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<https://doi.org/10.5109/4772336>

出版情報：九州大学大学院農学研究院紀要. 67 (1), pp.9-16, 2022. Faculty of Agriculture, Kyushu University

バージョン：

権利関係：

Feasibility of Mass Production of Laminated Veneer Lumber (LVL) from Japanese Cedar (*Cryptomeria japonica*) in Taiwan

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(Received October 30, 2021 and accepted November 5, 2021)

The thinned *Cryptomeria japonica* (Japanese cedar, JC) log with a length of 3.6 m above and the diameter at breast height with an end diameter larger than 25 cm was manufactured to JC veneers by rotary cutting. The veneers were dried at a temperature of 150–160°C for 980–1020 s. The veneers with a width less than 4 feet (ft) were side-glued to reach 4 ft, and the veneers with lengths less than 8 ft were edged by gluing. The veneers were classified manually after the natural defects on veneer surface were patched, and arranged in even/odd plies. The adhesive was urea-formaldehyde resin with the amount of glue of 240–270 g/m². The prepressing was 6–8 kgf/cm², the hot-pressing pressure was 10 kgf/cm², the hot-pressing temperature was 100°C, and the hot-pressing time was 60 s/mm from the target thickness preset. The JC laminated veneer lumber (LVL) was mass-produced and compared with *Pinus radiata* (Radiata pine, RP) LVL. The delamination (%) in boiling water of JC LVL was 24.39%. The modulus of rupture (MOR) and modulus of elasticity in bending, the shearing strength, and the nail withdraw strength of JC LVL were 42.73 MPa, 6.35 GPa, 4.01 MPa, and 13.48 N/mm, respectively. After the 36-week outdoor corridor test, the color differences of JC LVL and RP LVL were 9.75 and 54.73; the contact angle of JC LVL was 35.67° and that of RP LVL was 15.00°; the increase of Ra, Rmax and Rz for JC LVL was 3.70, 21.38 and 15.94%, and those for RP LVL were 110.13, 53.45, and 39.06%; the MOR of JC LVL was decreased by 1.70%, for RP LVL it was 18.65%, and the delamination of JC LVL and RP LVL were 34.52 and 44.72%.

Key words: *Cryptomeria japonica* (Japanese cedar, JC), Mass Production, Laminated Veneer Lumber (LVL), Properties

INTRODUCTION

The total annual demand for wood is 5–6 million m³ in Taiwan. However, as environmental awareness has risen since 1990, the logging of natural forests is prohibited, and the annual logging quantity is restricted. The annual domestic produced wood supply is only 40 000–60 000 m³, and the yield is lower than 1% of import (Taiwan Forest Bureau, 1995 and 2016). Moreover, the urgent issues include the terms of uncertified imported wood, the difficulty to obtain forest certification, and the global climate changes influence our living, ecology, and life year by year, leading to catastrophes (Lin *et al.*, 2015; Lo, 2006). Since 2017, to increase the utilization of domestic timber, the Forestry Bureau defined the year 2017 as the first year of domestic timber. The application and development of domestic timber are popularized extensively hoping to increase Taiwan's forestry and develop the market of domestic timber. To increase the self-sufficient ratio of wood effectively and to concern the policy of sustainable forestry, the utilization ratio of domestic timber is expected to be higher than 3–5% in

the next 5 years.

According to the Statistics Database Query, Customs Port Trade Single Window, Customs Administration, Ministry of Finance (2020) in Taiwan, the annual total imported amount of logs was 400 000–720 000 m³ from 2011 to 2018. The total price of imports was NT\$ 3.0–7.2 million. The wood self-sufficient ratio can be increased effectively by replacing the imported log with the domestic wood. The amount of growing stock of *Cryptomeria japonica* (Japanese cedar, JC) is the largest among artificial coniferous forests, and the tall straight timber is its appearance. This is because the JC was densely planted in the early stages, and is mostly tall and has small diameters. The laminated composites are manufactured by slicing and veneering rotary cut, the veneers are parallel with fiber direction to produce laminated veneer lumber (LVL) and perpendicular to fiber direction for plywood. The LVL is veneered parallel with fiber direction, the maximum strength and stiffness can be obtained and the structure-property of wood can be maintained. And, LVL can be used as a log material and is a structural laminated composite (Kamala *et al.*, 1999; Nzokou *et al.*, 2005).

The LVL in any length and thickness can be produced by using continuous lamination to produce large-sized (Jagadish, 1991). The LVL has better dimensional elasticity and proportion limit than the log because its manufacturing technology in wood-based industries is advanced, and without dispersed defects, can be applied to different sizes, and is characterized by high usage of

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wood (Bodig and Fyle, 1986; Gomben and Gorman, 1994). The cooperation of academic research and industry with the mass production of LVL can be added the productive forces of traditional wood-based materials. It solves the interrupted inheritance of industry and can increase the market value of JC development, and the utilization value of plantation wood in forestation and thinning. Therefore, this study used the mass production of LVL from JC log at the industrial factory as manufacture method. The physical and mechanical properties and the properties after placement in the outdoor corridor were compared with the commercially available *Pinus radiate* (Radiata pine, RP) LVL, expecting to provide a reference for mass-produced JC into LVL.

