Interfacial Adhesion and Damping Characteristics of Laminated Veneer Lumber Intercalated with Rubber Sheets

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Laminated wood veneer lumber intercalated with rubber sheets (LLVR) was fabricated using a layered adhesive system composed of polyaryl polymethylene isocyanate (PAPI) for wood-rubber inter-bonding and phenol formaldehyde (PF) resin to glue the wood veneers. The optimized manufacturing process (chloroprene rubber: CR; PAPI: 80 g/m^2; PF: 200 g/m^2; and silane: 9.0 wt.%) was determined. The process as developed was then utilized to fabricate nine-ply LLVRs of five balanced constructions with two or three CR laminates used as various layers. The physico-mechanical properties of the LLVRs were evaluated, and the results showed that LLVRs had strong shear strength, sound dimensional stability, decent bending strength, and favorable toughening and buffering performances. The newly developed product is an interesting potential alternative to traditional laminated veneer lumber or plywood.

Keywords: Wood; Poplar; Laminated veneer lumber; Mechanical properties; Rubber

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INTRODUCTION

With the dramatic reduction of the world's forest resources and the increasing demand for automobiles, a severe dilemma between environmental pollution from waste tires and the shortage of wood resources will develop. Thus, protecting the environment by reducing "black rubber pollution" and saving wood resources have both become critical issues. Effectively utilizing wood resources and recycling waste rubber tires through manufacturing wood-rubber based composites is considered one of the most promising solutions to both problems (Jun *et al.* 2008). On the one hand, wood composites possess many characteristics inherited from wood, such as high strength-to-specific gravity ratio, satisfactory durability (after proper pretreatment), excellent bio-degradability, energy absorption, and damping performance. On the other hand, waste tire rubber is an ideal alternative material for functional wood-based composite panels because of its unique properties, such as characteristically large elastic deformation, good sound insulation, excellent energy absorption, good durability and abrasion resistance, and anti-rot and anti-caustic properties (Ayrilmis *et al.* 2009a). In addition, wood is a highly hygroscopic material, resulting in a low dimensional stability in humid environments. Meanwhile, tire rubber is almost hydrophobic and is only minimally affected by atmospheric humidity. The combination of wood and rubber has the potential to create more competitive capabilities (Ayrilmis *et al.* 2009b). Specifically, intercalation of laminated veneer lumber (LVL) with rubber sheets may improve its physical and mechanical properties, such as water resistance and bending properties. Therefore, the novel composites can be potentially applied in many fields, such as an alternative railway sleeper or sports ground floor, meeting the demand for green construction materials and a low-carbon emission economy (Zhao *et al.* 2013; Ashori *et al.* 2015; Wang *et al.* 2015; Xu *et al.* 2015).

Studies in other fields on hybrid plywood composites have provided a wealth of valuable information and practical references, and the fabrication of a table tennis paddle is actually a great example (Manin *et al.* 2012; Liu *et al.* 2014; Manin *et al.* 2014). A table tennis paddle is typically composed of three laminate layers, *i.e*., the bottom plate, rubber, and sponge. The primary concern of the table tennis paddle design is typically the impact load delivery performance of the rubber cover, which must be adaptive to the high speed and intense rotation of the ball. Relatively little attention, however, is typically given to the interfacial bonding between the rubber cover and wood base (Lu *et al.* 2016).

There have been notable recent studies conducted on the utilization of recycled tire rubber in plywood manufacturing. One very popular research direction is blending waste tire rubber (WTR) powders in resin systems to optimize glue line elasticity. Ong *et al*. (2015), for example, used waste rubber powder (WRP) as a filler for melamine urea formaldehyde (MUF) to manufacture plywood. The WRP was first treated with chemicals like nitric acid, hydrogen peroxide, and acetone, which benefited resin penetration in the WRP and resulted in higher shear strength and lower formaldehyde emission in the plywood. Ashori *et al*. (2015) investigated a novel hybrid seven-layer plywood material composed of wood (beech and alder) veneers and rubber particles. First, WTR particles were pre-pressed to a single laminate layer with methylene diisocyanate (MDI) resin, and the layer was subsequently bonded to wood veneers, or, alternately, WTR particles were *in-situ* hot-pressed with wood veneers. The addition of rubber improved certain physical properties (*e.g.*, water absorption, thickness swelling, and sound absorption) of the manufactured panels, but degraded the mechanical properties (*e.g.*, bending strength and impact strength). The physical and mechanical performance of the plywood panels improved as resin content increased.

Full understanding of the response behaviors of a designated material is crucial to assess the applicability of the material to vibration-sensitive applications, such as high-speed railways or sports ground floor. Rubbery substances have good damping performance and are commonly utilized in aviation, aerospace, navigation, submarine, or other large machinery applications for which vibration attenuation is essential. Rubber sheets can be adhered to metal or engineering plastic substrates to form free or constrained damping constructions.

