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EFFECT OF COMBINED COMPRESSION AND THERMAL MODIFICATION ON MECHANICAL PERFORMANCE OF ASPEN AND BIRCH WOOD

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Abstract

As a wood modification method, a combination of compression and thermal modification of solid wood aims at increasing the durability and strength of wood products. The objective of this study was to investigate the changes in density, hardness, modulus of elasticity and modulus of rupture as a result of combined compression and thermal modification of sawn timber in industrial scale modification process. European aspen and Silver birch sawn timber were compressed at two different moisture contents. Optional thermal modification at 190°C was used as a means to reduce the post-compression set recovery. Density along the thickness profile, Brinell hardness, modulus of elasticity (MOE) and modulus of rupture (MOR) of modified and reference specimens were measured. The density profile through the thickness was dependent on wood species and modification process parameters. The Brinell hardness profile along the thickness correlated with the changes in density profile. Compared to the untreated reference specimens, the MOE of aspen wood increased with all combinations of compression and thermal modification, whereas the MOE values of birch wood did not change significantly. MOR increased only in aspen wood when it was compressed without thermal modification. In conclusion, the changes in mechanical properties of low or medium density diffuse porous hardwoods can be adjusted and improved using a combination of compression and thermal modification.

Key words: *Brinell hardness; densification; modulus of elasticity; modulus of rupture.*

INTRODUCTION

Mechanical properties of wood are strongly related to its density. In case of light weighted wood species, the low density restricts the use of wood in applications where durability and strength is required. However, the low density wood species are abundant and considered as relatively low price materials. This makes them an interesting raw material source, as soon as their mechanical performance could be improved. The most abundant hardwood species in Finland, birch (basic density approximately 480-520kg/m^3 (Heräjärvi 2004)) and aspen (390-440kg/m^3 (Heräjärvi 2009)), represent medium and low density species, respectively. Birch is a common raw material in products where hardness and wear resistance are needed, i.e., in parquet and furniture. Due to the low density and softness of aspen wood, it is used in applications where hardness is not needed, e.g., paneling or sauna benches.

Compression is a process whereby the wood density is increased by reducing the void volume of lumens in the wood material (Navi & Sandberg 2012). The viscoelastic behaviour of wood plays an important role in compression. When heated, wood softens, with the lignin, hemicellulose and cellulose displaying different softening behaviours depending upon the temperature and moisture content (Hillis & Rozsa 1978, Uhmeir et al. 1998). Thus, when heated above its glass transition temperature, wood can be compressed without rupturing the cell walls (e.g., Rautkari et al. 2011). One of the emerging eco-friendly modification methods is the combined use of temperature, moisture and mechanical action, so called Thermo-Hydro-Mechanical (THM) treatment (Navi & Sandberg 2012).

Compression with heat and moisture is an essential part of particle board (e.g., Maloney 1993) and plywood (e.g., McKay 1997) manufacturing but it has not become a widespread treatment method for solid wood since there have been only few industrial systems available, and problems related with the set-recovery have not been totally solved. A lot of work has been carried out since the early 20th century to develop industrial wood compression and stabilisation methods (see: Rowell and Konkol 1987, Blomberg 2006, Rautkari 2012, Laine et al. 2013a). However, only few production scale applications have been commercialised, one of them being introduced in this paper.

OBJECTIVE

The main objective of the present research was to evaluate the changes in Brinell hardness, modulus of elasticity (MOE) and modulus of rupture (MOR) which may occur in wood as a result of THM treatment. Both tangential and radial sawing patterns and compression at two different stages of treatment process were compared for the two wood species. The objective was also to analyse the changes in mechanical properties in relation to changes in density.

MATERIALS AND METHODS

A total of 112 European aspen (*Populus tremula* L.) and 104 silver birch (*Betula pendula* Roth) boards were sawn from freshly harvested logs to nominal cross-cut dimensions of 40×100mm. Both tangentially and radially sawn boards were produced. The modification processes were carried out in a pilot modification kiln patented by Korwensuun Konetehdas Ltd, Finland (Fig. 1). Specimens for gravimetric moisture content (MC) and basic density measurements were cut from the ends of the boards before modification treatments. The length of the boards was then adjusted to 2,700mm, which is the effective length of the modification kiln.

