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Properties of curved laminated veneer lumber made from fast-growing species with radiofrequency heating for use in furniture*

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Abstract Curved laminated veneer lumber (LVL) is manufactured from glue-coated pieces of rotary-cut veneers assembled and pressed between molds. In this study, curved LVLs were produced from two fast-growing wood species such as massion pine (*Pinus massoniana* Lamb.) and poplar (*Populus euramericana* CV. I.) for use in furniture. In addition to the applicability of the two wood species used, the optimum technological conditions of curved LVL production with radiofrequency (RF) heating and the physical and mechanical properties of curved LVL were investigated. The results are as follows: (1) Curved LVL made from massion pine and fast-growing poplar shows excellent mechanical properties. These fast-growing wood species are suitable for curved LVL being used as furniture structural members. (2) The mechanical properties of curved LVL are affected by frequency, voltage, RF application time, and moisture content, with the RF application time and moisture content having more important effects on the mechanical properties than the frequency and the voltage. (3) The mechanical properties of curved LVL increase with a linear increase in the density of curved LVL.

Key words Fast-growing species · Curved LVL · Radiofrequency heating · Property

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Introduction

The original method of making curved laminated veneer lumber (LVL) was to press the materials in molds and keep them at room temperature until the glue had set, which could take many hours. With the introduction of synthetic resins, heat was applied to the assembly and the time in the press was reduced. When radiofrequency (RF) heating was used to make curved LVL, the heat was generated in the whole mass of the assembly, and the glue-line could be cured quickly. Curved LVL members can be produced in large numbers and can be easily formed into a curved shape with a small radius of curvature from veneers using a bending and gluing operation. Therefore, curved LVL can provide a variety of functional and aesthetically pleasing wood materials for furniture such as chairs, sofas, tables, and others.

In recent years, because greatly valued and durable timbers are decreasing continuously, the percentages of low-grade wood or fast-growing wood species are increasing, and hence the utilization of fast-growing wood species is one of the themes of investigation in the wood industry. Massion pine (*Pinus massoniana* Lamb.) and fast-growing poplar (*Populus euramericana* CV. I.) have been planted successfully and grown over a wide area in China; they are two fast-growing species from among the most important and well-known commercial trees. With a view to developing these wood species for furniture production, we studied their applicability for use as raw material in the manufacture of curved LVL, their optimum technological conditions of curved LVL production with RF heating, the physical and mechanical properties of curved LVL, and the influences of major factors such as frequency, electrode voltage, heating time, and moisture content on the mechanical properties.

Materials and methods

Veneers

The rotary-cut veneers were made from massion pine (*Pinus massoniana* Lamb.) and fast-growing poplar (*Populus euramericana* CV. I.). Their dimensions were 1250mm in length, 150mm in width, and 1.0 or 1.2mm in thickness. These veneers were dried to 6%–18% of the moisture content required.[1]

Adhesives

The glue used in this study was urea formaldehyde (UF) resin with a solid content of 61%–62%. A suitable hardener (ammonium chloride) and extender (wheat flour) were well mixed with the UF resin in the correct proportions. The resin/hardener/extender ratio was 100.0:0.5:8.0. The amount of the adhesives applied by a hand roller to the veneers was 200g/m^2 (single spread).[1]

Shape of curved LVL and molds

The curved LVL produced for this study was in the shape of a seat back for a chair. There were 20 or 24 veneers, so the curved LVL was maintained at 20mm in thickness.[1] The wooden molds were pairs of male and female forms. The working faces of the molds were covered with aluminum electrodes.[1-3] The shape and dimensions of curved LVL and molds were the same as those in our previous paper.[1] The curvature radius of the male mold and the inside curvature radius of curved LVL in the minimum curved part were 44.5mm and 46.0mm, respectively. The curve angle was 95°.