MATERIALS AND METHODS

Test materials

The *Cryptomeria japonica* (Japanese cedar, JC) log was thinned wood, at the length of 3.6 m above and the diameter at breast height with an end diameter larger than 25 cm was taken, mass-produced into veneers by rotary cutting and manufactured into JC laminated veneer lumber (LVL). The *Pinus radiate* (Radiata pine, RP) LVL was used as the control group. The mass production of JC LVL and PR LVL specimens were provided from WAND TSAI INDUSTRIAL CO., LTD. in Chiayi County, Taiwan ROC.

Test method

Determination of physical properties of veneer and LVL

1. Specific gravities in air-dried and absolute-dried moisture content (MC): determined by CNS 1349 (2014) and CNS 11818 (2014).
2. Surface roughness: the size of the specimen was $100 \times 5 \times$ veneer thickness mm. Centerline average roughness (Ra), maximum roughness (Rmax), and 10-point average roughness (Rz) of veneer were determined by the surface roughness tester (Surfcom, Tokyo).
3. Contact angle: the size of the specimen was 60×25 mm \times specimen thickness. The half contact angle ($\theta/2$) of the veneer was determined by the contact angle determinator (Face Co.) using distilled water as liquid drop, and then the contact angle (θ) was obtained.
4. Surface color: the size of the test specimen was 100×50 mm \times specimen thickness. L^* , a^* , and b^* were determined by Chroma Meter CR-400 (Konica Minolta) color difference meter according to CNS 10136 (2018) and the International Commission on Illumination (Robertson, 1977), and then the color difference (ΔE^*) was calculated.
5. Hygroscopicity: referring to CNS 6715 (2018) wood – determination of hygroscopicity, the specimen section 4×4 cm \times thickness was put in an environmental chamber for a conditioning treatment. Water content $\leq 10\%$, the temperature was $40 \pm 1^\circ\text{C}$, relative humidity (RH) was $75 \pm 2\%$, till the specimen weight

remains constant, the weight W75 was taken and the baseline was determined. The temperature was adjusted to $40 \pm 1^\circ\text{C}$ and the RH was set at $90 \pm 2\%$. Till the specimen weight remained constant, the weight W90 and base length were measured. Finally, the specimen was placed in the oven at $103 \pm 2^\circ\text{C}$ till absolute-dried. The weight W_0 and base length were measured. Equations to calculate either of equilibrium moisture content were as follows.

Equilibrium moisture content (%) at temperature 40°C and 75% RH = $[(W75 - W_0) / W_0] \times 100$

Equilibrium moisture content (%) at temperature 40°C and 90% RH = $[(W90 - W_0) / W_0] \times 100$

Linear expansion ratio (%) = $[(L90 - L75) / L75] \times 100$
 where L90 indicating dimensions in longitudinal, width and thickness directions at 90% RH;
 L75 indicating dimensions in longitudinal, width and thickness directions at 75% RH

6. Delamination: according to CNS 14646 (2015) delamination testing method for structural laminated veneer lumber, 75×75 mm square specimen was conditioned in the environment at a temperature of 20°C and 65% RH. The length of each veneering line was measured on each side of LVL. Afterward, the LVL specimen was boiled in boiling water for 4 h, and 1000 mL water was added every 30 min to keep the boiling state. The specimen was taken out and soaked in water at 25°C for 1 h, and then it was put into the oven at $70 \pm 3^\circ\text{C}$. When its weight was decreased by 100–110%, the delaminated lengths of veneering lines on the four sides of the LVL specimen were determined. The delamination of four sides and the total delaminated length in the same veneering lines was calculated. The delamination (%) = total delaminated length of four sides / total length of veneering lines of four sides $\times 100$.

Determination of mechanical properties of LVL

1. Bending strength: referring to CNS 14646 (2015) bending testing method for structural laminated veneer lumber, the width of the LVL specimen in the parallel direction was a multiple of the thickness of the specimen, and the length of the rectangular specimen was 23 times the thickness of the specimen. And, the same as that the width of the LVL specimen in the perpendicular direction was a multiple of the thickness of the specimen, and the length of the rectangular specimen was 23 times the thickness of the specimen. The upper and lower limit loads within the proportional limit and the corresponding deflection and maximum loads were determined. The span was 21 times of specimen thickness and the average load was 14.7 MPa/min. The same load was applied to two key points. Bending strength and modulus of elasticity were calculated according to the following equations.

Modulus of rupture (MOR) (MPa) = $P_b l / bh^2$

where P_b : maximum load (N); l : span (mm); b :

specimen width (mm);

h: specimen thickness (mm)

Modulus of elasticity (MOE) (GPa) = $23\Delta P^3 / 108bh^3 \Delta y$

where ΔP : Difference (N) between upper and lower limit loads within

Proportional limit; Δy : Deflection difference (mm) corresponding to ΔP

2. Shearing strength: referring to CNS14646 (2015) shearing testing method for structural wood laminates. There were 6 LVL specimens in the parallel and perpendicular directions respectively. The width of the LVL specimen in the parallel direction was 40 mm, and the length of the rectangular specimen was 6 times the thickness of the specimen. And, the same as the LVL specimen in the perpendicular direction. The maximum load was determined. The span was 4 times of specimen thickness. The average loading speed was lower than 14.7 MPa/min. The shearing strength was calculated using the following equation.