The boards were modified using four different combinations of compression and thermal modification (Table 1). The system allows drying, compressing and thermal modification in a single process, and different combinations of process and modification parameters can be used. In the kiln, the boards are stacked between aluminium plates structured of hollow pipes and the compression is carried out using hydraulic press. The kiln air circulates through the hollows of aluminium plates which are also perforated in order to enable the evaporation of moisture from the wood surface. Air and wood temperature, MC of wood, compression force and degree of compression were measured, each at two different locations in the kiln. In this study, compression was started either when the wood material was green or when it was pre-dried down to 20% MC. In case of two modification processes for aspen, namely the ones including the thermal modification phase, the wood material had to be rewetted by immersing in water, because the wood had dried below the fiber saturation point during the storage before the start of the process. During the process, the wood temperature was first increased gradually up to 100 ºC during 3 hours, and stabilised until the MC of wood reached a level of 30%. Below the 30% MC, the wood temperature was raised up to 130 ºC for the rest of the drying phase. The target degree of compression for birch and aspen were set to 10% and 30%, respectively. The different degrees of compression were based on differences in the initial basic density of the species. Further on, half of the wood material of both species was thermally modified at 190 °C after the drying and compression phases.

The reference boards (N=27) were air dried outdoors until their average MC was approximately 15%. Then they were moved indoors and further dried in the conditions of the production facilities until they reached a final MC of 8–10%.

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Fig. 1.
A set of aspen boards (40×100×2700mm) before and after the compression and thermal modification process started at green state. Photos: Korwensuun Konetehdas Ltd.

Table 1

Combinations of compression and thermal modifications used in the processes. G = compression started with green wood, MC20 = compression started at 20% MC, TM = thermal modification, N = number of specimens

Process	N	Compression		Thermal modification
		Starting of compression	Target degree of compression	
Birch G	28	Green	10%	-
Birch G + TM	28	Green	10%	3 hours at 190°C
Birch MC20	24	At 20% MC	10%	-
Birch MC20 + TM	24	At 20% MC	10%	3 hours at 190°C
Aspen G	28	Green	30%	-
Aspen G + TM	28	Green	30%	3 hours at 190°C
Aspen MC20	28	At 20% MC	30%	-
Aspen MC20 + TM	28	At 20% MC	30%	3 hours at 190°C

Density

Gravimetric method was used to measure the average density of modified and reference wood material.

The density profile of compressed and reference specimens in the direction of board thickness was measured using X-ray microdensitometry. A slice of 10mm was cut from the end of each board, and these slices were further cut into rectangular specimens in the direction of board thickness using a twin blade circular saw. The cross dimensions of the specimens in the microdensitometry tests were 5×5mm, the length varying according to the actual thickness of each board. The specimens were not conditioned in order to avoid the possible set-recovery of densification before the density analysis. A voltage of 30kV and current of 25mA was used for X-ray intensity with an exposure time of 20ms, and the movement steps between measuring points being 25µm. The density profile of specimens through the thickness was transformed to density values at relative depths in order to compute the mean density profile within each process.

Brinell hardness

Specimens with length of 300mm were prepared from each board for Brinell hardness (HB) measurements. Approximately 60mm long steps were machined with spindle moulder to expose surfaces at different depths (0, 3, 6, 9 and 12mm) from the surface. HB of wood was measured and calculated at steps of 0, 6, and 12mm according to EN 1534:

$$HB = \frac{2 \times F}{\pi \times D\left[D - \left(D^2 - d^2\right)^{\frac{1}{2}}\right]} \quad \text{[MPa]} \qquad (1)$$

where: *F* is the nominal force (N), *D* is the diameter of the steel ball (mm), and *d* is the diameter of the residual indentation (mm). As a difference from EN 1534, the estimated value for the diameter of the residual indentation was calculated from the depth of the residual indentation (*h*, mm) measured by the material testing machine as follows:

$$d = 2\sqrt{10h - h^2} \quad \text{[mm]} \qquad (2)$$

MOE and MOR

The tests for MOE and MOR were carried out according to standards ISO 3349 (1975) and ISO 3133 (1975), respectively, using 20×20×340mm, clearwood specimens. Regardless of the sawing pattern, specimens were always tested in the direction of thickness of the original board.

