8	4.6	4.7
L, MPa	33.1	32.4	32.6	36.2	35.4	35.7	38.3	35.8	36.9	36.6	34.9	35.6
Density, kg/m^3	390	414	405	410	417	414	439	437	438	417	422	420
Annual rings	4.3	2.8	3.3	5.0	3.6	4.2	7.3	4.7	5.9	5.7	3.7	4.5
Brinell hardness (EMC of the specimens: 12.2%)												
Hardness, MPa	13.1	11.7	12.2	15.3	14.9	15.1	16.4	16.7	16.5	15.0	14.2	14.5
Density, kg/m^3	407	417	414	430	433	432	449	439	444	429	429	429
PRESS DRIED SPECIMENS												
Bending												
MOR, MPa	71.1	65.6	68.2	84.4	77.4	80	90.1	85.3	87.2	83	77.7	79.9
MOE, GPa	12.1	11.2	11.6	13.9	12.9	13.2	15.3	13.7	14.3	13.9	12.8	13.3
Density, kg/m^3	423	415	419	452	411	426	469	422	441	450	415	429
Annual rings	5.0	3.8	4.4	5.9	4.4	4.9	5.8	4.7	5.1	5.6	4.4	4.9
Compression												
R, MPa	4.4	4.1	4.2	5.0	4.8	4.8	5.6	5.3	5.4	5.0	4.8	4.9
L, MPa	42.9	39	40.7	45.4	43.4	44.2	47.2	44.3	45.5	45.4	42.8	43.9
Density, kg/m^3	419	400	408	444	420	429	464	448	455	445	424	432
Annual rings	5.0	3.4	4.1	6.2	4.6	5.2	6.0	5.1	5.5	5.8	4.5	5.0
Brinell hardness (EMC of the specimens: 8.7%)												
Hardness, MPa	17.1	13.1	14.9	18.5	16.3	17.1	21.0	17.4	18.9	18.6	15.5	16.8
Density, kg/m^3	462	427	443	467	418	437	472	428	446	466	423	441
HEAT TREATED SPECIMENS												
Bending												
MOR, MPa	40.5	41.2	40.9	64.1	54.7	58.9	77	74.1	75.6	65.4	58.7	61.8
MOE, GPa	12.6	11.2	11.8	13.8	12.2	12.9	15.2	13.1	14.2	14.2	12.3	13.2
Density, kg/m^3	414	392	401	438	394	414	454	423	439	441	404	421
Annual rings	4.4	3.4	3.8	4.8	3.6	4.2	5.5	4.4	5.0	5.0	3.9	4.4
Compression												
R, MPa	4.6	4.4	4.5	5.3	5.0	5.1	5.8	5.9	5.9	5.4	5.2	5.3
L, MPa	40.9	38.3	39.5	44.9	38.8	41.4	45.6	44.1	44.9	44.4	40.6	42.4
Density, kg/m^3	416	383	399	433	394	412	457	427	442	439	404	421
Annual rings	4.2	3.4	3.8	4.8	3.7	4.2	5.5	4.7	5.1	5.0	4.0	4.5
Brinell hardness (EMC of the specimens: 8.9%)												
Hardness, MPa	16.0	11.7	13.7	15.6	12.6	14.1	15.9	15.9	15.9	15.8	13.3	14.5
Density, kg/m^3	445	412	427	422	410	416	460	426	443	440	415	427

Table 5. Tensile and shear strengths of conventionally dried (CD), press dried (PD) and heat treated (HT) clearwood specimens of European and hybrid aspen.