Shearing strength (MPa) = $3P_b / 4bh$

where P_b : maximum load (N); b: specimen width (mm) (i.e. specimen thickness in a perpendicular direction); h: specimen thickness (mm) (i.e. specimen width in a perpendicular direction)

3. Nail withdraw strength: referring to CNS 6719 (2015) wood-determination of nail withdraw resistance. To determine the same perpendicularity, load, and depth of various nails in the test specimen, a nail fixer was used to make sure the nail could be driven in the test specimen perpendicularly and the nail was driven at the depth of 2 cm in parallel direction by a universal testing machine at speed of 3.6 mm/min. The nail was driven at a depth of 3 cm in perpendicular, parallel, and end directions at speed of 5.4 mm/min. A withdraw test was performed by a universal testing machine (MTS Landmark, USA). The withdraw speed was about 2 mm/min. The maximum load of withdraw strength was recorded. The nail withdraw strength was calculated using the following equation.

Nail withdraw strength (N/mm) = P / L

where P: maximum pullout load (N); L: driving depth (mm)

Determination of properties of LVL after placement in an outdoor corridor

The JC and RP LVLs were placed in the corridor. The area was free from direct sunlight and was ventilated. The specimens were placed at 45 cm above the ground and the air circulates between the layers of the stack. The period lasted 36 weeks. The temperature and RH in Chiayi provided by Central Weather Bureau were used as reference data. The LVL specimens placed in the environment at the temperature of 20°C and 65% RH for two weeks were used as the control group. These were taken out of the outdoor corridor in 0, 4, 8, 12, 24, and 36 weeks and placed in the environment at the tem-

perature of 20°C and 65% RH for two weeks, and then were used as the test group. The specimen sizes and determinations were compared according to the above color difference, roughness, contact angle, delamination, and bending strength tests.

Statistical analysis

The results were represented by mean (standard deviation). Statistical analysis was performed by using T-test and one-way analysis of variance followed by Duncan's multiple comparison test using Statistical Product and Service Solutions. Differences were considered statistically significant when $\rho < 0.05$.

RESULTS AND DISCUSSION

LVL mass production procedure

The mass production procedure of JC LVL followed the RP LVL from WAND TSAI INDUSTRIAL CO., LTD. in Chiayi County, Taiwan including rotary cutting of veneer, veneer drying, and veneers for side-glued and end-glued of connection, veneering engineering, conditions, and edge trimming. This was to produce laminated veneer board (LVB) which was cut to make LVL, as shown in **Fig. 1**. The thinned JC log was manufactured to JC veneers by rotary cutting and the veneers were dried at 150–160°C for 980–1020 s. The veneers with a width less than 4 feet (ft) were side-glued to reach 4 ft, and the veneers with lengths less than 8 ft were edged by gluing, and the veneers were arranged as even/odd plies before LVL manufacturing. The adhesive was urea-formaldehyde resin with the amount of glue of 240–270 g/m². The prepressing was 6–8 kgf/cm², the hot-pressing pressure was 10 kgf/cm², the hot-pressing temperature was 100°C, and the hot-pressing time was 60 s/mm from the target thickness preset.

Physical properties of veneer and LVL

The JC log used was about 44 years old with MC of 235.29%. The log of RP was about 20 years old with MC of 49.91%. The MC in the air-dried JC veneer was 9.06%. The specific gravity of JC veneer in air-dried and absolute-dried was 0.37 and 0.32 respectively. The MC in the air-dried RP veneer was 9.12%. The specific gravity of JC veneer in air-dried and absolute-dried was 0.41 and 0.37. The contact angles of JC and RP veneers were 79.17° and 75.89°. The R_a , R_{max} , and R_z of surface roughness of JC veneer were 5.96, 56.69, and 38.59 μm , and for RP, they were 5.68, 56.28, and 31.04 μm .

The MC, specific gravity in air-dried and absolute-dried of JC LVL were 12.03%, 0.40 and 0.36; RP LVL were 9.88%, 0.56 and 0.51, respectively. The L^* of JC LVL was 59.30 which was lower than 78.18 of RP. This indicates that the surface of JC LVL has a darker color. The a^* of JC LVL was 12.88 which was higher than 5.61 of RP. The surface of JC LVL was redder. The b^* of JC LVL was 24.84 which was close to 24.76 of RP. It is suggested that the surface color of JC LVL is dark reddish-brown, and that of RP LVL is whitish-yellow.