Radiofrequency generator and pressure

The RF generator was a GP8-4/13.56C type. Its power was 8kW; the frequencies were 4.0 and 13.56MHz; and voltage scales were from 500 to 6000V (steps of 500V).[1,4] The unit pressure of 1MPa was applied to the glue-line (the total pressure was 250kN) by a hydraulic press under a one-step hot-pressing curve with RF heating.[1,4]

Design of the factors and levels of experiments

Curved LVL was produced with RF heating. It was found that many factors had important effects on the properties of the curved LVL. To determine the optimum technological conditions and analyze the effects of the factors, the main factors and experiments in this study were designed according to the results of the preparatory exploratory experiments and are shown in Table 1.

Testing properties

The dry (tensile) shear strength (DSS), wet (tensile) shear strength (WSS, soaked in water at 60°C for 3h, left at 20°C and 65% relative humidity for 10min, and tested in the wet state), modulus of rupture (MOR), modulus of elasticity (MOE), screw-holding strength in parallel to the glue-line (SHP), screw-holding strength vertical to the glue-line (SHV), moisture content (MC), and the density of the curved LVL were measured. The test specimens of the linear part were prepared and tested according to some Chinese standards such as GB (guo-biao) 4903, GB 4904, GB 5852, GB 5853, and GB 5854.[5,6] The rupture strength (RS) of the curved part was measured by the method shown in Fig. 1.

Effects of factors on mechanical properties

The effects of the main factors such as frequency, voltage, RF application time, and moisture content on the mechani-

Table 1. Main factors and experiments

Test no.	Frequency (MHz)	RF application time (min)	Voltage (V)	Moisture content (%)
1	13.56	5	3000	6–10
2	13.56	7	4000	14–18
3	13.56	9	3500	10–14
4	4	5	4000	10–14
5	4	7	3500	6–10
6	4	9	3000	14–18
7	13.56	5	3500	14–18
8	13.56	7	3000	10–14
9	13.56	9	4000	6–10

This table was designed according to an orthogonal experiment method. Each of the tests (1–9) were of two wood species repeated three times.

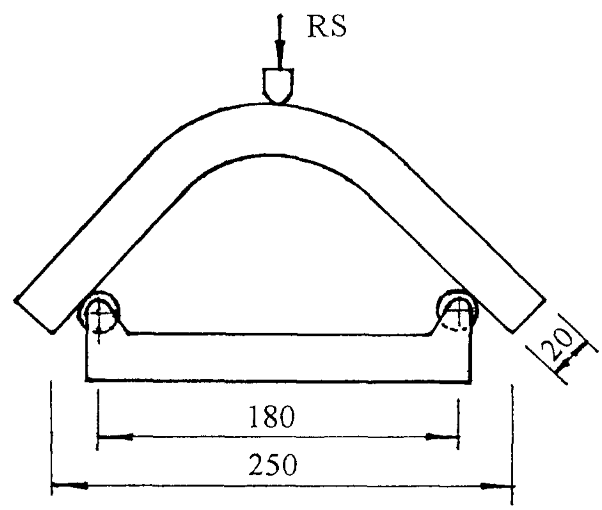

Fig. 1. Method of rupture strength (*RS*) testing in the curved part of curved laminated veneer lumber (*LVL*). The dimensions of the specimens were 250mm in length between ends, 20mm in thickness, and 50mm in width. The inside curvature radius was 46mm, and the curve angle was 95°

cal strengths such as DSS, WSS, MOR, MOE, RS, SHP, and SHV were studied. The optimum technological conditions of curved LVL production with RF heating were thus determined. Curved LVLs of two wood species were produced under optimum technological conditions, and their properties were tested according to the methods noted above.

Relations between mechanical properties and densities

The relation between the mechanical properties and the densities of the curved LVL produced from two fast-growing species was investigated and analyzed with a regression method according to the testing results noted above.