The aim of this study was therefore to attempt to build sound composite panels with laminated poplar wood-veneer/rubber-sheet by optimizing their interfacial bonding and physico-mechanical properties. The effects of rubber type, PAPI, silane coupling agent (Bis[3-(triethoxysilyl) propyl]tetrasulfide, KH69), silane, PF content, and panel structure on the interfacial bonding properties, wood/rubber glue line shear strength, static bending strength (MOR: modulus of rupture, MOE: modulus of elasticity), 24-hour thickness swelling (24-h TS), dimensional recoverability, and damping properties were comprehensively examined. The results obtained may provide useful information for the manufacture of full-scale wood/rubber composite panels in the future.

EXPERIMENTAL

Materials

Poplar (*Populus deltoids* Bartr. cv. ‘Lux, I-69 poplar) was initially introduced to China from Italy in 1972, and subsequently planted widely throughout the southern region of China. The veneers (W) used to make LLVR were rotary-cut from poplar logs with a diameter at breath height (DBH) of 30 to 35 cm. Veneers 1.8 mm in thickness were oven-dried to a moisture content of 12% and then cut into 500 mm by 500 mm pieces. The rubber sheets (R), 2 mm in thickness, were specially supplied by Shanghai Mujing Rubber and Plastics Co. Ltd, and were cut as-is into the same size as the poplar veneer pieces. Three types of rubber, acrylonitrile butadiene rubber (NBR), natural rubber (NR), and chloroprene rubber (CR), were selected to test their differential interfacial bonding with poplar veneers. Polyaryl polymethylene isocyanate (PAPI) resin was used as the W-R interfacial bonding agent, and phenol formaldehyde (PF) resin was used to bond the poplar veneers. The coupling agent applied to reinforce the interfacial bonding between wood veneers and rubber sheets was bis-(3-triethoxysilicyl propyl)-tetrasulfide (BTESPT), *i.e.*, $(C_2H_5O)_3\text{-Si-}(CH_2)_3\text{-}S_4\text{-}(CH2)_3\text{-Si-}(C_2H_5O)_3$, commercially marketed as KH69 (sulfur content above 22.5%).

Experimental Design and Process

The typical three-step technical route for LLVR manufacturing is shown in Fig. 1. The first step was to establish an optimized interfacial bonding process between poplar veneers and the three kinds of rubber sheets (NBR, NR, and CR). The PAPI resin was spread onto the rubber sheets at four loading levels (40, 60, 80, and 100 $g.m^{-2}$). Three-layer LVLR segments (W-R-W) were paved and hot-pressed at 160 °C and 1.5 MPa for 4 min using a 600 mm x 600 mm single-opening hot-press.