The delamination of JC and RP LVLs in the delami-

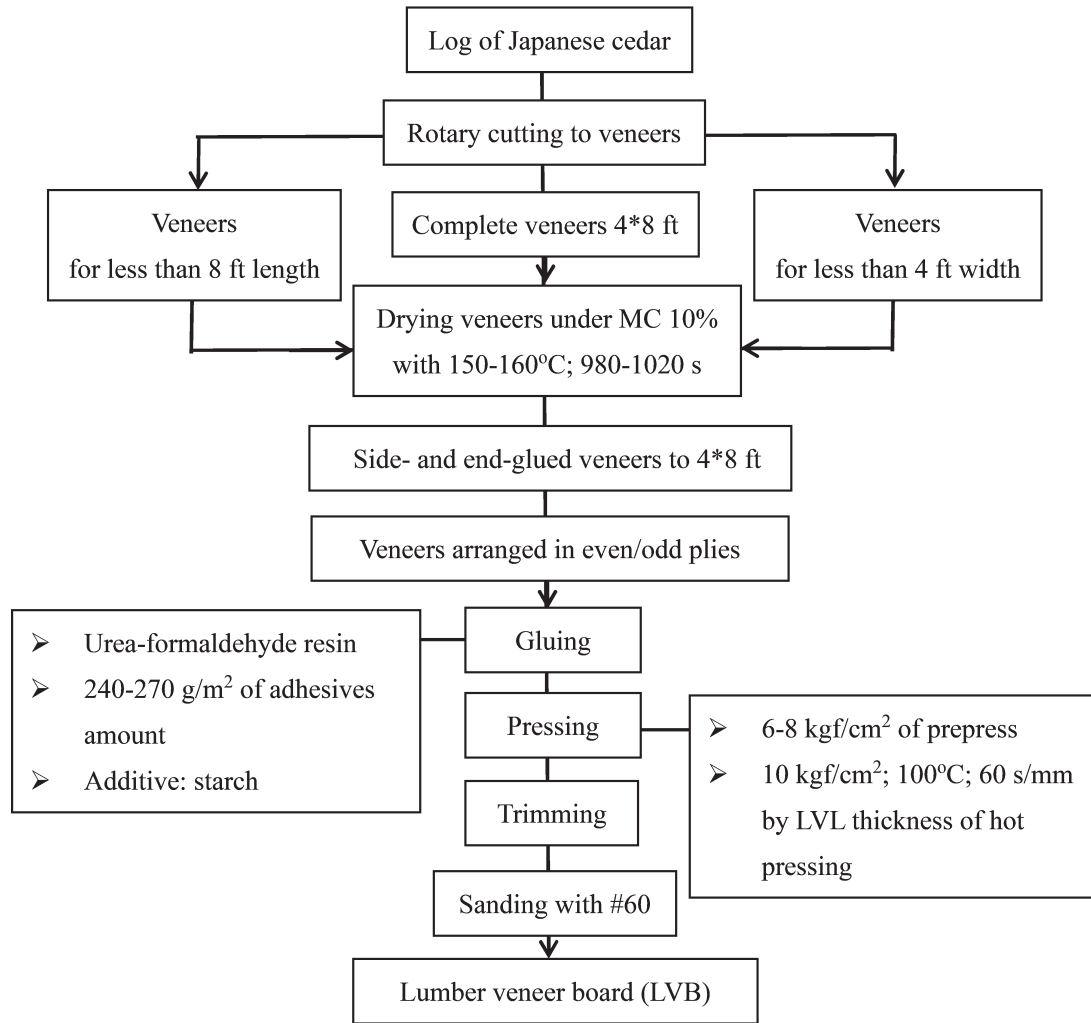


Fig. 1. Procedures of mass production of LVL at WAND TSAI INDUSTRIAL CO., LTD.

Table 1. Moisture content and linear expansion of laminated veneer lumber with different species in 75 and 90% relative humidity

Specimen ¹⁾	75% RH MC (%) ²⁾	90% RH MC (%)	Longitudinal expansion ratio (%)	Width expansion ratio (%)	Thickness expansion ratio (%)
JC LVL	19.79 (0.51) ^a	31.29 (1.08) ^a	0.02 (0.01) ^a	1.82 (0.38) ^a	2.13 (1.51) ^a
RP LVL	16.53 (0.72) ^b	24.78 (2.04) ^b	0.03 (0.01) ^b	2.17 (0.51) ^a	2.43 (0.79) ^a

¹⁾ JC: Japanese cedar; RP: Radiata pine; LVL: Laminated veneer lumber

²⁾ Moisture content (MC) of specimen after conditioning with 75% and 90% RH

³⁾ Mean (standard deviation) with the different superscripts is significantly different ($\rho < 0.05$) by T-test

nation testing method for structural LVL was 24.39 and 33.15% respectively and showing a significant difference. The wood composite is likely to form internal stress during hot-pressing when it contacts water or moisture the internal stress is released. Interfacial adhesion strength and cohesion between wood material and adhesive are insufficient to resist the internal stress of wood material. There is a higher thickness swelling situation because the internal stress increases with the compression ratio and specific gravity as material compressed (Shukla and Kamdem, 2009; Wong *et al.*, 1999).

The MC in JC LVL in the environment at 75% RH

was 19.79%, and the MC in the environment at 90% RH was 31.29%. The MC in RP LVL at both of 75 and 90% RH were 16.53 and 24.78% (**Table 1**). In terms of linear expansion ratio, the longitudinal, width, and thickness expansion ratios of JC LVL were 0.02, 1.82, and 2.13%, and those of RP LVL were 0.03, 2.17, and 2.43%, respectively. The RP LVL had a higher linear expansion ratio than JC because the internal stress of wood composite increased with the compression ratio and the specific gravity of material in the course of hot-pressing. As the RP veneer had a higher specific gravity than the JC veneer, when the RP and JC LVLs contacted water or

moisture, the internal stress was released. RP LVL showed a higher thickness swelling, but there was insignificant difference between RP and JC LVLS according to T-test. This result and the result of delamination had the same trend. The delamination in boiling water of JC LVL was 24.39%, and 33.15% for RP LVL.