Results and discussion

Properties

Curved LVLs were produced from massion pine and fast-growing poplar under the experimental conditions mentioned above, and the mechanical and physical properties of the curved LVL were then tested. The results obtained are shown in Table 2. It is clear that the mechanical and physical properties of curved LVL made from two wood species were good. Moreover, the curved LVL had better waterproofing (comparing the DSS with the WSS). The SHP of curved LVL was larger than that of massion pine. In contrast, there was no significant difference between SHP and SHV in curved LVL made from fast-growing poplar. Although curved LVL made from massion pine exhibited favorable results for MOR and MOE compared with curved LVL made from fast-growing poplar, the other mechanical strengths (e.g., RS, SHP, SHV) in curved LVL made from fast-growing poplar were higher than those of massion pine. This is due to the fact that massion pine contains large amounts of oleoresin, which can influence the wettability of the adhesive and the uniformity of the glue-line.

The tensile shear strength tests revealed shear failures of the veneers. It was apparent that the specimens produced considerably more wood failures. The wood failures in DSS and WSS of the specimens of curved LVL made from massion pine were 63% and 37%, respectively. The ones made from fast-growing poplar were 65% and 44%, respectively.

Effects of factors on the mechanical properties

The relations between the mechanical strengths (e.g., DSS, WSS, MOR, MOE, RS, SHP, SHV) and the main factors (e.g., frequency, voltage, RF application time, moisture content) are shown in Figs. 2 and 3. The results showed that these factors affected the mechanical properties.

The mechanical strengths increased slightly with an increase in frequency and voltage, although the variances of the mechanical strength values were not significant. Because the glue-line temperature was slightly higher under a frequency of 4 MHz than that under 13.56 MHz,[1] curing of the adhesive was rapid for curved LVL comprising many layers of the veneer, and the setting rate of adhesive was faster than the evaporating rate of water steam under a frequency of 4 MHz. On the other hand, arcing was easily caused in the assembly with a frequency of 4 MHz. These conditions could result in a weak bond. Therefore, the opti-

