Ten new poplar cultivars provide laminated veneer lumber for structural application

Istie Rahayu · Louis Denaud · Remy Marchal · Wayan Darmawan

Abstract
• ***Key message*** **Lambro, Brenta, Taro, Alcinde and Soligo are new poplar cultivars suitable for laminated veneer lumber (LVL) for structural purposes. While Lena, Koster, Dvina, Mella and Trichobel must be used with careful veneer material selection to obtain high value of mechanical properties.**
• ***Context*** In France, the veneer processing industry uses only a very small number of different poplar cultivars.
• ***Aims*** This paper set out to investigate the potential of laminated veneer lumber made from 14 new cultivars for structural purposes, with a focus on juvenility and veneer thickness effects.
• ***Methods*** The mechanical properties of laminated veneer lumber panels made from each cultivar (114 samples per cultivar) were characterized by measuring their density, modulus of elasticity and modulus of rupture.
• ***Results*** A tight correlation was found between destructive and non-destructive modulus of elasticity tests (R^2=0.90, 1,808 samples). Five cultivars had suitable mechanical properties for structural applications (‘Lambro’, ‘Brenta’, ‘Taro’, ‘Alcinde’ and ‘Soligo’). Five cultivars needed to be used with careful sample selection (‘Lena’, ‘Koster’, ‘Dvina’, ‘Mella’ and ‘Trichobel’), and the final four (‘I214’, ‘A4A’, ‘Triplo’ and ‘Polargo’) could not be recommended for structural purposes.
• ***Conclusion*** The advantage of using veneers of mature wood compare to juvenile wood for laminated veneer lumber (LVL) production was due to an improvement of modulus of elasticity and modulus of rupture in the range of 15 to 20 %. The use of thick veneers (5.25 mm compared to 3 mm) did not appear to be detrimental to laminated veneer lumber mechanical performance.

Keywords Cultivars · Juvenile wood · Engineered wood product · Modulus of elasticity · Modulus of rupture · Density

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1 Introduction

France is the largest grower of poplar in Europe. Average annual poplar harvesting between 2007 and 2011 reached 2.4 million m^3 (FCBA2013). According to FAO (2011), plywood and veneer still account for the largest share of poplar products with 59.9 % of total production. In France, the veneer processing industry uses one poplar cultivar almost exclusively (I-214) for light packaging products. The major risk of such a strategy is to face a shortage of raw materials or a significant loss in wood quality due to pest and disease issues (El-Haouzali 2009).

Consequently, it is necessary to diversify the source of genetic material. Most new cultivars display a very interesting growth rate, which implies a large proportion of juvenile wood (Rowell et al. 2005). According to Zhang et al. (2004), a high growth rate induces lower density, lower strength, numerous knots and possibly a large proportion of juvenile wood. These factors appear to contribute to low veneer stress grading.

One of the most significant technical advantages of laminated veneer lumber (LVL) is that specific performance characteristics can be considered in its design. By strategically placing selected veneer sheets within the composite, it is possible to manufacture a wood-based product that has well-controlled physical and mechanical properties (Wang et al. 2003). Daoui et al. (2011) recommend carefully selecting the veneers to be used in composing LVL.

LVL presents the inconvenience of using a large amount of adhesive during its manufacturing, which can be up to 20 % of its total mass (Daoui et al. 2011). According to De Melo and Del Menezzi (2014), the adhesive is a component with significant technical and economic implications with regard to the utilization of wood products, and its cost can be half the product price. Therefore, increasing veneer thickness can enable a decrease in adhesive use for these panels.

Dynamic analysis is a simple and efficient way of characterizing the BING module of elasticity (MOE) of many materials, including wood (Brancheriau and Bailléres 2002; Bucur 2006). Using various species of wood, sample dimensions and growth conditions, several studies have shown a strong linear correlation between the dynamic and static modulus of elasticity (Biblis et al. 2004; El-Haouzali 2009). Dynamic tests based on vibration frequency measurements have been applied successfully to analyze the dynamic MOE of structural timber (Haines et al. 1996; Ouis 1999). However, the use of such methods for estimating the MOE of engineered wood products, particularly LVL, has not been widely applied. To the best of our knowledge, only Daoui et al. (2011) used a vibrating method with limited success, probably because of the existence of important lathe checks according to the authors. In this study, the BING method was used to evaluate its efficiency in predicting the MOE of LVL.

This paper analyses and discusses:

1. Could the vibrating method (BING) be applied to predict LVL MOE even if made of thick veneers?
2. Should juvenility be taken into account in estimating LVL mechanical properties?
3. Which are new poplar cultivars (from 14 new cultivars) suitable for structural applications of LVL?
4. Is utilization of thicker veneers in LVL would reduce its mechanical properties?

2 Material and methods

2.1 Material

Poplar cultivars that were used in this research were as follows:

1. *Populus deltoides* Bartr. was crossed by *Populus nigra* L., produced poplar cultivars: ‘A4A’, ‘Brenta’, ’I-214’, ‘Koster’, ‘Lambro’, ‘Mella’, ‘Polargo’, ‘Soligo’ and ‘Triplo’
2. *Popolus* sp. was crossed by *Populus* sp., produced poplar cultivar: ‘Taro’
3. *P. deltoides* Bartr. produced poplar cultivars: ‘Dvina’, ‘Lena’ and ‘Alcinde’
4. *Popolus trichocarpa* was crossed by *P. trichocarpa*, produced poplar cultivar: ‘Trichobel’

and was peeled using the LaBoMaP instrumented lathe. Tree information details are presented in Tables 1 and 2.