Mechanical properties of LVL

The LVL is mass-produced by arranging plies and veneering rotary-cut veneers in parallel with fiber direction, and veneering in parallel with fiber direction can result in maximum strength and stiffness and maintain the structure property of wood (Kamala *et al.*, 1999; Nzokou *et al.*, 2005). **Table 2** showed the results of mechanical properties of both LVLS. The MC and specific gravity in air-dried of JC LVL were 8.88% and 0.38, and those of RP LVL were 8.35% and 0.45. The MOR of JC LVL in parallel direction was 42.73 MPa, and that of RP LVL was 67.28 MPa. There was a significant difference between them according to T-test. The optimum mechanical properties of laminated products include the minimum surface roughness of constitutional units, and influence the mechanical properties of LVL. This is because of different tree species, veneer specific gravity, veneer thickness, different processing conditions, and different adhesives (Hing *et al.*, 2001; Aydin *et al.*, 2004; Çolak *et al.*, 2007).

For this study, veneer thickness, processing conditions, and adhesive were the same in the mass production of JC and RP LVLS. The specific gravities of JC and RP veneers were 0.37 and 0.41 respectively. It might be because the MOR of JC LVL in parallel direction was a little lower than that of RP LVL as a result of veneer specific gravity, contact angle, and surface roughness. Triboulot *et al.* (1995) report that better mechanical properties of laminated products as the surface of constitutional units with minimum surface roughness.

The shearing strength and nail withdraw strength of JC LVL in parallel direction were 4.01 and 13.48 MPa, and its MOE was 6.35 GPa, for RP LVL they were 7.50 and 26.34 MPa and 10.58 GPa. There were all significant

differences after the T-test. The MOR, shearing strength, and nail withdraw strength in perpendicular direction of JC LVL were 53.10, 6.48, and 13.35 MPa, and its MOE was 9.82 GPa. For RP LVL these values were 53.67, 8.64, 19.08 MPa, and 8.78 GPa. The results also showed that the bending strength, shearing strength and nail withdraw strength of LVL in perpendicular direction were larger than those in parallel direction (Wang and Dai, 2005; Bal and Bektaş, 2012; Kurt *et al.*, 2011).

Properties of LVL after placement in outdoor corridor

Surface color change

The ΔE^* of JC LVLS in Weeks 4, 8, 12, 24, and 36 were 5.76, 4.84, 4.93, 8.48, 9.75, and for RP they were 60.15, 60.03, 58.88, 54.23, 54.73 respectively. The L^* of JC LVLS decreased from 59.30 to 53.57 after placed in an outdoor corridor for 36 weeks. The a^* decreased from 12.88 to 8.53. Similarly, the b^* decreased from 24.84 to 18.98. The L^* of RP LVLS decreased from 78.18 to 53.31. The a^* increased from 5.61 to 8.85 while the b^* decreased from 24.76 to 21.43. However, the JC LVL had a smaller color difference than RP LVL (**Table 3**).

Li (2000) indicates that the wood loses its original surface color in the outdoor atmospheric exposure test, and the L^* of wood surface color decreases as the atmospheric exposure test proceeded. Kim *et al.* (2016) indicate that the lignin and hemicellulose are first influenced by natural deterioration. Heitner (1993) indicates that the lignin formed photodegradation after ultraviolet (UV) – irradiation. Therefore, the b^* of JC LVL and RP LVL increased in 0 to 8 weeks of placement. The RP LVL was apparently yellow according to visual observation and the b^* of JC LVL and RP LVL began to decrease after Week 8. Denes and Young (1999) and Kalnins and Feist (1993) also indicate that the photodegradation products formed from photo-destruction of wood are likely to be degraded by rain and the wood surface fades.

Surface roughness and contact angle

The contact angle of JC LVL decreased from 75.50°

Table 2. Mechanical properties of two types of laminated veneer lumbers

Specimen ¹⁾	MC ²⁾ (%)	Specific gravity ²⁾	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Shearing strength (MPa)	Nail withdraw strength (N/mm)	
JC LVL	Parallel direction		42.73 (10.35) ^{ab)}	6.35 (1.23) ^{a)}	4.01 (0.68) ^{a)}	13.48 (2.10) ^{a)}	
	Perpendicular direction	8.88(0.04) ^{ab)}	0.38 (0.01) ^{a)}	53.10 (10.77) ^{A)}	9.82 (1.80) ^{A)}	6.48 (0.78) ^{A)}	13.35 (3.01) ^{A)}
	End direction		–	–	–	5.73 (1.32) ^{x)}	
RP LVL	Parallel direction		67.28 (18.43) ^{b)}	10.58 (2.34) ^{b)}	7.50 (1.27) ^{b)}	26.34 (3.47) ^{b)}	
	Perpendicular direction	8.35 (0.03) ^{a)}	0.45 (0.02) ^{a)}	53.67 (16.29) ^{A)}	8.78 (2.62) ^{A)}	8.64 (1.47) ^{B)}	19.08 (5.78) ^{B)}
	End direction		–	–	–	11.57 (2.16) ^{y)}	