Statistical analyses

In the case of BH, MOE, and MOR, the terms of parametric tests were fulfilled. Thus, analysis of variance was used to compare the averages of changes and interactions between wood species, treatment processes and sawing patterns. Tukey’s test was used for multiple comparisons.

RESULTS AND DISCUSSION

Density

The increase in average density of aspen wood after the modifications ranged between 9-25% (Table 2). The modifications did not change the average density of birch wood. Regarding the density profile through the board thickness, compression of green aspen boards resulted in a maximum density at the surface or at the relative depth of 10-15% from the surface (Fig. 2). Starting of compression at 20% MC resulted in slight increase in density towards the core of boards. The compression of birch boards at green state also resulted in a narrow layer of densified wood near to the board surface (Fig. 3). Starting of compression of birch boards at 20% MC resulted in a uniform density profile through the thickness. In addition, radial sawing pattern resulted in higher density than tangential sawing pattern for both species especially when compression was started at 20% MC.

Table 2

Density of wood (kg/m^3) at 12% MC of reference material and after different modification processes analysed using X-ray (A) and gravimetric (B) methods. Mean ± standard deviation.

	Reference		G		G + TM		MC20		MC20 + TM	
	A	B	A	B	A	B	A	B	A	B
Birch	525±31	611±29	539±45	610±36	550±32	610±29	517±21	602±37	532±31	618±45
Aspen	436±46	474±51	530±55	595±51	517±58	567±66	427±32	465±39	457±49	503±52

The density increment as a result of compression appears to be dependent on moisture content of wood and degree of compression. Starting the compression with green wood resulted in the highest density increment at or near the board surface, whereas starting the compression at 20% MC gave the highest density in the core of boards. The difference in the density profile between the two green-wood-started treatments of aspen (in the first one the compression was started after normal storage time between sawing and drying, and the second one was rewetted before the treatment) indicates that even a short-term storage may effect on the location of the densification of wood. The results are in accordance with those of Laine et al. (2013), where compression ratio and closing time had the strongest effect on the formation of the density profile, as well as the hardness and elastic recovery.