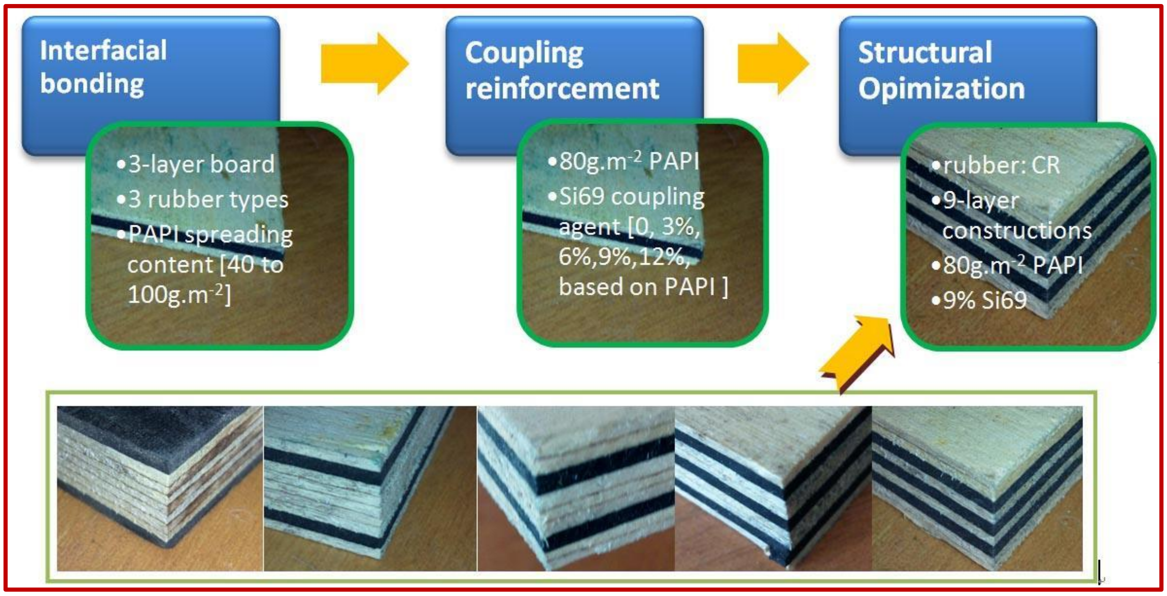


Fig. 1. Three-step experimental technical route for manufacturing LLVRs

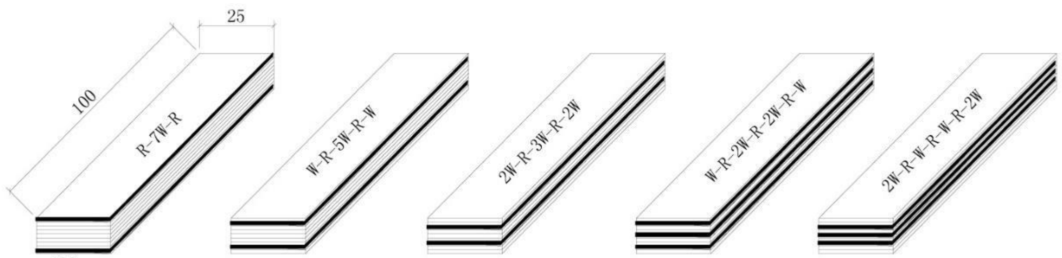
For the second step, a single-factorial experiment was conducted to study the influence of KH69 dosage (0%, 3%, 6%, 9%, and 12%, based on PAPI resin content,) on

W-R interfacial bonding strength. The KH69 coupling agent was blended evenly in the PAPI resin before the glue was spread. Finally, based on the process parameters determined above, five types of wood-rubber hybrid structures were designed to fabricate nine-layer LLVRs: R-7W-R, W-R-5W-R-W, 2W-R-3W-R-2W, W-R-2W-R-2W-R-W, and 2W-R-W-R-W-R-2W. The poplar veneers were laid in a parallel direction in all the LLVRs.

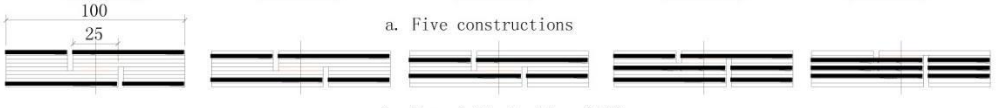
Mechanical and Physical Properties

All the boards were conditioned at room temperature (RT) for 48 h before testing. Basic mechanical and physical properties, including wood/rubber glue line shear strength, static bending strength (MOR and MOE) and 24-h TS, were tested according to the Chinese national standard for wood-based panels, GB/T 17657 (2013). A two-way analysis of variance (ANOVA; MATLAB software version 7.0, MathWorks, Beijing, China) was conducted for the data obtained.

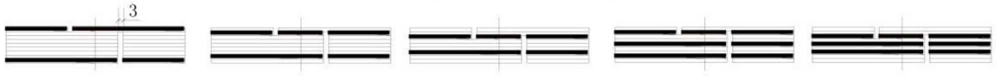
Glue line shear strength is a key index to evaluate the interfacial bonding between poplar veneers and rubber sheets. As shown in Fig. 2, specimens were cut into segments 100 mm in length and 25 mm in width. Two narrow slots 25 mm apart were sawn to test the selected W/W or W/R interfacial glue lines. The depth of sawn slots was dependent on the specific position of W/W or W/R interfacial glue lines in the laminated construction. After submersion in boiling water for 3 h, the specimens were subjected to a tensile load in the lengthwise direction at a speed of 2 mm/min until failure occurred. Specimens for the static bending test were 50 mm in width and length 20 times that of the thickness (span for centering loading) plus 50 mm. A three-point static bending test was conducted to obtain MOR and MOE values, where a uniform moving rate of motion for the crosshead was set at 5 mm/min. Both shear strength and bending performance values were tested using an Instron universal mechanical testing machine (TestResources, Inc, Shakopee, MN, USA). A water soaking experiment was also conducted to test the dimensional stability of the LLVRs in moist conditions, in which specimens 50 mm x 50 mm by thickness were submersed horizontally under 10 mm of water at RT for 24 h. The thickness of the soaked specimens was then immediately measured upon removal of surface water to calculate the amount of swelling.



a. Five constructions



b. Tested PF gluelins (W/W)



c. Tested PAPI gluelines (W/R)

Fig. 2. Schematic diagrams of shear strength testing specimens with five constructions; the slots are cut at a depth so that the designated glue line is exposed for tensile testing

Dimensional Recoverability under Repetitive Compression Loading

As a type of functional composite panel, LLVRs should have good dimensional recoverability under frequent compression loads. To reflect this quality, a five-cycle loading and unloading test was conducted using the Instron machine (Fig. 3). Specimens 30 mm x 30 mm by thickness were loaded in compression mode perpendicular to the surface at a loading rate of 3 mm/min, and the ending compression load for every cycle was controlled at 5 kN. The output load-deflection curve (L-D curve) was drawn to reveal the mechanical behavior of the specimens. The linear stage of each L-D curve can be described mathematically as $L = f \bullet D + c$, where f is the slope reflecting the stiffness under compression.