Table 2. Properties of curved LVL under different experimental conditions

Test no.	DSS (MPa)	WSS (MPa)	MOR (MPa)	MOE (GPa)	RS (kN)	SHP (kN)	SHV (kN)	MC (%)	D (g/cm^3)
Massion pine									
1	2.69 (0.45)	2.17 (0.46)	84.85 (9.31)	5.91 (1.89)	1.39 (0.18)	2.15 (0.21)	1.63 (0.28)	17.43 (0.33)	0.84 (0.07)
2	2.73 (0.59)	2.44 (0.23)	90.70 (8.63)	6.23 (2.87)	1.62 (0.22)	2.18 (0.30)	1.51 (0.13)	15.46 (0.48)	0.77 (0.04)
3	2.50 (0.54)	2.44 (0.55)	87.92 (8.59)	6.25 (2.61)	1.65 (0.38)	2.16 (0.28)	1.56 (0.11)	17.09 (0.44)	0.83 (0.05)
4	2.66 (0.46)	2.02 (0.50)	86.19 (7.57)	5.93 (1.54)	0.91 (0.15)	2.15 (0.41)	1.60 (0.06)	16.85 (0.47)	0.83 (0.02)
5	2.71 (0.60)	2.32 (0.32)	93.93 (7.95)	6.78 (2.01)	1.23 (0.35)	2.19 (0.34)	1.53 (0.14)	15.26 (0.57)	0.78 (0.07)
6	2.44 (0.56)	2.05 (0.61)	80.57 (8.40)	5.15 (2.67)	0.90 (0.09)	2.13 (0.41)	1.47 (0.28)	16.39 (0.42)	0.82 (0.02)
7	2.57 (0.69)	1.97 (0.59)	82.06 (7.39)	5.98 (2.98)	1.32 (0.22)	2.12 (0.20)	1.60 (0.21)	15.52 (0.52)	0.77 (0.04)
8	2.59 (0.71)	2.18 (0.63)	90.05 (9.54)	5.69 (1.90)	1.50 (0.28)	2.20 (0.23)	1.58 (0.19)	16.75 (0.30)	0.89 (0.06)
9	2.61 (0.61)	2.15 (0.56)	95.91 (8.15)	6.03 (2.10)	1.61 (0.31)	2.15 (0.31)	1.62 (0.07)	17.31 (0.35)	0.86 (0.03)
Fast-growing poplar									
1	2.93 (0.64)	2.26 (0.27)	89.61 (8.09)	4.75 (1.29)	2.12 (0.16)	2.35 (0.25)	2.29 (0.39)	14.48 (0.61)	0.62 (0.03)
2	2.69 (0.61)	2.07 (0.39)	84.95 (7.53)	5.11 (1.02)	2.47 (0.48)	2.26 (0.27)	2.24 (0.20)	15.65 (0.57)	0.57 (0.05)
3	2.96 (0.62)	2.32 (0.50)	86.17 (9.14)	4.83 (0.84)	1.89 (0.33)	2.25 (0.24)	2.11 (0.20)	14.83 (0.31)	0.63 (0.03)
4	2.85 (0.53)	2.20 (0.47)	90.24 (9.87)	5.19 (1.09)	2.46 (0.30)	2.32 (0.21)	2.33 (0.28)	14.41 (0.49)	0.61 (0.03)
5	2.88 (0.62)	2.23 (0.59)	83.34 (6.35)	4.58 (0.88)	2.48 (0.28)	2.20 (0.22)	2.14 (0.16)	15.71 (0.84)	0.62 (0.03)
6	2.69 (0.70)	1.94 (0.44)	81.07 (7.81)	4.46 (1.01)	1.53 (0.44)	2.09 (0.26)	2.01 (0.35)	14.10 (0.77)	0.62 (0.02)
7	2.89 (0.51)	2.31 (0.49)	80.27 (9.20)	4.86 (0.95)	2.63 (0.19)	2.27 (0.27)	2.23 (0.66)	14.14 (0.23)	0.54 (0.03)
8	2.94 (0.52)	2.11 (0.36)	83.99 (8.20)	5.25 (1.17)	2.06 (0.15)	2.20 (0.25)	2.11 (0.48)	15.82 (0.72)	0.58 (0.04)
9	2.63 (0.50)	2.04 (0.52)	85.95 (5.95)	4.41 (0.58)	2.06 (0.33)	2.21 (0.23)	2.02 (0.21)	14.35 (0.38)	0.55 (0.05)

DSS, dry shear strength; *WSS*, wet shear strength; *MOR*, modulus of rupture; *MOE*, modulus of elasticity; *RS*, rupture strength; *SHP*, screw-holding strength in parallel to glue-line; *SHV*, screw-holding strength vertical to glue-line; *MC*, moisture content; *D*, density.
Each value is the average of nine specimens. Values in parentheses represent the standard deviation.