2.2 Laminated veneer lumber production

2.2.1 Veneer selection and panel composition

Logs were peeled by using a 0° clearance angle, 1 m/s speed and with a moderate pressure rate of 10 % to limit lathe check growth and thickness variation (Lutz 1974; Feihl 1986; Marchal et al. 2009).

The effect of lathe check measured using a SMOF© device (Pałubicki et al. 2010) could be discarded since this phenomenon was limited, thanks to the adapted settings. For each tree, two logs were peeled with a different thickness (3 and 5.25 mm). Two types of 50×50-cm^2 panels were manufactured (Fig. 1):

– A panel made of assumed mature veneer (M)/outerwood made from the most peripheral area of the ridge from sapwood for both logs.
– A panel made of assumed juvenile veneer (J)/corewood composed of veneers from the most central part of the bolt (from false heartwood) for both logs.

Outerwood/corewood was distinguished by visual observations. False heartwood, which is situated in the centre of logs and is darker coloured, was assumed to be corewood. Sapwood, which is situated near bark, was assumed to be

Table 1 Hybrid origin, taxonomy names, gender and growing rate comparison of each poplar cultivar to I214

No.	Cultivar	Originality	Taxonomy names	Gender	Comparison growing rate to I214
1	A4A	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Female	Fast growing
2	Brenta	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Female	Moderate to fast growing
3	I 214	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Female	Reference
4	Koster	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Male	Fast growing
5	Lambro	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Male	Equal or more than 'I-214'
6	Mella	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Female	Equal or more than 'I-214'
7	Polargo	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Female	Identical with 'Koster'
8	Soligo	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Male	Better quality than 'I-214'
9	Taro	*P. canadensis* × *P. interamerican*	*Popolus sp.* × *Populus sp.*	Male	Equal or more than 'I-214'
10	Triplo	*Euramerican*	*P. deltoides* Bartr. × *P. nigra* L.	Male	Fast growing
11	Alcinde	*Populus deltoides*	*P. deltoides*	Male	Moderate growing
12	Dvina	*Populus deltoides*	*P. deltoides*	Male	Equal or more than 'I-214'
13	Lena	*Populus deltoides*	*P. deltoides*	Male	Equal with 'I-214'
14	Trichobel	*Populus trichocarpa*	*P. trichocarpa* × *P. trichocarpa*	Male	Fast growing

outerwood. We assumed that outerwood was composed not only of mature wood but also of transition wood since the selected trees were too young to give enough full mature veneers. Thus, the most central part of the bolt consisted of 'more juvenile' wood. Indeed, most authors show that the transition between juvenile wood and mature wood is not abrupt and that wood properties evolve gradually (Lewark 1986; Maeglin 1987; Darmawan et al. 2013). The objective of this research was to obtain general data so that we could draw a global conclusion and propose recommendations for 14 new poplar cultivars for structural applications. The age and growth difference effects were considered second-order effects as regards juvenility. The results presented in this paper confirm our hypotheses (see Sect. 3).

Veneers were dried with a vacuum dryer to ensure a flat veneer surface (dried until they reached 8–10 % moisture content). Polyvinyl acetate (PVAc) was used as the adhesive. Table 3 summarizes the conditions of the gluing process. Veneers were selected randomly in each category (juvenile or mature) to avoid any layering effect. LVLs of seven layers of 3-mm veneer and four layers of 5.25-mm veneer were made, so that the target LVL thickness of 21 mm was achieved.

2.2.2 Sample preparation for mechanical properties

Each board was cut into standardized test samples (EN 789), parallel to grain with a total of 1,808 samples. Firstly, a dynamic test (BING) and then a static four-point bending test were performed for each sample (see Fig. 2).

Non-destructive test In order to estimate the dynamic MOE by a non-destructive test method, the BING bending vibration method was used for the 1,808 samples. This is a fully automated system designed by CIRAD-Forêt following work by Bordonne (1989) and Hein et al. (2010). It is based on measuring and interpreting natural vibration frequencies from a wood piece subjected to impulse loading.

The Timoshenko model was used. Thus, the dynamic MOE values were obtained through percussion bending perpendicular to the grain in two directions (flatwise and edgewise).

Destructive test Four-point bending tests were performed on an INSTRON universal testing machine (see Fig. 2) to measure MOE (static) and modulus of rupture (MOR). Sample moisture content values were very uniform (8.5 %±0.5) when the destructive tests were performed. Specific MOE and specific MOR were obtained by dividing static MOE and MOR by the LVL density at (8.5 %± 0.5) moisture content.

The density of the wood and wood composite is one of the most important physical parameters and generally considered as the first predictor of strength properties (Kollmann and Côté 1968; Guitard 1987; Shukla and Kamdem 2008). It was measured on anhydrous LVL samples.

2.3 Statistical analysis

Density (D), MOE, MOR, specific MOE (SMOE) and specific MOR (SMOR) were the observed parameters. The experimental results were statistically analyzed using an analysis of variance (ANOVA, Table 4) to test the effects of veneer thickness (3 and 5.25 mm), poplar cultivars, maturity (juvenile and mature) and loading direction (edgewise and flatwise). Mean differences between levels of factors were determined using Duncan's multiple range test (Table 5).