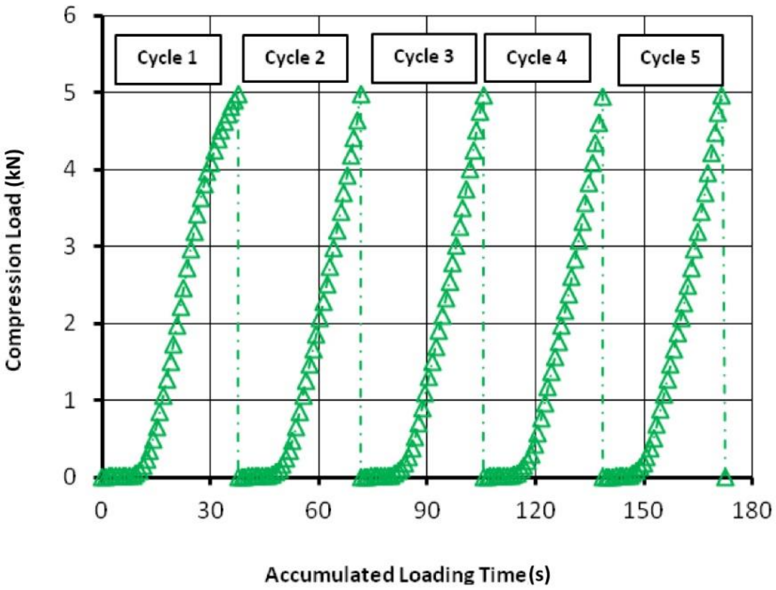


Fig. 3. Schematic of experiment using five loading-unloading cycles to detect the recoverability

Scanning Electron Microscope (SEM) Analysis

A scanning electron microscope (FEI QuantaTM 3D FEG Dual Beam SEM/FIB, Hillsboro, Oregon, USA) was used to characterize the micro-structure of wood-rubber interfacial glue lines. The scanning surfaces of the specimens were cut with a sharp blade, then the newly cut surface was sprayed with Au particles in a vacuum sprayer (ETD-2000C, Elaborate Technology Deve, Beijing, China) before observation. Magnifications were adjusted as necessary.

Damping Properties

A state-of-the-art forced vibration system (Fig. 4) was installed in the lab to test the damping characteristics of the LLVRs. The system includes a rigid sample clamper, a hammer with a Nylon cap (signal source), an accelerometer, an FFT analyzer (Japan Onosokki, CF-7200A), and an amplifier. A bar-shaped specimen, 300 mm x 50 mm by thickness, was steadily clamped at one end as a cantilever; then, the accelerometer was glued on one side 50 mm from the clamping end. The specimen was hit on another side along the half-width line to produce a transient stimulating signal. A similar study reported that chosen points have no significant influence on the final results (Wang *et al.* 2012), so in this study, only one point was set 50 mm from the free end. After hitting, the pressure sensor imbedded in the hammer captured and input the signals to the FFT analyzer along channel 1 after amplification. The stimulated vibration signal was simultaneously captured and input to the FFT analyzer by the accelerometer along channel 2. The output vibration attenuation waves from the FFT analyzer revealed the damping characteristics of the target material. Five repetitions were applied and averaged for each condition to form the final results. For the sake of comparison, pure LVL specimens of the same size as the experimental specimens were tested as a control.

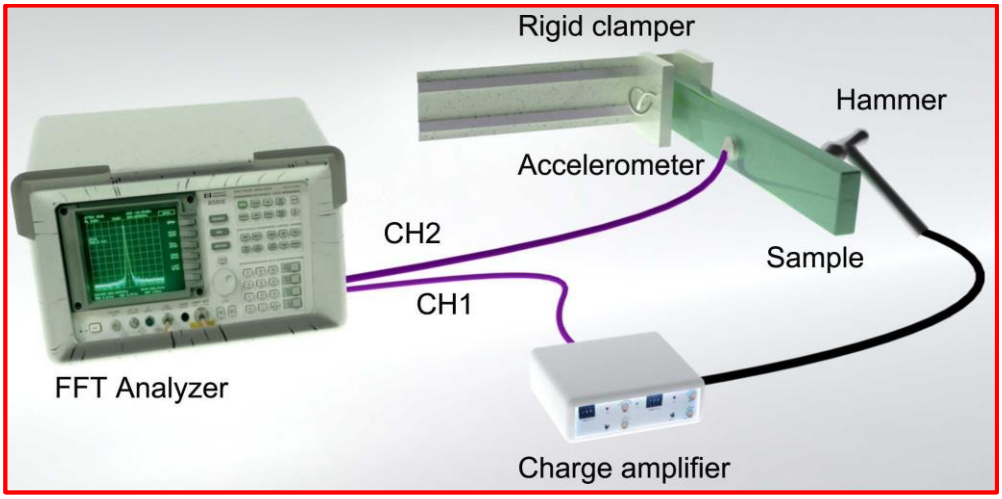


Fig. 4. Schematic diagram of the modal vibration test system

RESULTS AND DISCUSSION

Properties of Interfacial Bonding between Rubber Sheet and Poplar Veneers

The bonding strength between rubber and wood materials is the most crucial factor in manufacturing wood-rubber composite panels successfully. Many previous studies have tried various resin systems for wood-rubber adhesion. Ismail *et al.* (2001), for example, attempted to use phenol formaldehyde (PF), silica gel, and resorcinol formaldehyde (RF) to glue oil palm wood flour and rubber powders to make composites. Their results indicated that a hybrid system of RF, silica gel, and hexamethylene tetramine (HMT) was best suited to bonding the materials. Isocyanate resins (*e.g.*, diphenyl methane diisocyanate, MDI) have proven to be effective binders compared to traditional wood binders such as PF or urea formaldehyde (UF) at a designated spreading level. In particularly notable studies, Song and Hwang (2001) and Zhao *et al.* (2010) used isocyanate resin successfully to manufacture wood fiber/recycled tire rubber composites.