	European aspen			Hybrid aspen		
	CD	PD	HT	CD	PD	HT
Tensile strength, radial						
Mean, MPa	3.69	3.50	3.06	3.37	3.15	2.07
Std. error of mean	0.15	0.10	0.09	0.07	0.11	0.10
Number of specimens	15	25	32	42	29	24
Tensile strength, longitudinal						
Mean, MPa	102.2	82.0	64.3	92.6	88.6	58.1
Std. error of mean	2.7	3.2	5.4	3.7	3.7	5.5
Number of specimens	25	23	21	21	26	17
Shear strength, radial						
Mean, MPa	9.55	8.47	8.39	8.78	8.27	7.87
Std. error of mean	0.20	0.28	0.32	0.31	0.24	0.30
Number of specimens	24	24	26	22	25	22
Shear strength, tangential						
Mean, MPa	7.05	6.83	6.08	6.53	6.52	5.70
Std. error of mean	0.14	0.21	0.19	0.17	0.13	0.21
Number of specimens	25	24	27	24	24	23

difference being significant (t-tests: $p < 0.001$). Hardness of conventionally dried and heat treated specimens did not differ (t-test: $p = 0.965$). Hardness was not influenced by the vertical within-stem position of the specimen (t-test: $p = 0.417$), but horizontally it increased from the pith towards the surface approximately 35% in conventionally dried specimens, 27% in press dried specimens and 16% in heat treated specimens. Conventionally dried European aspen specimens did not differ from hybrid aspen specimens (t-test: $p = 0.223$). However, in case of press dried and heat treated specimens, the between-species difference was significant (t-tests: $p = 0.005$ and 0.001).

3.6 Tension

The average longitudinal and radial tensile strengths are presented in Table 5. In this chapter, all the significance levels are based on Mann-Whitney U-tests.

In case of European aspen specimens in longitudinal tensile test, the differences between the treatments were significant ($p < 0.017$). In hybrid aspen specimens, the average longitudinal tensile strengths between conventionally and press dried specimens did not differ ($p = 0.748$), but heat treated specimens showed significantly ($p < 0.001$) lower values. Considering the different treatments, aspen species was a significant factor in case of conventionally dried specimens ($p = 0.032$), whereas for the other treatments, no differences could be detected ($p = 0.105$–0.561).

Radial tensile strengths of European aspen did not differ between conventionally and press dried specimens ($p = 0.192$). Again, heat treated specimens were significantly weaker than the press ($p = 0.006$) and conventionally dried ones ($p = 0.002$). The results were similar for hybrid aspen specimens, i.e., there were no differences between conventionally and press dried specimens ($p = 0.147$), and heat treated specimens had significantly lower radial tensile strength than conventionally ($p < 0.001$) and press dried ($p < 0.001$) ones. There were significant between-species differences in case of all treatments ($p < 0.041$).

3.7 Shear

Table 5 shows the differences in the radial and tangential shear strengths between the species and treatments. Here, all significance levels presented are based on Mann-Whitney U-tests.

In radial shear strength test, conventionally dried European aspen specimens were significantly stronger than press dried ($p = 0.005$) and heat treated ($p = 0.002$) specimens. Press dried and heat treated specimens, on the other hand, did not differ from each other ($p = 0.698$). The average radial shear strength of conventionally dried hybrid aspen specimens was significantly higher than that of heat treated specimens ($p = 0.024$), but did not differ from the mean value of press dried specimens ($p=0.153$). Also the difference between press dried and heat treated specimens was insignificant ($p = 0.153$). The results differed significantly between the aspen species in case of conventionally dried specimens ($p = 0.010$), whereas press dried ($p = 0.562$) and heat treated ($p = 0.214$) specimens had similar radial shear strengths irrespective of the species.

Finally, tangential shear strength of conventionally dried European aspen specimens did not differ from the press dried ($p = 0.368$) specimens but was significantly higher than that of heat treated specimens ($p = 0.001$). Also press dried specimens were stronger than the heat treated ones ($p = 0.024$). In case of hybrid aspen, tangential shear strengths between conventionally and press dried specimens did not differ ($p = 0.821$). Heat treated specimens, on the other hand, were significantly weaker than the conventionally ($p = 0.001$) or press dried ($p < 0.001$) specimens. The average tangential shear strength of conventionally dried European aspen specimens was significantly higher than that of hybrid aspen specimens ($p = 0.012$), whereas in case of press dried specimens, the species did differ from each other ($p = 0.224$). Heat treated European aspen had slightly higher average tangential shear strength than hybrid aspen, but the difference was only indicative ($p = 0.089$).