Table 2 Tree sample information of 14 poplar new cultivars

Cultivar	Average value of proportion of false heartwood (%)	Tree reference	Veneer thickness	Growth site	Age (years)	Total length (m)	DBH (cm)	Diameter log (cm)
A4A	40	103	3 and 5.25 mm	Bussy les Daours	13	23.5	41.4	38.4
		109	3 and 5.25 mm	Clarques	13	23.0	49.0	42.2
		119	3 mm	Argenton	12	NC	44.6	39.0
Brenta	43	14	3 and 5.25 mm	Sainte Hermine	18	33.0	50.3	45.8
		38	3 mm	Saint Nicolas la Chapelle	18	32.0	43.3	38.1
I 214	40	26	3 and 5.25 mm	Saint Nicolas la Chapelle	18	34.5	50.3	46.2
		71	3 and 5.25 mm	La Réole	17	32.0	46.8	43.8
Koster	44	18	3 and 5.25 mm	Sainte Hermine	18	33.0	51.6	47.3
		68	3 and 5.25 mm	La Réole	17	32.0	50.3	43.7
Lambro	34	12	3 and 5.25 mm	Sainte Hermine	18	30.8	52.9	44.0
		50	3 and 5.25 mm	La Réole	17	34.0	47.1	50.0
Mella	45	23	3 mm	Saint Nicolas la Chapelle	18	32.5	38.9	36.0
		54	3 and 5.25 mm	La Réole	17	30.0	38.9	36.2
Polargo	37	107	3 and 5.25 mm	Bussy les Daours	13	24.0	43.6	38.0
		122	3 and 5.25 mm	Epieds	13	NC	NC	41.8
		124	3 mm	Saint Jean d'Angely	13	NC	NC	40.2
Soligo	38	8	3 and 5.25 mm	Sainte Hermine	18	33.3	54.5	51.4
		36	3 mm	Saint Nicolas la Chapelle	18	32.5	48.4	42.1
		46	5.25 mm	La Réole	17	34.0	56.4	52.5
Taro	52	20	3 mm	Saint Nicolas la Chapelle	18	32.5	45.2	40.6
		65	5.25 mm	La Réole	17	31.0	41.4	39.2
		81	3 and 5.25 mm	Blanzay sur Boutonne	17	34.0	62.7	38.6
Triplo	38	91	3 mm	Vervant	14	NC	46.8	41.0
		95	3 and 5.25 mm	Saint Jean d'Angely	13	NC	NC	41.3
		100	3 and 5.25 mm	Bussy les Daours	13	22.5	37.9	39.7
Alcinde	38	85	3 and 5.25 mm	Le Busseau	19	NC	45.9	40.6
		89	3 and 5.25 mm	Vervant	14	NC	46.2	40.9
		97	3 mm	Saint Jean d'Angely	13	NC	NC	44.2
Dvina	55	3	3 mm	Sainte Hermine	18	32.8	51.6	47.2
		42	5.25 mm	Blanzay sur Boutonne	17	31.0	42.4	38.0
		60	3 mm	La Réole	17	33.0	52.2	47.5
Lena	40	6	3 and 5.25 mm	Sainte Hermine	18	33.7	57.6	51.0
		62	3 and 5.25 mm	La Réole	17	33.0	52.2	49.0
Trichobel	42	83	3 and 5.25 mm	Le Busseau	19	NC	46.8	40.9
		113	3 mm	Long	14	31.0	42.7	42.4
		116	3 and 5.25 mm	Vauchelles les Authie	22	34.5	45.5	46.7

3 Results

3.1 Density

A tight correlation was found between the density of solid wood (Reuling et al. 2013) and LVL (Fig. 3). LVL of 3 mm had a higher density value than that of 5.25 mm.

The ANOVA (Table 4) showed that maturity, poplar cultivars and veneer thickness had significant influences on density ($p<0.01$). The average D of LVL (Table 5) made from mature veneers, (408±37) kg/m^3, was significantly higher than that of LVL made from juvenile veneers, (401±37) kg/m^3. However, this difference was not verified for each cultivar (Table 6). It was also found that this difference was still limited since it only amounted to less than 2.5 % of the increase. The density of panels (Table 6) made from 3 mm veneer, (415±35) kg/m^3, and 5.25 mm veneer, (395±40) kg/m^3, was similar.