Table 1 presents the mechanical properties of composite LVLR with three types of rubber sheets and at four levels of PAPI content. All three tested mechanical properties exhibited maximum values when PAPI content reached 80 g.m^{-2}, regardless of rubber type. At this resin content level, LVLR with a CR sheet performed best, at 0.93 MPa shear strength, 50.6 MPa MOR, and 2395 MPa MOE.

Table 1. Mechanical Properties of Three-Layer LVLR with Various PAPI Contents and Rubber Types

Mechanical Properties	Rubber Type	PAPI Content (g.m^{-2})			
		40	60	80	100
Shear Strength (MPa)	CR	0.63(0.08)*	0.84(0.15)	0.93(0.12)	0.89(0.09)
	NBR	0.67(0.03)	0.83(0.14)	0.91(0.10)	0.87(0.08)
	NR	0.62(0.05)	0.81(0.11)	0.87(0.08)	0.85(0.13)
MOR (MPa)	CR	40.60(2.1)	46.50(2.4)	50.60(2.5)	50.30(4.6)
	NBR	38.80(3.3)	48.70(2.1)	47.60(5.1)	45.50(3.4)
	NR	41.50(3.7)	47.60(4.0)	49.7(3.9)	48.30(5.2)
MOE (MPa)	CR	1645(155)	2100(158)	2395(231)	2265(212)
	NBR	1760(147)	2237(167)	2218(218)	2180(211)
	NR	1750(176)	2251(121)	2375(187)	1944(166)

*Data in parentheses are standard deviation values for six repetitions.

To further characterize the impact of rubber type and resin content on LVLR properties, a two-way analysis of variance was conducted for the data listed in Table 1. The PAPI content had a significant influence on shear strength, bending strength, and modulus, at a significance level (α) of 0.01 (P-values: 0.0001, 0.0014, and 0.0048, respectively), while rubber type only showed comparative significance with respect to the shear strength and no evident influence on MOR or MOE ($\alpha = 0.05$; P-values: 0.035, 0.2606, and 0.9667, respectively). For these reasons, a PAPI resin content of 80 g.m^{-2} and chloroprene rubber were selected for subsequent experiments.

Interfacial Bonding Reinforcement with Coupling Agent

Silanes are a family of hydrophobic compounds that have been extensively used for interfacial adhesion reinforcement of filled rubber composites. The fillers may be inorganic, such as silica (Kaewsakul *et al.* 2015), fly ash (Maan *et al.* 2015), attapulgite clay (Tang *et al.* 2015), mica (Ismail *et al.* 2014), or organic compounds such as plant fibers (Wang *et al.* 2011; Pang and Ismail 2014). The introduction of silane can enhance filler-filler interaction, reduce compound viscosity, and lead to better compatibility between fillers and rubber matrices compared with composites without silane, but the contribution may be closely dependent on their specific functionalities. Using a silane coupling agent, fillers can be better dispersed to form a more homogenous filler-matrix network, which can delay crack growth in rubber composites under tensile, bending, or impact loads (Yao *et al.* 2015). BTESPT, or KH69, is an important member of the silane family commonly used in the rubber industry as a coupling, vulcanizing, and/or reinforcing agent for rubber-carbon hybrid matrices.

Table 2 shows the variation in LVLR properties with changing KH69 coupling agent content. The mechanical properties of the board increased as silane content increased, reaching maximum values at 9 wt.% silane content. Further increasing the silane loading (to 12%) then caused the three tested properties to decline. Similar results were also observed in a study by Sae-oui *et al.* (2006). It is likely that excessive coupling agent content leads to a plasticization effect.

Table 2. Mechanical Properties of Three-Layer W-R-W LVLR as a Function of KH69 Content

Property	KH69 Content (%)				
	0	3	6	9	12
Shear strength (MPa)	0.93(0.05)*	1.22(0.06)	1.45(0.11)	1.63(0.12)	1.51(0.09)
MOR (MPa)	50.6(2.3)	56.8(2.8)	58.2(4.5)	62.5(5.1)	59.7(3.7)
MOE (MPa)	2395(46)	2510(37)	2620(44)	2985(52)	2755(28)

*Data in parentheses are standard deviation values for six repetitions.

Figure 5 depicts the micro-layered structure of rubber sheet-PAPI glue line-wood veneer samples, where it is clear that PAPI successfully adhered to the poplar veneer and rubber sheet and the presence of KH69 enhanced the interfacial compatibility. At a magnification of over 1000x, no evident fissures were observed between the cured PAPI resin layer and rubber sheet.