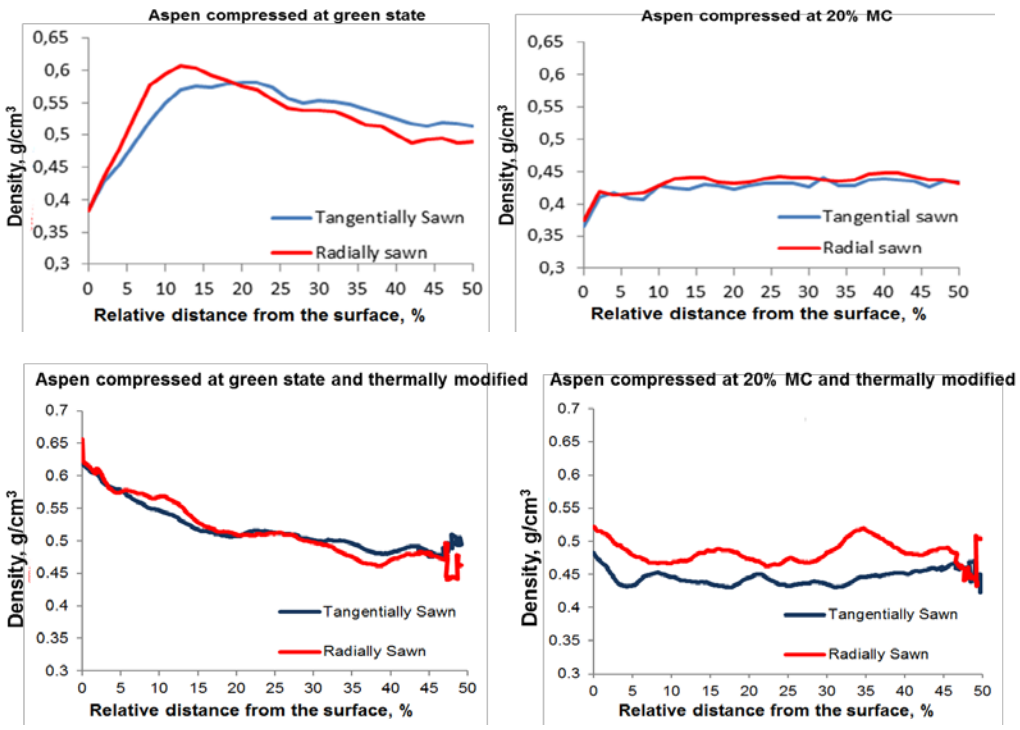


Fig. 2.
Average density profiles of aspen boards in different modification processes

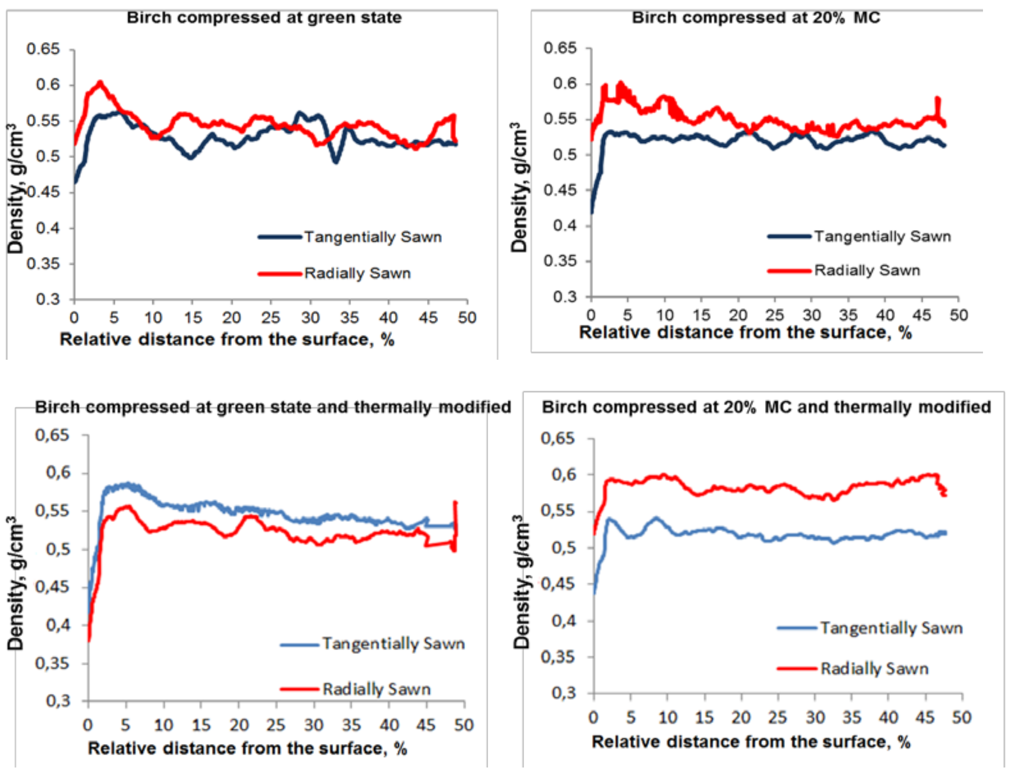
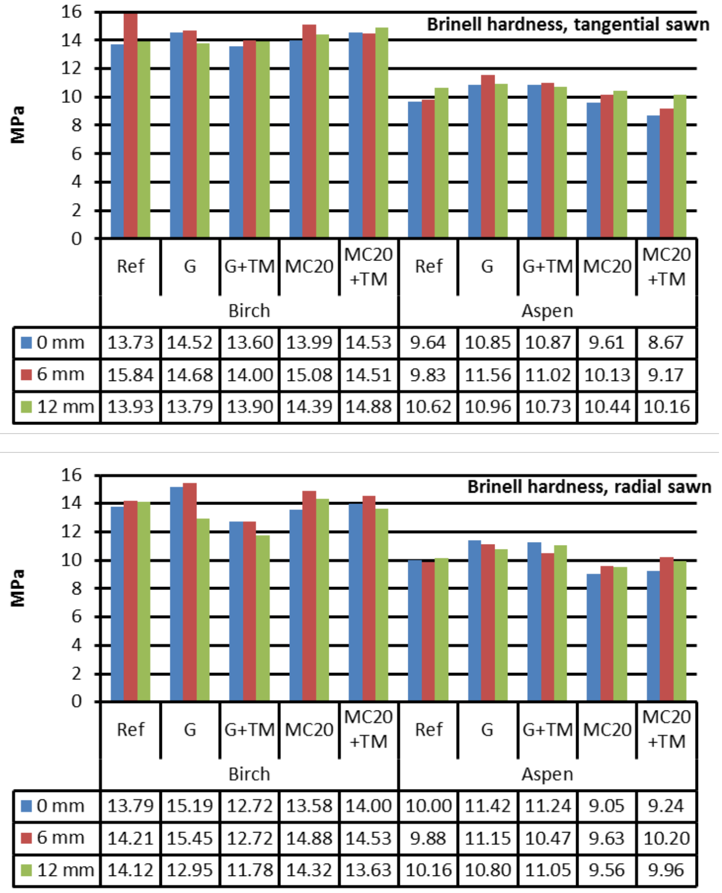