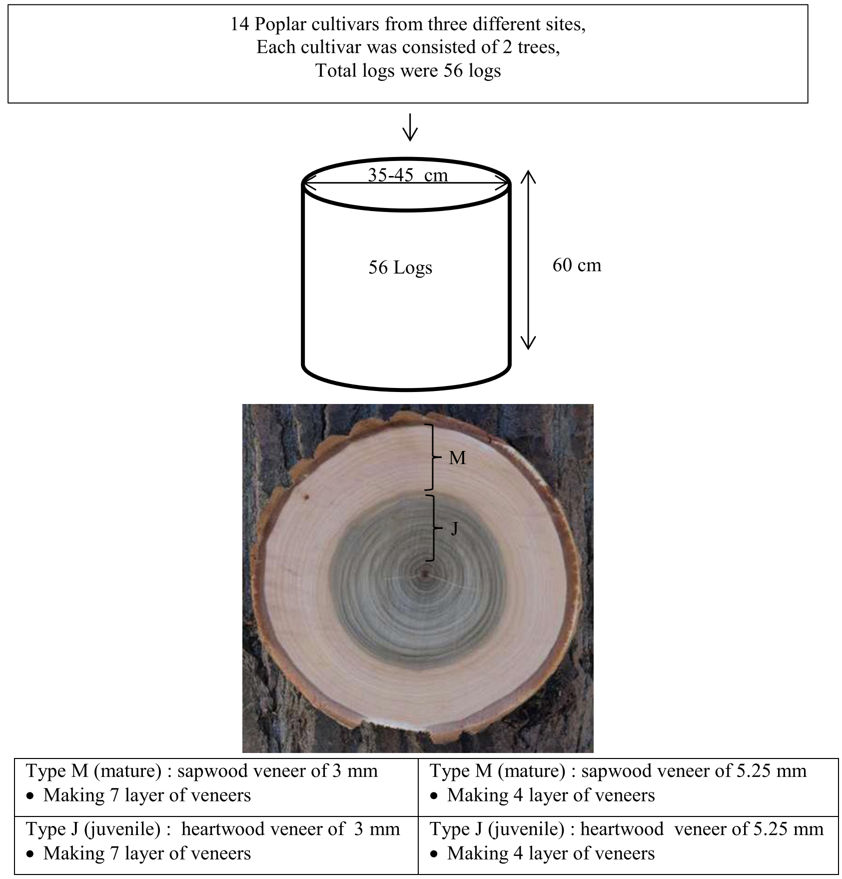


Fig. 1 Poplar cultivar sample preparation for peeling process

3.2 Modulus of elasticity

Figure 4 shows an excellent correlation (R^2=0.90) between static MOE and dynamic MOE for 1,808 samples made of 3 and 5.25-mm-thick veneers (LVL in flatwise and edgewise direction) even though there could be significant differences between the two MOE measurements according to Duncan's comparison test (Table 5).

3.3 Static module of elasticity

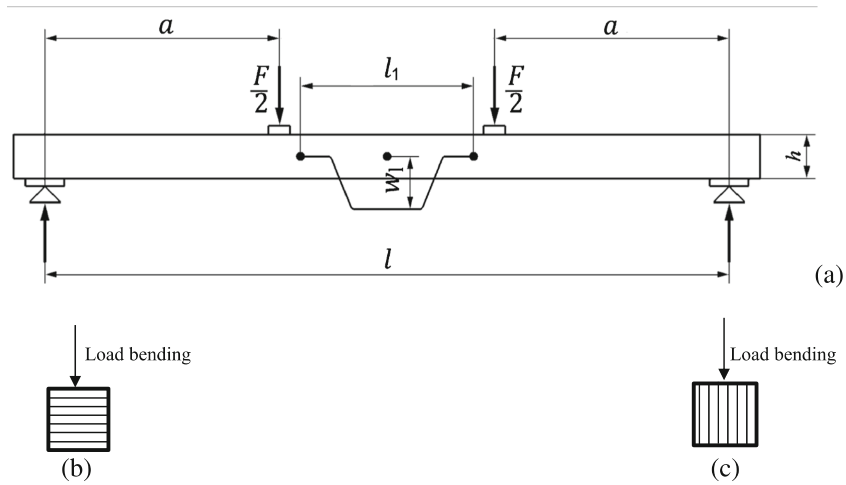
The ANOVA (Table 4) showed that maturity, cultivar and veneer thickness had a significant influence on static MOE (p<0.01). In Table 5, Brenta had the highest value of static MOE (9,439 MPa), while 'I214' had the lowest (6,713 MPa).

Duncan's multiple comparison test (Table 5) showed that the MOE static value for mature LVL (8,880 MPa) was

Table 3 Condition of gluing process of poplar laminated veneer lumber from 3 and 5.25-mm veneers

	LVL (from 3-mm veneer)	LVL (from 5.25-mm veneer)
Veneer moisture content	10–12 %	
Room temperature during gluing process	18–20 °C	
Relative humidity (RH)	60–65 %	
Type of adhesive	polyvinyl acetate (PVAc)	
Average adhesive weight application (g/m^2)	260	248
Application instrument	Glue machine	
Open assembly time	10 min	
Pressing application	Cold press by pressing machine	
Pressure	2.5 kg/cm^2	
Pressure time	45 min	

Fig. 2 Schematic diagram of destructive test for LVL from 14 poplar new cultivars: four-point bending test (**a**), flatwise direction (**b**), and edgewise direction (**c**)



statistically higher than for juvenile LVL (7,664 MPa). It also showed that there was a statistical difference between cultivars which could be mostly attributed to wood density. Indeed, R^2 between static MOE and density reached 0.6 whilst MOR and density reached 0.7 when using data from Table 6.

Duncan's multiple comparison test (Table 5) showed that the MOE static values for 3 and 5.25 mm were statistically different. It is interesting to note that for such a large number of samples, the effect of the veneer thickness on stiffness was not negative since the average MOE increased from 8,202 MPa for 3 mm to 8,416 MPa for the 5.25-mm veneer. Furthermore, Fig. 5 shows that the static MOE values between 3 and 5.25-mm LVL were well correlated (R^2=0.7), but this link was highly dependent on the cultivar.