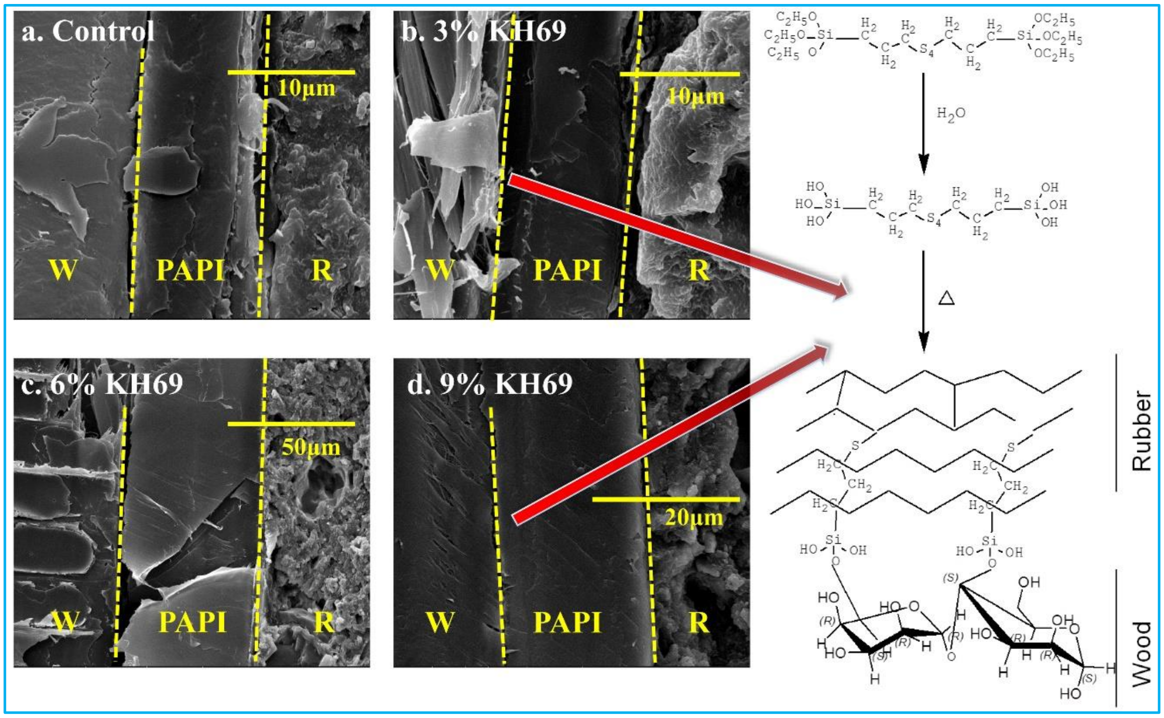


Fig. 5. W/R Interfacial glue lines at various content of KH69 coupling agents (W-poplar veneer; PAPI-glue line; R-rubber sheet) and the coupling mechanism between wood and rubber

Board Performance of Layer Construction

Rubber substances typically have high hydrophobicity, high ductility (elongation at break is normally higher than 200%), and relatively low strength (tensile strength is normally lower than 20 MPa.) These inherent characteristics of rubber are mutually complementary to wood, so it can be expected that compositions of rubber and poplar veneers may show balanced properties between the two types of elements.

Table 3 shows the tested values of the five LLVRs and LVL. The PAPI resin provided strong interfacial bonding between the rubber sheets and poplar veneers, which ensured the integrality of the LLVRs. In addition, rubber helped improve the LLVRs dimensional stability in the moist environment. The MOE is often used to simply judge the tenacity of a material – a relatively low MOE value may reflect toughening capacity. In this respect, the significantly lower MOE value of LLVRs compared with LVL indicates that the LLVRs had better tenacity. In other words, LLVRs are much more flexible than LVL for use.

One-way ANOVA analysis further revealed the significant influence ($\alpha = 0.01$) of five laminated constructions on the 24-h TS, MOR, and MOE of the LLVRs. The LLVRs containing three rubber sheets showed altogether higher dimensional stability, stronger bending performance, and better toughening capacity than those without rubber sheets.

Both wood and rubber can absorb energy exerted by static or impact load through deformation, but their deforming behaviors differ. Wood is viscoelastic, so plastic deformation may occur under designed conditions such as static load above its yield limit (σ_S, where wood may gradually yield), static load applied for too long even below σ_S, or under impact load. In such cases, the deformation of wood tends to be irrecoverable and wood gradually becomes denser, stronger, and stiffer. Hence, in designing functional composite wood panels, it is important to maintain maximum external loads lower than the yield limit of the selected wood species. Rubber, also called an "elastomer" in the literature, behaves differently – it absorbs and releases exerted energy by pure elastic deformation and complete recovery. An elastic system established combining both wood and elastomers should, then, accommodate the intensity of further applications.