¹⁾ See Table 1

²⁾ MC: see Table 1; MC and specific gravity of specimens were after air-dried

³⁾ Mean (standard deviation) with the different superscripts is significantly different ($\rho < 0.05$) by T-test, ab for parallel direction of LVL, AB for perpendicular direction of LVL, and XY for end direction of LVL

to 35.67° after 36 weeks, it was reduced by about 52.75%. For RP LVL it was reduced by 72.81% from 55.17° to 15.00°. The Ra, Rmax, and Rz of JC LVL and RP LVL increased with time of placement in the outdoor corridor. According to the comparison between the roughness after 36 weeks and the roughness before placement, the Ra of JC LVL was 3.70%, Rmax was 21.38% and Rz was 15.94%, which were lower than Ra 110.13%, Rmax 53.45%, and Rz 39.06% of RP LVL (**Table 4**). Hayashi *et al.* (2005) indicate in the durability test for the LVL on the local market that as the color difference is increased the roughness increases, and the contact angle decreases.

Evans *et al.* (2002) and Jebrane *et al.* (2009) indicate that the wood is influenced by outdoor environmen-

tal factors. In the UV and aerobic environment, the wood generated photooxidation and the chemical constituents of wood are degraded and destroyed. The lignin contains a higher amount in middle lamella, which are severely pyrolyzed, and the cell walls were destroyed or/and lost. This resulted in many micro-cracks in the wood cell wall. Flæte *et al.* (2000) indicate that the wood is hygroscopic. The atmospheric water molecules show the wood of shrink and swell, and then the generated stress accelerates the outdoor deterioration of wood. This indicates in end check, deformation and warp, the wood surface roughness increases and the contact angle decreases, and the mechanical properties of wood are degraded eventually.

Table 3. Color difference of laminated veneer lumber under outdoor corridor

Specimen ¹⁾	Week	L*	a*	b*	$\Delta E^{*2)}$
JC LVL	0	59.30 (2.94)	12.88 (1.40)	24.84 (0.90)	–
	4	53.84 (2.82)	11.69 (1.06)	24.50 (0.83)	5.76 (1.56) ^{a3)}
	8	55.30 (2.08)	11.23 (0.56)	26.31 (0.98)	4.84 (1.43) ^a
	12	55.62 (1.71)	10.40 (0.51)	23.95 (1.08)	4.93 (1.21) ^a
	24	55.84 (1.19)	8.22 (0.42)	19.29 (0.79)	8.48 (1.56) ^b
	36	53.57 (1.16)	8.53 (0.57)	18.98 (0.92)	9.75 (2.06) ^b
RP LVL	0	78.18 (3.83)	5.61 (1.70)	24.76 (1.74)	–
	4	57.53 (3.07)	6.83 (1.01)	24.37 (1.49)	60.15 (3.52) ^a
	8	56.97 (2.70)	8.95 (0.95)	26.63 (1.37)	60.03 (3.27) ^a
	12	56.44 (2.85)	9.02 (0.96)	25.07 (1.29)	58.88 (3.32) ^a
	24	52.67 (2.28)	7.95 (0.84)	20.86 (1.33)	54.23 (2.90) ^b
	36	53.31 (2.25)	8.85 (0.94)	21.43 (1.27)	54.73 (2.86) ^b

¹⁾ See Table 1

²⁾ ΔE^* : Color difference

³⁾ Mean (standard deviation) with the different superscripts is significantly different ($\rho < 0.05$) by Duncan's multiple range test

Table 4. Contact angle and surface roughness of laminated veneer lumber under outdoor corridor

Specimen ¹⁾	Week	Contact angle (°)	surface roughness (μm) ²⁾		
			R _a	R _{max}	R _z
JC LVL	0	75.50 (4.32) ³⁾	3.24 (0.76)	24.98 (6.07)	16.62 (3.84)
	4	75.83 (10.85)	3.44 (0.92)	28.18 (15.16)	18.00 (4.53)
	8	58.17 (9.99)	3.71 (0.80)	28.18 (6.34)	17.41 (4.40)
	12	38.33 (5.72)	3.67 (0.90)	29.73 (8.72)	18.57 (4.68)
	24	39.33 (8.07)	3.50 (0.70)	29.47 (9.05)	19.60 (6.29)
	36	35.67 (14.42)	3.36 (0.93)	30.32 (12.63)	19.27 (6.38)
RP LVL	0	55.17 (10.01)	2.72 (0.92)	23.18 (6.85)	15.31 (4.19)
	4	57.67 (19.93)	4.03 (0.62)	35.07 (8.63)	22.68 (5.74)
	8	36.67 (12.11)	4.24 (0.98)	35.24 (9.41)	22.68 (6.85)
	12	15.33 (5.20)	4.15 (1.32)	35.61 (16.58)	20.72 (5.70)
	24	15.50 (3.08)	4.12 (1.17)	36.66 (13.06)	24.69 (5.19)
	36	15.00 (1.67)	4.77 (4.33)	35.57 (12.83)	21.29 (5.91)

¹⁾ See Table 1

²⁾ R_a, R_{max} and R_z: Average roughness, maximum roughness, and mean peak-to-valley height

³⁾ Mean (standard deviation)

Table 5. Delamination in boiling water and bending strength of durability of laminated veneer lumber under outdoor corridor