The ANOVA (Table 4) showed that the sample position factor did not have a significant effect on static MOE. Mean flatwise static MOE (8,267 MPa) was not statistically different from the mean edgewise MOE (8,279 MPa).

3.4 Dynamic module of elasticity

As for static MOE, the ANOVA (Table 4) showed that all factors significantly influenced dynamic MOE (p<0.01), except veneer thickness. In Table 5, LVL made from mature veneer (9,298 MPa) resulted in a higher dynamic MOE value than for juvenile LVL (8,158 MPa).

Table 4 Analysis of variance (ANOVA) results of dynamic MOE, static MOE, MOR, density, SMOE and SMOR (p=0.05)

Source	Dynamic MOE *Pr>F*	Static MOE *Pr>F*	MOR *Pr>F*	Density *Pr>F*	SMOE *Pr>F*	SMOR *Pr>F*
Veneer thickness (1)	0.4614	0.0028	<.0001	<.0001	<.0001	0.1247
Poplar cultivars (2)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
1*2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Maturity (3)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
1*3	0.191	0.2771	0.0668	0.2199	0.1444	0.0271
2*3	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
1*2*3	<.0001	<.0001	<.0001	0.0019	<.0001	<.0001
Load direction (4)	<.0001	0.9435	<.0001	0.7307	0.8374	<.0001
1*4	0.0112	0.9724	0.3674	0.9554	0.9957	0.1351
2*4	0.0057	0.0517	<.0001	1	0.0529	<.0001
1*2*4	0.5305	0.5072	0.0351	1	0.3541	0.0079
3*4	0.6903	0.9458	0.0245	0.7611	0.8191	0.0196
1*3*4	0.2135	0.455	0.3333	0.623	0.6429	0.4661
2*3*4	0.3214	0.8268	0.5822	1	0.7771	0.4372
1*2*3*4	0.5616	0.2761	0.4846	0.9999	0.1052	0.3776

Table 5 Duncan's multiple comparison test: the effects of veneer thickness, cultivar, maturity and sample position on dynamic MOE, static MOE, MOR, SMOE, SMOR and density

Veneer Thickness							
Source of variance	n	Dynamic MOE	Static MOE	MOR	SMOE	SMOR	Density
3 mm	1203	8707.18A	8201.54B	51.40A	19.8 B	0.124 A	414.58A
5 mm	604	8774.34A	8415.64A	49.58B	21.3 A	0.126 A	394.91B

Maturity							
Source of variance	n	Dynamic MOE	Static MOE	MOR	SMOE	SMOR	Density
Mature	905	9298.49A	8879.95A	55.00A	21.6 A	0.134 A	408.25A
Juvenile	902	8157.86B	7664.24B	46.57B	19.0 B	0.115 B	401.26B

Sample Position							
Source of variance	n	Dynamic MOE	Static MOE	MOR	SMOE	SMOR	Density
Flatwise	949	8654.64B	8267.40A	52.53A	20.3 A	0.129 A	407.91A
Edgewise	858	8811.50A	8278.70A	48.86B	20.2 A	0.12 B	408.11A

Cultivar							
Source of variance	n	Dynamic MOE	Static MOE	MOR	SMOE	SMOR	Density
I-214	120	7039.62I	6712.90G	44.57E	18.9E	0.126CD	354.97J
A4A	166	7539.84G	7140.15F	47.15D	18.5E	0.122EF	384.26H
Triplo	158	7272.14H	6851.37G	45.28E	17.6F	0.116G	389.74G
Polargo	145	7916.65F	7410.27E	47.88D	18.9E	0.121EF	395.48F
Dvina	114	8540.33E	8043.88D	44.94E	20.2D	0.113H	397.13F
Koster	120	8838.47D	8546.63C	53.98C	20.2D	0.127C	424.05D
Mella	115	8781.34D	8220.44D	47.66D	20.6C	0.12F	398.48F
Trichobel	154	9158.40C	8660.39C	46.59D	23.1A	0.124DE	375.86I
Lena	120	9253.98C	8701.81C	55.76B	20D	0.129C	433.22C
Alcinde	128	9569.85B	9185.20B	57.98A	20.9C	0.132B	439.47B
Brenta	116	9760.09AB	9439.11A	56.31B	23.3A	0.139A	405.34E
Soligo	117	9897.93A	9197.90B	56.64AB	19.8D	0.122EF	467.77A
Lambro	116	9754.91AB	9437.09 A	57.98A	21.9B	0.134B	430.16C
Taro	118	9903.12A	9273.68AB	52.97C	20.9C	0.119F	442.44B

Results are expressed as the mean values. Different letters (A, B, etc.) in the same column indicate significant difference between sources of variance at a 95 % confidence level ($p \leq 0.05$)

3.5 Modulus of rupture

The ANOVA (Table 4) showed that all factors significantly influenced MOR ($p<0.01$). LVL made from mature veneer (55 MPa) resulted in a higher MOR value than juvenile veneer (47 MPa).

The strength (MOR) of laminated wood assembled with high-density veneers tends to be greater than that made with low-density veneers, which was also observed for solid wood samples by (Reuling et al. 2013).