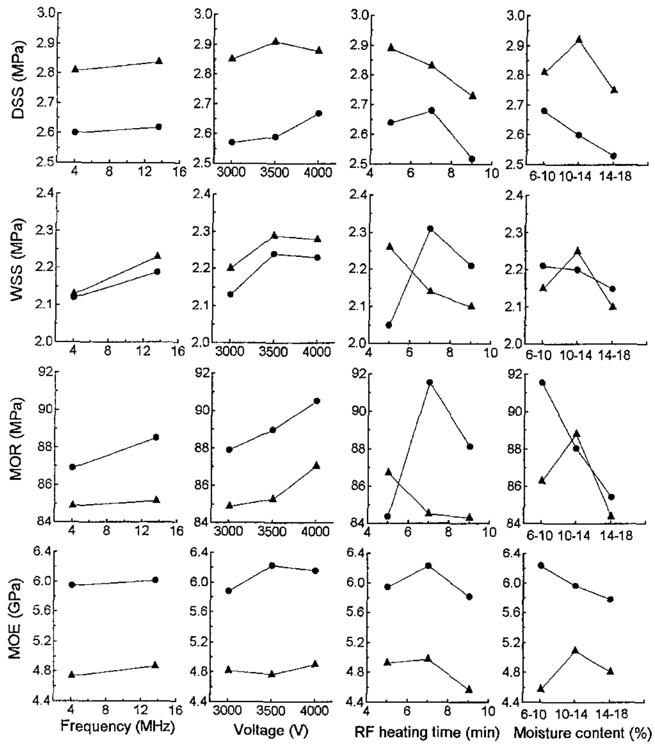

Fig. 2. Effects of main factors on shear strengths and bend strengths. See Table 2 for explanation of abbreviations. *Circles*, massion pine; *triangles*, fast-growing poplar

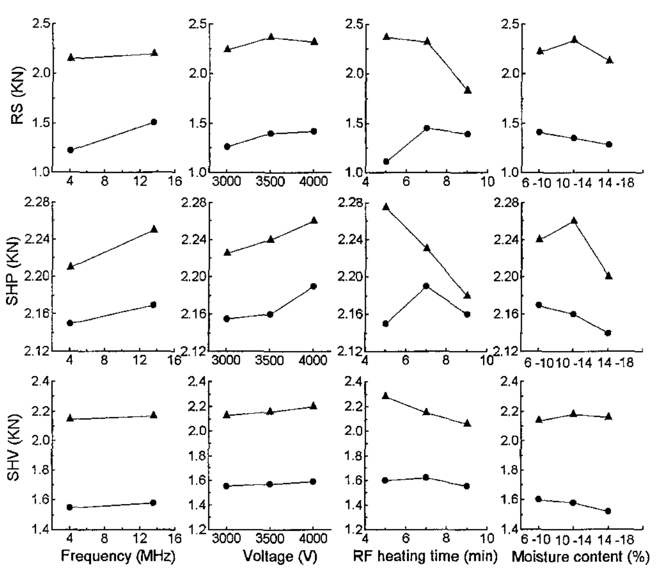

Fig. 3. Effects of main factors on rupture strengths and screw-holding strengths. See Table 2 for explanation of abbreviations. *Circles*, massion pine; *triangles*, fast-growing poplar

mum frequency of the RF regenerator used to make curved LVL was 13.56MHz even though the effects of frequency on the mechanical properties were not significant. The result of this study was identical with the viewpoint of Houwink and Salomon that a common frequency for gluing wood is 10–15MHz, and an internationally agreed value has been fixed at 13.56MHz.[7]

From the theory of RF heating, when the power concentration that was related to frequency and voltage provided by the RF regenerator was not sufficiently high to cause burning or charring in the glue-lines, the power level did not influence the quality of UF resin glue bonds.[8] Moreover, suitable frequency and voltage are necessary so full power is delivered to give the maximum possible heating effect.[9] However, the variation of frequency is difficult to determine for the generator. In common practice, only the voltage is under the control of the generator operator.[7] Nevertheless, from the preparatory exploratory experiments for this study, if the voltage was higher than 4000V to obtain full power, it also could cause arcing in the assembly. Therefore, the suitable voltage for the RF regenerator in this study was 4000V.

The RF application time and the moisture content of the veneer were more important factors than frequency and voltage. They significantly influenced the strength of the bonds owing to the fact that the variations of RF application time and moisture content had a greater effect on the temperature of the glue-line.[1,4,10–13]

If the moisture content of the veneer for the curved LVL is high, more RF energy to raise the glue-line temperature and to turn the water of the veneers into steam must be provided, and the curing time must be extended; otherwise the glue would not be fully cured. When a large volume of steam is produced in the assembly, it can result in a weak bond, such as blowing the veneers apart, rupturing, and blistering when the molds are opened.[1] If the moisture content is low, the glue is absorbed into the veneers, giving a starved glue-line with little strength. If the RF application time is short, the heating temperature of the glue-line is lower than the curing temperature of the adhesive required, and the glue-lines are not completely and adequately cured. This situation can result in little bonding strength. In contrast, if the RF application time is long, the glue-lines are excessively cured under high temperature, which can result in a brittle and weak glue-line.