Fig. 3.
Average density profiles of birch boards in different modification processes

Brinell hardness

The results show that the Brinell hardness ranged between 8.7-11.6MPa for the aspen wood, and between 13.3-15.8MPa for the birch wood, the highest values being recorded at the depth of 6mm for aspen and at the depth of 12mm for birch (Fig. 4). With aspen, it was obvious that the average Brinell hardness was greater when compression was started at green state than when it was started at 20% MC (F: 12.52, p: 0.000). With birch, any treatment did not stand out with higher Brinell hardness values than reference, but the lowest Brinell hardness values were recorded for the sawn timber which was compressed starting at green state, and subsequently thermally modified (F: 6.61, p: 0.000). The treatment of birch that was compressed at green state with thermal treatment gave the lowest Brinell hardness (p: 0.000), whereas the differences between the other treatments were insignificant. There were no differences in changes of Brinell hardness with regards to sawing pattern.



Brinell hardness, tangential sawn (MPa)

	Birch Ref	Birch G	Birch G+TM	Birch MC20	Birch MC20 +TM	Aspen Ref	Aspen G	Aspen G+TM	Aspen MC20	Aspen MC20 +TM
0 mm	13.73	14.52	13.60	13.99	14.53	9.64	10.85	10.87	9.61	8.67
6 mm	15.84	14.68	14.00	15.08	14.51	9.83	11.56	11.02	10.13	9.17
12 mm	13.93	13.79	13.90	14.39	14.88	10.62	10.96	10.73	10.44	10.16

Brinell hardness, radial sawn (MPa)

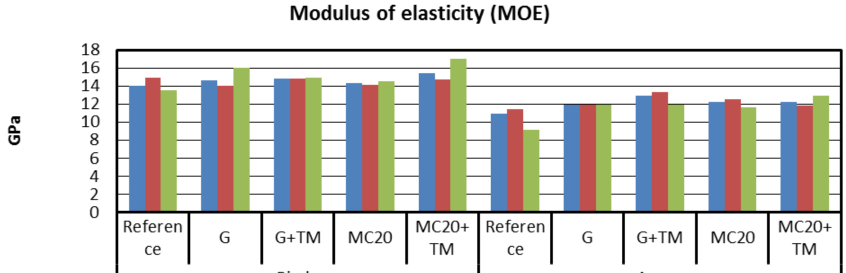
	Birch Ref	Birch G	Birch G+TM	Birch MC20	Birch MC20 +TM	Aspen Ref	Aspen G	Aspen G+TM	Aspen MC20	Aspen MC20 +TM
0 mm	13.79	15.19	12.72	13.58	14.00	10.00	11.42	11.24	9.05	9.24
6 mm	14.21	15.45	12.72	14.88	14.53	9.88	11.15	10.47	9.63	10.20
12 mm	14.12	12.95	11.78	14.32	13.63	10.16	10.80	11.05	9.56	9.96