According to Duncan's multiple ranges (Table 5), Alcinde and Lambro had the same highest value for MOR (58 MPa), while Dvina, Triplo and I214 had approximately the same value (45 MPa) considered as the lowest. The average MOR values for 5.25-mm LVL (49.6 MPa) and 3-mm LVL (51.4 MPa) were statistically different (Table 5). The flatwise position (52 MPa) gave a higher MOR value than the edgewise position (49 MPa). According to Duncan's multiple ranges (Table 5), those values were statistically different.

3.6 Specific module of elasticity and specific modulus of rupture

Several researchers have used SMOR and SMOE to evaluate MOE and MOR results by taking into account the effect of density on flexural properties (Bao et al. 2001; Bal and Bektas 2012). As for MOE, the ANOVA (Table 4) showed that veneer thickness, poplar cultivars and maturity had significant effects on SMOE.

For SMOR, only veneer thickness did not show any significant effect, while other factors did (comparable to MOR). The Duncan's test (Table 5) also showed that the statistical analyses between MOE and SMOE and between MOR and SMOR were similar, except for veneer thickness.

4 Discussion

4.1 Density

Mature veneer (M) LVL D was significantly higher than juvenile veneer (J) LVL D. However, as mentioned before, this improvement did not exceed 2.5 % (see Table 7). Panel

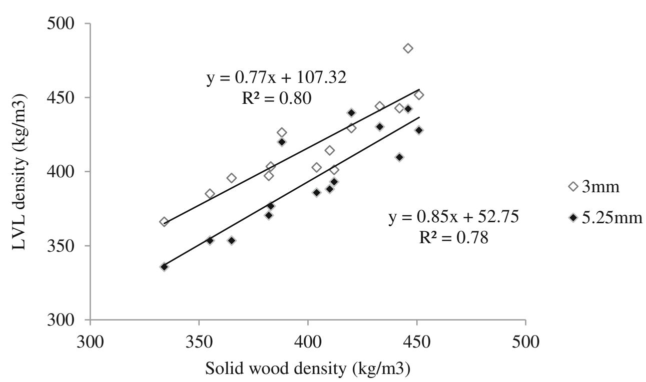


Fig. 3 Correlation between LVL and solid wood density of 14 poplar new cultivars at (8.5±0.5 %) moisture content

Table 6 Density, static MOE, MOR, SMOE and SMOR values of each poplar cultivar LVL made from juvenile and mature veneers

Cultivars	Sample number		Density (kg/m^3)		Static MOE (MPa)	
	Juvenile	Mature	Juvenile	Mature	Juvenile	Mature
I-214	60	60	355±17.6	362±20.0	6,034.2±474.6	7,391.6±616.6
Triplo	79	79	391±23.2	388±17.8	6,452.3±667.1	7,250.4±550.5
A4A	71	95	375±20.9	391±24.1	6,363.7±717.6	7,720.4±984
Polargo	76	69	402±25.3	389±43.3	6,926.5±865.2	7,943.1±760.5
Dvina	58	56	393±14.6	401±13.6	7,639.3±588.8	8,462.9±632.7
Mella	58	57	402±12.8	395±10.1	7,876.6±660.3	8,570.4±619.6
Koster	60	60	416±16.0	433±18.2	7,832.9±815.7	9,260.7±564.2
Trichobel	75	79	364±21.2	388±21.0	8,142.5±745.2	9,152.1±1,105.1
Lena	59	61	428±31.5	438±15.7	7,765.6±1,270.9	9,607.3±1,013.5
Alcinde	68	60	432±22.5	448±18.4	8,631.9±556.2	9,812.3±930.7
Soligo	60	57	476±33.8	459±25.7	8,545.2±1,024	9,884.9±642.7
Taro	61	57	427±28.8	459±36.8	8,303±943.4	10,312.5±1,073
Lambro	59	57	429±23.7	432±24.8	8,598.3±743	10,305.3±925.4
Brenta	58	58	405±17.0	406±13.7	8,808.6±658.6	10,069.3±517

Cultivars	MOR (MPa)		SMOE (MNm/kg)		SMOR (MNm/kg)	
	Juvenile	Mature	Juvenile	Mature	Juvenile	Mature
I-214	42.0±4.70	47.1±4.88	17.4±1.95	20.4±1.50	0.121±0.0150	0.130±0.0143
Triplo	43.3±5.47	47.2±4.00	16.5±1.34	18.7±1.81	0.111±0.0112	0.122±0.0118
A4A	42.3±5.85	50.8±6.85	16.9±1.54	19.7±2.02	0.113±0.0147	0.130±0.0155
Polargo	43.7±5.49	52.5±6.95	17.3±2.29	20.6±2.21	0.109±0.0137	0.135±0.0134
Dvina	42.6±5.49	47.3±7.82	19.4±1.38	21.1±1.18	0.108±0.0124	0.118±0.0177
Mella	45.1±5.58	50.2±4.33	19.6±1.70	21.7±1.52	0.112±0.0138	0.127±0.00975
Koster	49.0±6.34	58.9±5.54	18.9±2.13	21.4±1.55	0.118±0.0162	0.136±0.0138
Trichobel	42.2±4.98	50.8±5.40	22.4±2.09	23.6±2.89	0.116±0.0143	0.131±0.0116
Lena	50.8±6.00	60.5±6.79	18.1±1.85	21.9±1.94	0.119±0.0127	0.138±0.0141
Alcinde	52.0±5.46	64.8±6.26	20.0±1.65	21.9±1.64	0.120±0.0122	0.144±0.0124
Soligo	49.7±7.08	64.0±6.04	18.1±2.95	21.6±1.62	0.105±0.0162	0.139±0.0135
Taro	48.2±6.42	58.0±7.00	19.4±1.70	22.5±1.96	0.113±0.0131	0.126±0.0116
Lambro	51.5±7.35	64.7±7.59	20.1±1.67	23.8±1.56	0.120±0.0150	0.150±0.0135
Brenta	52.5±6.72	60.2±5.34	21.7±1.24	24.8±1.38	0.129±0.0153	0.148±0.0135