Table 3. Performance of Nine-Layer Laminated Lumbers

Board Type	Shear Strength (MPa)		24-h TS (%)	MOR (MPa)	MOE (MPa)
	PF Glue Line	PAPI Glue Line			
Control (LVL)	1.3(0.09) *	—	7.8(0.65)	135(11.3)	13859(128)
R-7W-R	1.3(0.10)	1.6(0.14)	4.1(0.47)	42.6(4.4)	2965(30)
W/R/5W/R/W	1.4(0.09)	1.7(0.23)	3.8(0.33)	46.8(5.1)	3397(31)
2W/R/3W/R/2W	1.2(0.05)	1.5(0.07)	3.0(0.27)	45.3(2.3)	2988(28)
W/R/2W/R/2W/R/W	0.9(0.12)	1.5(0.16)	2.0(0.14)	47.1(4.3)	2730(19)
2W/R/W/R/W/R/2W	1.1(0.06)	1.4(0.11)	2.2(0.23)	47.5(3.1)	2714(22)

*Data in parentheses are standard deviation values for six repetitions.

Figure 6 depicts changes in *f* (slope of L-D curve at the elastic stage) for six types of lumber as a function of compression cycle times. LVL showed overwhelmingly higher *f* values than all the LLVRs and continuously increasing *f* values after the first compression cycle. The poplar veneers, naturally, were gradually densified from surface to core layers with accumulated plastic deformation under transverse compression. The rubber laminates in the LLVRs, however, were highly elastic, so the compression may have been easily consumed through "proactive" deformation. Additionally, the rubber sheets successfully transferred and dispersed the compression load, preventing poplar veneer densification to some extent. As a result, the *f* values of all LLVRs were lower than that of LVL, and they tended to be steady (or change only slightly,) even after five cycles. Further analysis of tested specimens after five cycles of compression showed that LVL specimens became significantly thinner than they were initially, while LLVRs showed no evident change in thickness. This further proved the active role of rubber laminates in maintaining toughening and recovery effects in the LLVRs.

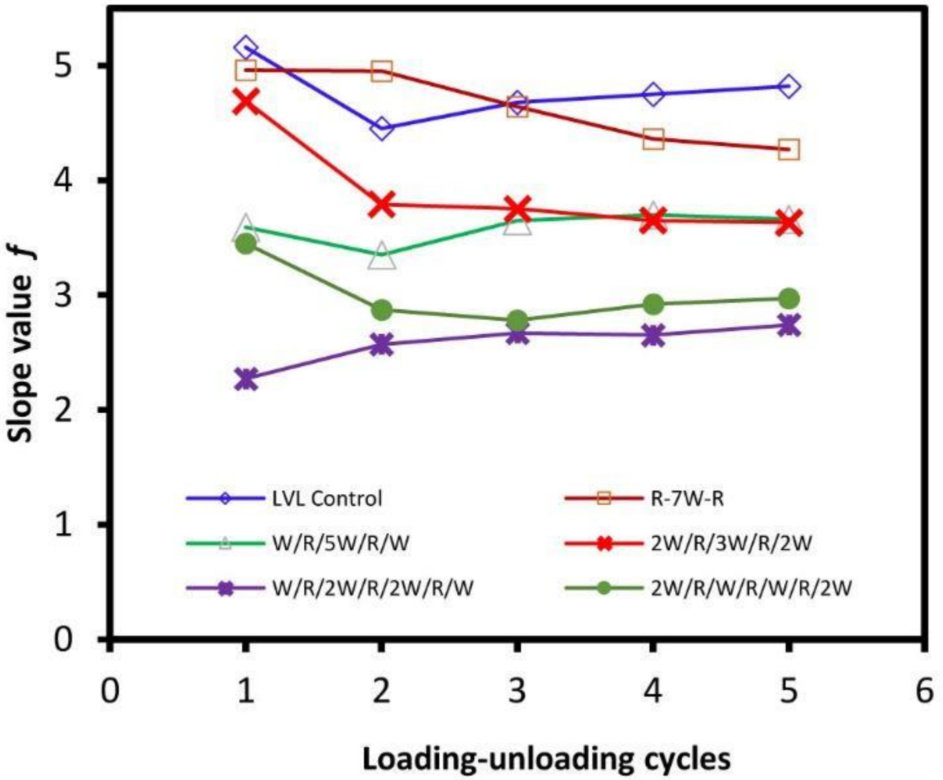


Fig. 6. Change in LLVR stiffness under compression

Damping Properties

Rubber sheets were glued to poplar veneers (which also show good damping performance,) as laminated lumber materials, (actually layered damping structures based on wood substrates). Only the W-R-5W-R-W construction was a free damping structure; the other four LLVRs were constrained damping structures with surface poplar veneers as the restricted layers. The damping mechanism of these materials is fairly simple. When an LLVR receives an outer stimulating signal, both rubber sheets and wood veneers vibrate. Their vibrations are anisotropic, however, which facilitates micro-interfacial friction and consumption of input energy. Figure 7 depicts this mechanism visually.

The LLVRs with three rubber laminates showed a shorter attenuation time compared to other samples under a similar transient signal from an impacting hammer. Figure 8 shows where the vibration-response behavior of LLVR was controllable by adjusting the lamination parameters of rubber sheets, such as layers and paving position. The tested natural frequencies of five LLVRs were all within in a low-frequency range, which is incongruous to most running vehicles; therefore, significant resonance is avoidable using LLVRs. LVL showed first-order natural frequency at 95 Hz, reflecting the known vibration response characteristics of poplar wood veneers glued together with synthetic resins. Natural frequencies of wood are dependent upon many factors including wood species, density, hardness, moisture content, vibration directions, and others. So far, little is known about the vibration frequencies of planted poplar wood. Referring to a study by Wang *et al.* (2012) on the natural frequency of catalpa wood (density 0.453 g/cm^3, moisture content 9%), it was found that the first-, second-, and third-order natural frequencies of catalpa are 40 to 42 Hz, 108 to 109 Hz, and 211 to 215 Hz, respectively.