4 Discussion

This paper aimed at comparing some physical and mechanical properties of European and hybrid aspen clearwood specimens after three different drying treatments (conventional warm air drying, press drying and heat treatment). Some of the results presented in this article have also been reported in previous project reports (see: Heräjärvi et al. 2006, Junkkonen and Heräjärvi 2006, Heräjärvi 2007).

Based on measurements of previous materials (see: Heräjärvi et al. 2006), it is known that the equilibrium moisture content (EMC) of the specimens differed according to the drying treatment. Thus, heat treated and press dried specimens should have been conditioned at approximately 20–30 per cent higher RH in order to get them into the same EMC with the conventionally dried ones. The results concerning the mechanical properties of heat treated and press dried specimens are therefore overestimates in comparison to the conventionally dried specimens. However, this study aimed at detecting the differences between the specimens in equal environmental conditions, and neglected the possible differences in the EMC of wood.

One problem related to the manufacture of press dried specimens is that some wood was inevitably lost in order to prepare specimens with wanted dimensions. Thus, the surface with most compressed cellular structure, highest density and best mechanical performance, was planed away.

Since aspen wood is mainly used in decorative or visual end uses, often its density and mechanical performance are of minor importance. However, in some end uses, such as ice hockey sticks, stiffness and lightness are the most important material requirements. Furthermore, in damp conditions such as saunas, or under weather exposure, the low density and high porosity improve aspens usability. Perng et al. (1985) noticed that aspens heartwood contains lots of extractives that hinder the fluid transportation. This effects not only the dimensional stability but obviously also the weather resistance of wood.

The moisture induced dimensional changes between European and hybrid aspen were irrelevant, but heat treated wood showed clearly different results compared to the other treatments. Also the radial swelling of press dried specimens was significantly larger than in case of the other treatments. Concerning the shrinkage and swelling properties of conventionally dried aspen, Kärki (2001) and Peters et al. (2002) reported results that were rather equal to the results of this study.

Brinell hardness was not measured exactly according to EN 1534 (2000) (see: Materials and methdods). Therefore, the results are, technically speaking, not comparable with the values presented in literature. However, the between-stratum comparability of the hardnesses became more reliable when slightly modified measurement system was used in this study. The low hardness of aspen wood limits its end uses. However, it also has a positive side: soft and porous wood surface is more comfortable for human touch since it feels warm and absorbs moisture rapidly.

Measuring the longitudinal compression strength is rather straightforward procedure, but very sensitive to certain errors. The first problem is related to the possibility of buckling of the specimen during the test. This possibility is pronounced if the cross cut surfaces of the 60-mm-long specimens are not exactly parallel. In this study, some specimens were disqualified from the data due to buckling. Another problem is the friction between the specimen and steel press plates. Friction is caused as the specimens cross cut surface area increases during the test as a function of Poisson ratio of aspen wood. This problem cannot be eliminated. Jalava (1945) reported that at 12% MC, the longitudinal compression strength of European aspen is 42.5 MPa. In this study, press dried and heat treated specimens showed slightly higher values, whereas conventionally dried specimens had lower compression strength. Otherwise, heat treatment generally decreased the mechanical performance of aspen in comparison to the other treatments. For example, in the radial compression strength tests, the limit of proportionality was reached within the shortest time in case of heat treated wood. This indicates that heat treated aspen is stiff until certain compressive stress, after which it collapses. Such behaviour is typical for fragile materials (e.g., Madsen 1992, Smith et al. 2003, Thelandersson 2003).

This study showed that both European and hybrid aspen wood provide satisfactory physical and mechanical properties for selected interior and exterior wood products. Properties can be further improved by varying modifications that change not only the water uptake and swelling and shrinkage behaviour, but also the mechanical properties. Some wood properties of aspen species change markedly as a function of the distance from the pith. Considering aspen wood's density, the same was noticed by (Heräjärvi and Junkkonen 2006). This might be problematic considering the current markets that increasingly require homogeneity from wood products.

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