density is naturally more influenced by cultivar density itself. This is in line with several results in the literature (H'ng et al. 2010; Daoui et al. 2011; De Melo and Del Menezzi 2014). The thinner is the veneer, the more numerous are the glue

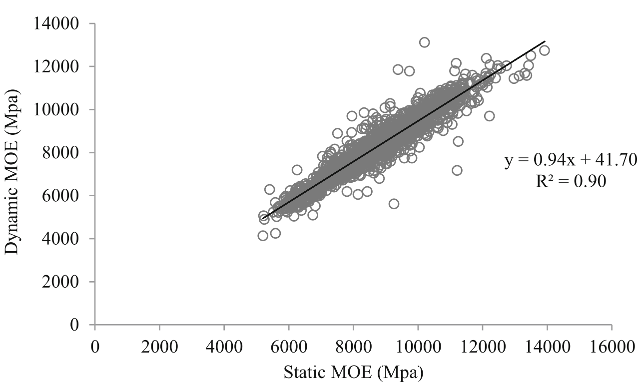


Fig. 4 Correlation between dynamic MOE (vibration method) and static MOE (four-point bending test) for LVL (1,808 samples) made from 14 poplar new cultivars

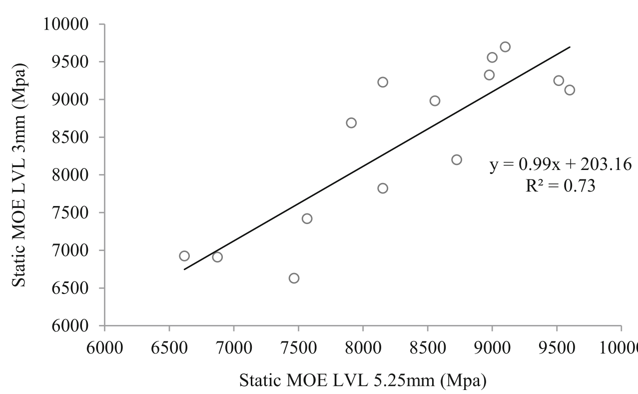


Fig. 5 Correlation between static MOEs of LVL made from 3 and 5.25-mm veneers (in flatwise direction) of 14 poplar new cultivars

bonds and the greater is the amount of glue used. Thus, the observed discrepancy between the densities of 3 and 5.25-mm LVL was systematic (difference in intercept of linear regressions about 55 kg/m^3; see Fig. 3). It was mainly due to the removal of three glue lines between the two lay-ups. About 37.5 kg/m^3 could be attributed to the adhesive application weight (using 250 g/m^2; Table 3). Finally, LVLs made with thicker veneer were significantly lighter (5 %, on average) when each process parameter was constant (Table 7).

4.2 Modulus of elasticity

When grading poplar, the MOE, MOR and D of the set of samples are required. MOR is rarely the penalizing criterion for poplar mechanical grading compared to MOE or D. The excellent correlation presented in Fig. 4 indicates that BING (vibrating method) is a reliable non-destructive instrument to help predicting LVL MOE of poplar even if made from 5-mm veneer. This is in agreement with the results of El-Haouzali (2009), who found the same relationship between the dynamic MOE (using Timoshenko approximation) and the static MOE of poplar LVL (R^2 was 0.77), with high statistical significance at the 99 % level. It was also shown that dynamic MOE (using Timoshenko approximation) was always slightly higher than static MOE, as observed many times in the literature (Kollmann and Côté 1968; Haines et al. 1996; El-Haouzali 2009; Daoui et al. 2011). According to the authors, this point needs to be discussed, but the reason behind this trend may be the anisotropy and the heterogeneity of wood. For the rest of the paper, most of the conclusions and discussions dealing with MOE could be verified for both methods.

4.3 Static modulus of elasticity

The ANOVA and Duncan's multiple comparison test results were in agreement with observations in the literature regarding the effect of juvenile wood on solid wood and LVL stiffness (Kretschmann et al. 1993; Kretschmann 1997; Nazerian et al. 2011).

It is interesting to note that for such a large number of samples, the effect of veneer thickness on stiffness was not negative since the average MOE increased from 8,202 MPa for 3 mm to 8,416 MPa for 5.25 mm (see Table 5). Furthermore, the use of thicker veneers could reduce adhesive consumption and simplify and accelerate the production of panels without altering their mechanical properties.

The ANOVA (Table 4) showed that the sample position factor did not have a significant effect on static MOE. MOE is measured in a zone of pure bending (local modulus EN408). This is why the MOE values between flatwise and edgewise positions were quite the same, contrary to the Bing measurements for which shear deformation occurred. Indeed, shear deformations are different since shear modulus differs due to wood orthotropy and slightly to lathe check orientation. This is also the expected reason why some differences in MOE can be seen in Table 5.