Because massion pine contains large amounts of oleoresin, it can influence the wettability of the adhesive, the uniformity of the glue-line, and the evaporating rate of the steam. Therefore, the most suitable moisture content of the veneers and the RF application time were 6%–10% and 7min for massion pine and 10%–14% and 5min for fast-growing poplar, respectively.

Optimum technological conditions and possibilities of two wood species for curved LVL

From the results of property testing and analysis in this study, the optimum technological conditions of curved LVL production with RF heating were noted as follows: For massion pine (*Pinus massoniana* Lamb.) the RF application time was 7min and the moisture content of the veneers 6%–10%. For fast-growing poplar (*Populus euramericana* CV. I.) the RF application time was 5min and the moisture content of the veneers 10%–14%. For both wood species,

Table 3. Properties of curved LVL under optimum technological conditions

Property	Massion pine				Fast-growing poplar			
	Min	Max	Ave	SD	Min	Max	Ave	SD
DSS (MPa)	1.78	3.86	2.76	0.56	1.90	3.88	2.92	0.53
WSS (MPa)	2.01	2.82	2.42	0.34	1.68	3.26	2.12	0.48
MOR (MPa)	76.54	122.17	96.33	9.24	70.23	114.24	92.53	8.05
MOE (GPa)	3.60	12.04	6.84	2.94	4.02	6.82	5.55	1.12
RS (kN)	1.11	2.01	1.73	0.35	2.01	2.67	2.21	0.29
SHP (kN)	1.86	2.78	2.24	0.25	1.92	2.68	2.39	0.22
SHV (kN)	1.52	1.74	1.62	0.08	1.86	2.40	2.33	0.06
MC (%)	15.79	17.93	16.85	0.87	13.76	14.93	14.41	0.49
D (g/cm^3)	0.80	0.85	0.83	0.04	0.58	0.64	0.60	0.03

DSS, WSS, MOR, MOE, RS, SHP, SHV, MC, D: refer to Table 2. *Max*, maximum; *Min*, minimum; *Ave*, average; *SD*, standard deviation.
Nine specimens were tested for each property.

the frequency of the RF regenerator was 13.56MHz, and the RF voltage was 4000V.

The properties of curved LVL produced from two wood species under optimum technological conditions are presented in Table 3. The results show that the properties of curved LVL of two wood species under optimum technological conditions are excellent compared to the results of property testing (Table 2).

The shear strength (DSS, WSS), bending strength (MOR), and rupture strength (RS) are the most important mechanical properties of the curved LVL with respect to their practical application as structural elements for furniture. Table 4 compares the mechanical properties of the curved LVL in this study and those required in some standards and in other studies.[14–17] It is clear from Table 4 that the shear strengths (DSS, WSS) of curved LVL made from two fast-growing species were large compared to the values (2.0 or 1.8MPa) required in ГОСТ21178 (the standard of Russia in Curved Glued Member)[16] and DB/3702-Y81006 (the Standard of Qing-Dao City of Shan-Dong Province of China in Curved Glued Furniture).[17] MORs of curved LVL were rather more than those required in the JAS (Japanese Agricultural Standard) of Structural Laminated Veneer Lumber.[14] MOEs and RSs of curved LVL were slightly less than those of JAS[14] and Kenmochi,[15] respectively, but they would be sufficient for general structural materials in furniture designed by suitable methods.

On the other hand, massion pine and fast-growing poplar grow over a wide area of China. They are the most important fast-growing commercial trees. The veneers of these two wood species are suitable for the production of curved LVL used in furniture.