Fig. 4.
Brinell hardness in reference material and after different modification processes measured at different depths from the wood surface in tangentially and radially sawn boards

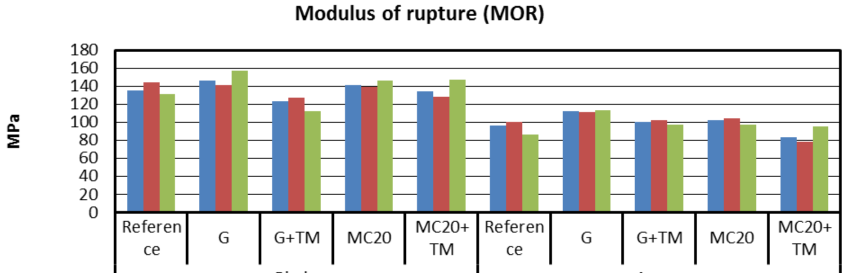
MOE and MOR

Within wood species, the compression of aspen boards at green state without thermal modification resulted in the highest MOE and MOR compared with the untreated wood (MOE: F: 3.39, p: 0.011; MOR: F: 8.686, p: 0.000) (Fig. 5). The lowest MOR of aspen wood was observed for the treatment where compression started at 20% MC and was followed by thermal modification. MOE values of birch wood did not differ between the treatments. However, MOR of birch wood was lower for treatments that included thermal modification than for treatments without thermal modification (F: 6.293, p: 0.000). This result indicates the degradation of wood material at high temperature. Previously Fang et al. (2011) concluded that with too high temperature and long compression process time the surface might lose some of its mechanical properties because of thermal degradation. Several studies show that in case of thermal treatment, the MOE may even increase as a result of increase in the degree of crystallinity of the cellulose, whereas MOR, as a rule, decreases (e.g., Millett & Gerhards 1972, Heräjärvi 2009, Widmann et al. 2012, see also: Hill 2006).

The mechanical properties of aspen wood did not improve markedly compared with untreated birch wood; MOE and MOR of the compression and thermally modified aspen were clearly lower than those of birch. It is probable that the compression took place mostly in the lumens of earlywood. To improve the mechanical properties in greater extent would need the compression of latewood, as well. The differences in MOE and MOR between sawing patterns were insignificant.



	Reference (Birch)	G	G+TM	MC20	MC20+TM	Reference (Aspen)	G	G+TM	MC20	MC20+TM
Average	14.0	14.6	14.9	14.3	15.4	10.9	12.0	12.9	12.3	12.2
Tangential	14.9	14.0	14.9	14.2	14.7	11.5	12.0	13.3	12.5	11.8
Radial	13.6	16.1	14.9	14.6	17.0	9.2	12.0	12.0	11.6	12.9



	Reference (Birch)	G	G+TM	MC20	MC20+TM	Reference (Aspen)	G	G+TM	MC20	MC20+TM
Average	135	146	123	141	134	97	113	101	103	84
Tangential	144	141	127	139	128	101	112	103	105	79
Radial	131	157	113	146	147	87	114	98	98	96

Fig. 5.
MOE and MOR of birch and aspen wood after different modification processes and in reference specimens

CONCLUSIONS

In this study, the changes in the wood properties as a result of THM treatment were found to be dependent on wood species, moisture content at the beginning of compression, and inclusion of the thermal modification phase into the modification process. The results obtained indicate that:

- The density increment as a result of compression appears to be dependent on moisture content of wood and degree of compression. Changes in density are possible to enhance using moistening of wood material as a pre-treatment method.
- Compression of green boards resulted in a maximum density at the surface or at the relative depth of 10-15% from the surface.
- Due to the slower drying of the core than the surface of boards, starting of compression at 20% MC resulted in slight increase in density towards the core of boards.
- Increase in Brinell hardness was the greatest with aspen when the compression was started at the green state. With birch, changes in Brinell hardness were insignificant.
- In regard to aspen wood the highest MOE values were obtained when compression was started at the green state. The starting time of compression did not effect on the MOE of birch wood.
- Treatment including the thermal modification phase resulted in lowest MOE and MOR values with both wood species.

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