Specimen ¹⁾	Week	Delaminated (%)	Modulus of rupture (MPa)
JC LVL	0	24.39 (9.04) ^{az2)}	52.97 (3.29) ^a
	4	23.97 (8.37) ^a	52.13 (6.02) ^a
	8	24.53 (10.01) ^a	52.23 (4.62) ^a
	12	33.02 (9.34) ^a	52.16 (12.62) ^a
	24	34.17 (11.13) ^a	52.00 (8.80) ^a
	36	34.52 (8.21) ^a	52.07 (8.52) ^a
RP LVL	0	33.15 (9.27) ^a	75.35 (9.55) ^a
	4	33.67 (7.39) ^a	75.98 (9.43) ^a
	8	35.21 (10.21) ^a	72.47 (3.40) ^{ab}
	12	40.18 (8.52) ^a	67.14 (8.43) ^{abc}
	24	43.68 (9.73) ^b	63.31 (9.15) ^{bc}
	36	44.72 (7.89) ^b	61.30 (6.34) ^c

¹⁾ See Table 1²⁾ See Table 3

Delamination and bending strength

According to the 36-week test in the outdoor corridor, the delamination in boiling water of JC LVL increased from 24.39 to 34.52%. For RP, this increase was from 33.15 to 44.72%. According to Duncan's multiple range analysis, there was no significant difference between the delamination of JC LVL before and after placement, whereas there were significant differences between the delamination of RP LVL in Weeks 24 and 36 before placement (**Table 5**). The MOR of JC LVL decreased from 52.97 to 52.07 MPa. The percentage of reduction was about 1.70%. These values for RP decreased from 75.35 to 61.30 MPa with a reduction rate of 18.65%. There were significant differences between them.

In the outdoor durability test, the lignin of wood is likely to perform a light deterioration reaction after UV-irradiation. The wood deteriorates, the texture is softened and fragile, and the mechanical properties are degraded (Stark and Matuana, 2006). Bal and Bektaş (2012) also indicate that the mechanical properties in parallel direction of LVL were closely correlated with the adhesion strength of adhesives. The JC LVL had a better delamination after 36 weeks than the RP LVL. It is suggested that the bending strength of durability for JC LVL in the outdoor corridor is better than that for RP LVL.

CONCLUSION

This study manufactured JC LVL by mass production. The properties of JC LVL were compared with those of RP LVL. Both LVLs were placed for 36 weeks in the outdoor corridor for difference of evaluated properties. The MC, specific gravity in air- and absolute-dried of JC LVL was 12.03%, 0.40 and 0.36, respectively. For RP LVL, these were 9.88%, 0.56 and 0.51. The JC LVL

had a lower delamination than RP LVL. The longitudinal expansion ratio of JC LVL was 0.00–0.02%, the width expansion ratio was 1.31–1.82%, and the thickness expansion ratio was 1.57–2.13%. After placement in the outdoor corridor for 36 weeks, the JC LVL of ΔE^* and contact angle less than the RP LVL; the increase of Ra of JC LVL was 3.70%, Rmax was 21.38%, and Rz was 15.94%, and these for RP LVL were 110.13, 53.45, and 39.06%, respectively. After placing in boiling water, the delamination of JC and RP LVLs was 34.52 and 44.72%; the MOR of JC and RP LVLs was 52.07 and 61.30 MPa, respectively. There was no significant difference among the MOR of JC LVL after placement in outdoor corridor for 36 weeks, but there was a significant difference in the MOR of RP LVL. The mass production of JC LVL from JC is therefore feasible while considering value-added JC.

AUTHOR CONTRIBUTION

Han Chien LIN designed the study and wrote this paper. Li-Sheng LIN performed the course/experiments and evaluated data with the statistical analysis. Yiren WANG provided the equipment of MTS Landmark and guided the experiments of mechanical properties. Tsang-Chyi SHIAH discussed the experiments and offered some of equipment. Noboru FUJIMOTO supervised the work. The authors assisted in editing of the manuscript and approved the final version.

ACKNOWLEDGEMENTS

The authors offer our sincere appreciation to the Chiayi Forest District Office, Forest Bureau, Council of Agriculture, Executive Yuan, Taiwan ROC through No. Ze107-51 for financial support.

REFERENCES

- Aydin, I., S. Çolak, G. Çolakoğlu and E. Salih 2004 A comparative study on some physical and mechanical properties of Laminated Veneer Lumber (LVL) produced from Beech (*Fagus orientalis* Lipsky) and Eucalyptus (*Eucalyptus camaldulensis* Dehn.) veneers. *Holz als Roh- und Werkstoff*, **62**(3): 218–220
- Bal, B. C. and I. Bektaş 2012 The effects of wood species, load direction, and adhesives on bending properties of laminated veneer lumber. *BioResources*, **7**(3): 3104–3112
- Bodig, J. and J. Fyie 1986 Performance requirements for exterior laminated veneer lumber. *Forest products journal*, **36**(2): 49–54
- Çolak, S., G. Çolakoğlu and I. Aydin 2007 Effects of logs steaming, veneer drying and aging on the mechanical properties of laminated veneer lumber (LVL). *Building and Environment*, **42**(1): 93–98
- Denes, A. R. and R. A. Young 1999 Reduction of weathering degradation of wood through plasma-polymer coating. *Holz-forschung*, **53**(6): 632–640
- Evans, P. D., A. F. A. Wallis and N. L. Owen 2000 Weathering of chemically modified wood surfaces. *Wood Science and Technology*, **34**(2): 151–165
- Flæte, P. O., O. A. Høibø, F. Fjærtoft and T. N. Nilsen 2000 Crack formation in unfinished siding of aspen (*Populus tremula* L.) and Norway spruce (*Picea abies* (L.) Karst.) during accelerated weathering. *Holz als Roh- und Werkst*, **58**(3): 135–139