Table 4. Comparison of mechanical properties

DSS (MPa)	WSS (MPa)	MOR (MPa)	MOE (GPa)	RS (kN)	Ref.
3.00	–	30.00	8.00	–	14
–	–	103.8	–	2.42[a]	15
2.00	–	–	–	–	16
1.80	–	–	–	–	17
2.76	2.42	96.33	6.84	1.73	Pine
2.92	2.12	92.53	5.55	2.21	Poplar

See Table 2 for explanation of abbreviations.
[a] The average value is half the value (4.85kN) in the reference because the widths of the specimens were twice those of this study.

Relations between mechanical properties and densities

Figures 4 and 5 show that the relations between the mechanical properties and densities of curved LVL produced from two fast-growing species. Table 5 shows the formulas of the regression lines for properties and densities noted above.

The results show that the mechanical properties of curved LVL increased with an increase in the density of curved LVL. The fields of scattering points of measurement may be equalized by the following linear function.

$$y = Ax + B$$

where y is the mechanical property, x is the density, and A and B are the regression constants determined by experiments. Therefore, the relations between mechanical properties and densities can be expressed by theoretical linear regression equations. The relations between the mechanical properties and densities were large, as expressed by high correlation coefficients.

From Figs. 4 and 5 we can see clearly that the experimental values of the mechanical properties of curved LVL made from massion pine and fast-growing poplar were distributed mainly from 0.75 to 0.95g/cm^3 and from 0.55 to 0.65g/cm^3, respectively. The distribution ratios of the experimental values for the mechanical properties in the density were 80% or more. The density ranges in curved LVLs of two wood species were different because of the difference in their structures, properties, and compression. In Fig. 4 the WSSs were slightly less than the DSSs. In Fig. 5 the SHVs also were slightly less than the SHPs. In Table 5, for curved LVLs made from two wood species, the differences were not so clear for the correlation between DSS and density, MOR and density, RS and density, or SHP and density, respectively. Their correlation coefficients are almost identical and are high (R = 0.805 or more).

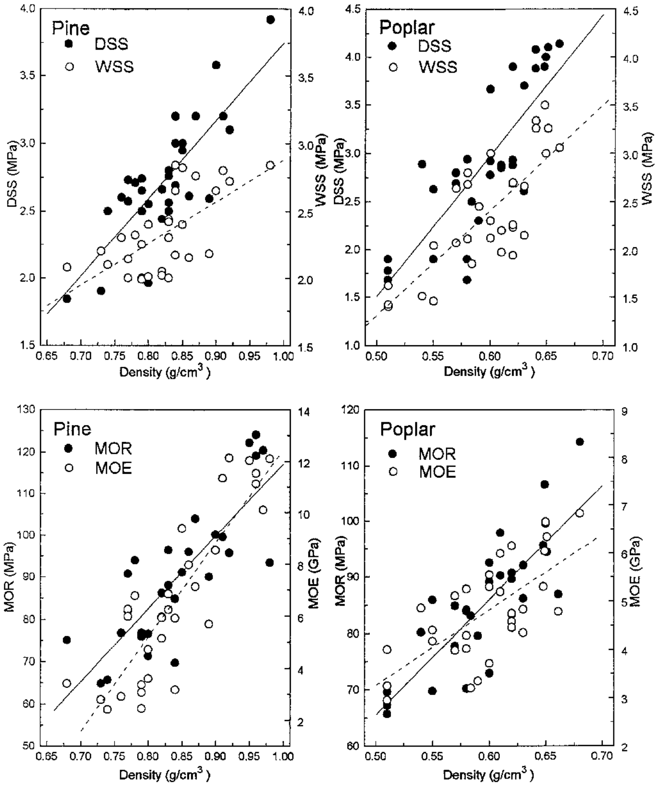

Fig. 4. Relations between shear strengths or bend strengths and densities. See Table 2 for explanation of abbreviations