4.4 Modulus of rupture

The effect of lamination improved the tensile limit of these cultivars by about 20 %, on average, compared to solid wood (Rahayu et al. 2013). Poplar LVL properties can be influenced considerably by the cultivar, the glue type and the veneer thickness (El-Haouzali 2009). According to El-Haouzali (2009), the station effect is not very relevant.

LVL made from mature veneer resulted in a higher MOR value than juvenile veneer. Indeed, because of the specific physical and mechanical properties of juvenile wood, its proportion can have a significant impact on wood mechanical properties such as lumber strength (Panshin and Zeeuw 1980).

The average MOR values for 5.25 and 3-mm LVL were statistically different (Table 5) in line with the results of H'ng et al. (2010) who reported that LVL with thinner veneers (15 plies) had better mechanical performances compared to those of thicker veneers (11 plies). However, the improvement was still limited in that case and could be attributed mainly to the upgrading of lamination effects and, to a lesser degree, to the reduction in lathe check

Table 7 The increasing percentage of dynamic MOE, static MOE, MOR, density, SMOE and SMOR value of 3 and 5.25-mm LVL poplar made from juvenile to mature veneers

		Dynamic MOE (MPa)	Static MOE (MPa)	MOR (MPa)	Density (kg/m^3)	SMOE (MNm/kg)	SMOR (MNm/kg)
LVL 5.25 mm	Mature	9,431	9,104	54	400	22.7	0.136
	Juvenile	8,126	7,736	45	390	19.8	0.115
Gain (%)		+16.1	+17.7	+20	+2.6	+12.8	+15.4
LVL 3 mm	Mature	9,233	8,769	55	417	21.0	0.132
	Juvenile	8,174	7,628	47	412	18.5	0.115
Gain (%)		+13.0	+15.0	+17.0	+1.2	+11.9	+12.9

depth. This improvement was also limited because the material used was almost free of defects such as knots.

As observed in the literature (Daoui et al. 2011; El-Haouzali 2009), the flatwise position gave a higher MOR value than the edgewise position. The explanation might be linked to orthotropy.

4.5 Specific modulus of elasticity and specific modulus of rupture

The veneer thickness, poplar cultivar and maturity factors had significant effects on SMOE, independently from D. Anatomical factors such as fibre length and microfibril angle also probably contributed to this effect. Further research is required to conclude.

Veneer thickness showed a significant effect for MOR but not for SMOR. This shows that, in this context, the use of thick veneers is not penalizing for intrinsic LVL mechanical properties.

4.6 Structure application

The advantage of using veneers taken from the sapwood and therefore deemed more mature is obvious since mechanical properties were improved by 13 to 20 % for a comparable density (Table 7). This proves that there is an effect due to juvenility for each poplar cultivar. Therefore, users should consider juvenility in estimating LVL mechanical properties.

Dynamic MOE, static MOE, MOR and density were lower for LVL made from juvenile veneers than for LVL made from mature veneers. This was in agreement with Kretschmann et al. (1993). A significant difference was found between Southern Pine and Douglas Fir LVL manufactured with mature or juvenile material. The ratio of juvenile to mature material was approximately 0.8 for strength and stiffness, which was comparable with ours.

According to static MOE values of poplar cultivars and the results of Duncan's multiple comparison test (Table 5) for static MOE values, three categories were established. Taro, Lambro, Soligo, Brenta and Alcinde poplar cultivars could be considered as suitable for structural application (blue-coloured region in Table 5), whilst Lena, Trichobel, Mella, Koster and Dvina should be used with careful sample selection (red-coloured region). Polargo, Triplo, A4A and I214 should not be selected for such purposes (yellow-coloured region). Poplar cultivars with static MOE values more than 9,000 MPa and that, according to Duncan analysis, had 'A' and 'B' letters were classified in blue-coloured region, while poplar cultivars with values more than 8,000 MPa (had 'C' and 'D' letters) were classified in red-coloured region. Poplar cultivars with less than 8,000 MPa (had 'E', 'F' and 'G') were classified in yellow-coloured region.

5 Conclusion

The resonance technique is a reliable tool for estimating LVL MOE and avoiding destructive tests. It is particularly useful for poplar.

The advantage of using veneers from mature wood was proved with an improvement of 15 to 20 %, on average, for mechanical properties, with almost the same panel weight. This indicates that, for poplar, the selection of materials between veneers made from juvenile wood (corewood) and veneers made from mature wood (outerwood) is important.

Five cultivars have a real potential for structural applications (Lambro, Soligo, Alcinde, Brenta and Taro), and some should be used with careful sample selection ('Lena', Trichobel, Mella, Koster and Dvina), while Polargo, A4A, 'I-214' and Triplo should be excluded.

The sample position, as regards the direction of load application, tallied with common knowledge available in the literature. Comparable MOE values were measured for edgewise or flatwise solicitation, but the MOR for flatwise was always a little higher. SMOR was also comparable for both thicknesses.

Lastly, concerning this set of samples, the use of thicker veneers reduced the use of adhesive and simplified and accelerated the production of panels without altering their mechanical properties.

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Conflict of interest Authors indicated that they have no conflict of interest.

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