- Gomben, P. C. and T. M. Gorman 1994 Treatability of lodgepole pine laminated veneer lumber. *Forest Products Journal*, **44**(2): 39–41
- Hayashi, T., A. Miyatake, F. Fu, H. Kato, M. Karube and M. Harada 2005 Outdoor exposure tests of structural laminated veneer lumber (II): evaluation of the strength properties after nine years. *Journal of Wood Science*, **51**(5): 486–491
- Heitner, C. 1993 *Light-induced yellowing of wood-containing papers*. pp. 2–22. In C. Heitner and J. C. Scaiano eds. *Photochemistry of Lignocellulosic Materials*. American Chemistry Society, Washington D.C. pp. 223
- Hing, P. S., M. T. Paridah and A. Zakiah 2001 *Edgewise bending properties of LVL: effects of veneer thickness and species*. In The proceedings of USM–JIRCAS joint international symposium, lignocellulose material of the millennium: technology and application. pp. 20–22
- Jagadish, H. N. 1991 *The future of wood in the field of materials and the strategy for wood as a material (Not as a fuel)*. In National Workshop on “The future of wood in the world of materials,” July. National Material Policy Project, Bangalore, India. pp. 1–32
- Jebrane, M., G. Sèbe, I. Cullis and P. D. Evans 2009 Photostabilisation of wood using aromatic vinyl esters. *Polym. Degrad. Stab.*, **94**: 151–157
- Kamala, B. S., P. Kumar, R. V. Rao and S. N. Sharma 1999 Performance test of laminated veneer lumber (LVL) from rubber wood for different physical and mechanical properties. *Holz als Roh- und Werkstoff*, **57**(2): 114–116
- Kalnins, M. A. and W. C. Feist 1993 Increase in wettability of wood with weathering. *Forest Products Journal*, **43**(2): 55–57
- Kim, Y. S., K. H. Lee and J. S. Kim 2016 Weathering characteristics of bamboo (*Phyllostachys puberescence*) exposed to outdoors for one year. *Journal of Wood Science*, **62**(4): 332–338
- Kurt, R., M. Cil, K. Aslan and V. Çavuş 2011 Effect of pressure duration on physical, mechanical, and combustibility characteristics of laminated veneer lumber (LVL) made with hybrid poplar clones. *BioResources*, **6**(4): 4886–4894
- Li, R. 2000 Environmental degradation of wood–HDPE composite. *Polym. Degrad. Stab.*, **70**: 135–145
- Lin, J. C., S. J. Chen and M. S. Wu 2015 An analysis of the timber harvest volume and production in Taiwan between 1991 and 2013. *Taiwan Journal of Forest Science*, **30**(2): 121–130
- Lo, K. A. 2006 Challenge of the private holding forests toward sustainable management in Taiwan. *Quarterly Journal of Forest Research*, **28**(1): 39–52
- Nzokou, P., J. Zyskowski, S. Boury and D. P. Kamdem 2005 Natural decay resistance of LVL made of veneers from durable and non-durable wood species. *Holz als Roh- und Werkstoff*, **63**(3): 173–178
- Robertson, A. R. 1977 The CIE 1976 color-difference formulae. *Color Research & Application*, **2**: 7–11
- Shukla, S. R. and D. P. Kamdem 2009 Properties of laboratory made yellow poplar (*Liriodendron tulipifera*) laminated veneer lumber: effect of the adhesives. *European Journal of Wood and Wood Products*, **67**(4): 397–405
- Stark, N. M. and L. M. Matuana 2006 Influence of photostabilizers on wood flour–HDPE composites exposed to xenon-arc radiation with and without water spray. *Polymer degradation and stability*, **91**(12): 3048–3056
- Triboulot, P., C. Sales, A. Zerizer and P. Martin 1995 Correlation of fracture toughness of bonded joints with quality (roughness) of knife-planed MDF surfaces. *Holzforschung*, **49**(5): 465–470
- Wang, B. J. and C. P. Dai 2005 Hot-pressing stress graded aspen veneer for laminated veneer lumber (LVL). *Holzforschung*, **59**(1): 10–17
- Wong, E. D., M. Zhang, Q. Wang and S. Kawai 1999 Formation of the density profile and its effects on the properties of particle-board. *Wood Science and Technology*, **33**(4): 327–340
- Customs Administration, Ministry of Finance 2020 The Statistics Database Query, Customs Port Trade Single Window. <https://portal.sw.nat.gov.tw/APGA/GA02.20201129>
- Forest Bureau 1995 The third forest resource survey report. Forest Bureau, Council of Agriculture, Executive Yuan. <https://www.forest.gov.tw/0000052?iPage=2,07072021>
- Forest Bureau 2016 The fourth forest resource survey report. Forest Bureau, Council of Agriculture, Executive Yuan. <https://www.forest.gov.tw/00023930,07072021>