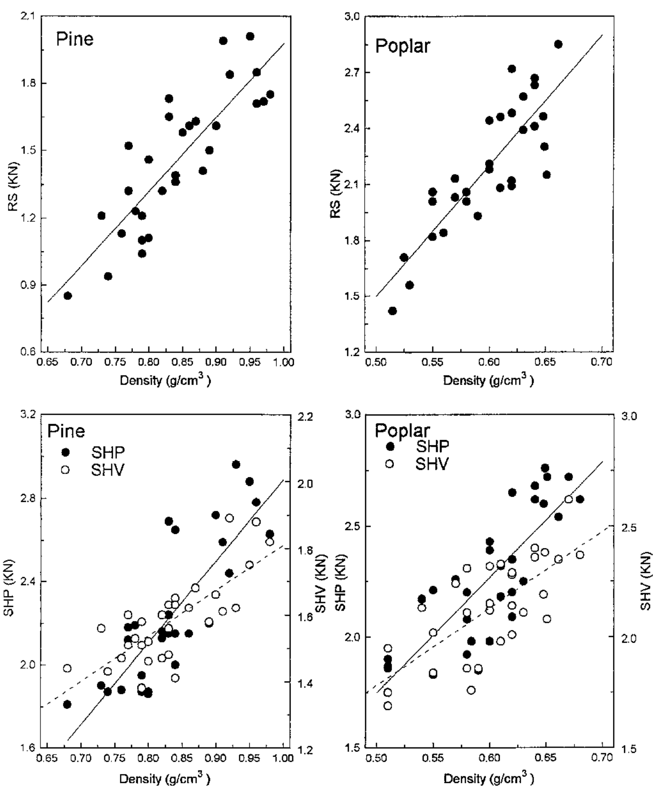

Fig. 5. Relations between rupture strengths or screw-holding strengths and densities. See Table 2 for explanation of abbreviations

Table 5. Regression formulas for density (x) and property (y)

Wood	Regression formula	r
DSS (MPa)		
Pine	$y = -2.020 + 5.771x$	0.808
Poplar	$y = -5.849 + 14.713x$	0.807
WSS (MPa)		
Pine	$y = -0.225 + 3.106x$	0.648
Poplar	$y = -4.183 + 10.994x$	0.779
MOR (MPa)		
Pine	$y = -55.601 + 172.794x$	0.819
Poplar	$y = -36.252 + 203.818x$	0.813
MOE (GPa)		
Pine	$y = -23.807 + 36.282x$	0.865
Poplar	$y = -4.539 + 15.613x$	0.686
RS (kN)		
Pine	$y = -1.328 + 3.310x$	0.845
Poplar	$y = -2.008 + 7.018x$	0.844
SHP (kN)		
Pine	$y = -1.029 + 3.923x$	0.819
Poplar	$y = -0.852 + 5.204x$	0.805
SHV (kN)		
Pine	$y = -0.446 + 1.365x$	0.766
Poplar	$y = -0.046 + 3.474x$	0.716

See Table 2 for explanation of abbreviations. r: Correlation coefficient. There were 30 specimens for each regression.

Conclusions

With the results obtained from this research, the following conclusions were reached. Massion pine and fast-growing poplar can be used as material for curved LVL production. The mechanical properties (DSS, WSS, MOR, MOE, RS, SHP, SHV) of curved LVL showed favorable results under optimum technological conditions. These fast-growing wood species are thus suitable for curved LVL used as structural material for furniture.

The main factors (e.g., frequency, electrode voltage, RF application time, and moisture content) affected the mechanical properties of curved LVL. Furthermore, the RF application time and moisture content were more important factors (affecting the mechanical properties of curved LVL) than the electric parameters (e.g., frequency and voltage).

The mechanical properties of curved LVL increased with an increase in the density of curved LVL. The relations between the mechanical properties and densities could be expressed by linear regression equations as the following: $y = Ax + B$ (y is the mechanical property; x is the density; A and B are the regression constants).

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