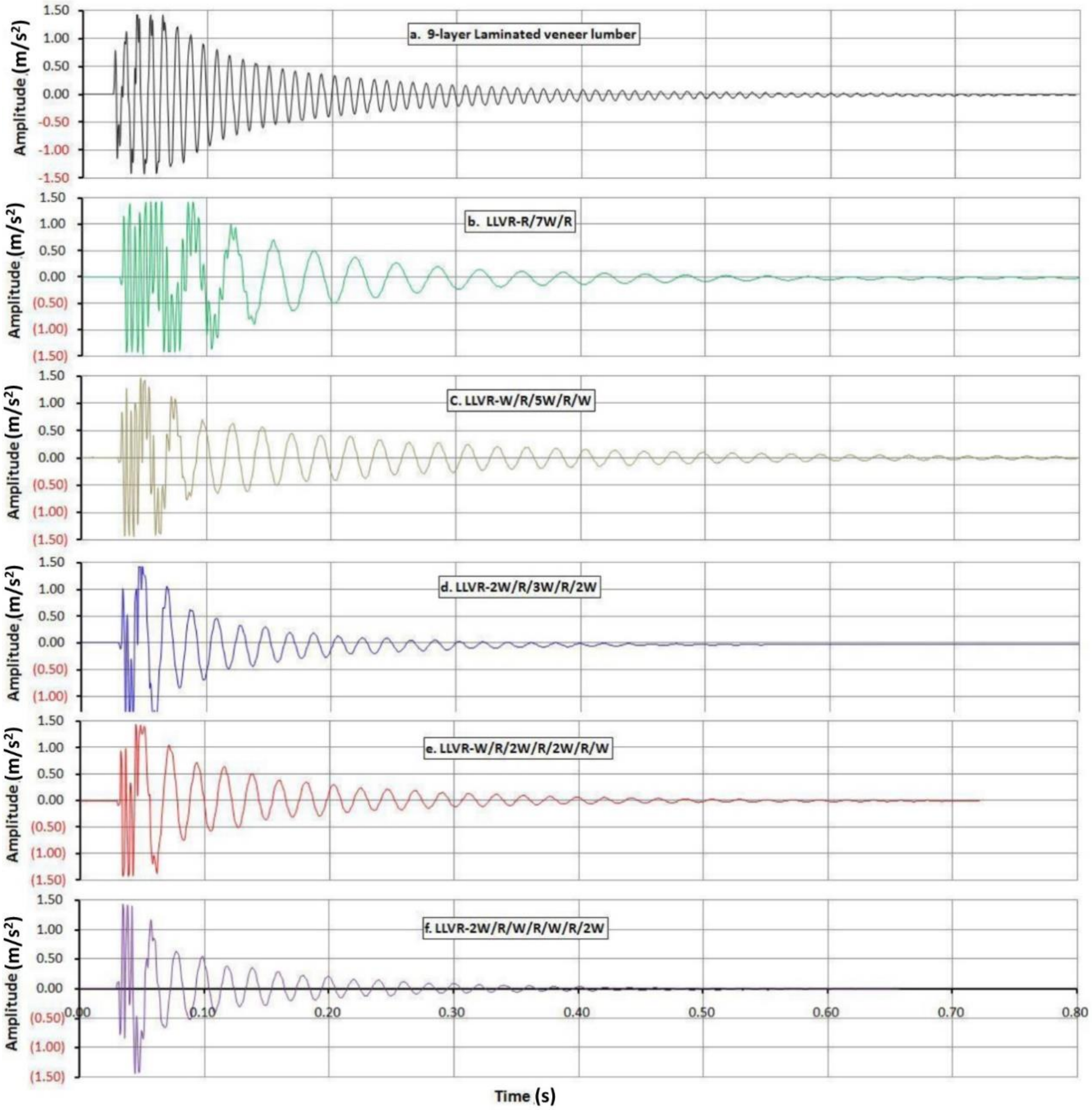


Fig. 7. Time-domain spectra of LVL and LLVRs

Interestingly, LLVRs showed two natural vibration frequencies, at 31 to 51 Hz and 234 to 317 Hz, because of the synergistic effect of wood veneers and rubber sheets. This phenomenon demonstrates that when receiving outer stimulating signals, wood and rubber laminates respond individually – in other words, the vibration of wood veneers and rubber sheets are asynchronized. This is the precondition for internal interfacial friction, leading to energy absorption. It was determined that the displacement of the natural frequency of wood veneers in lower-value domains (LVL: 95 Hz; LLVRs: 31 to 51 Hz), as poplar veneers in LVL showed more densification than the LLVRs.

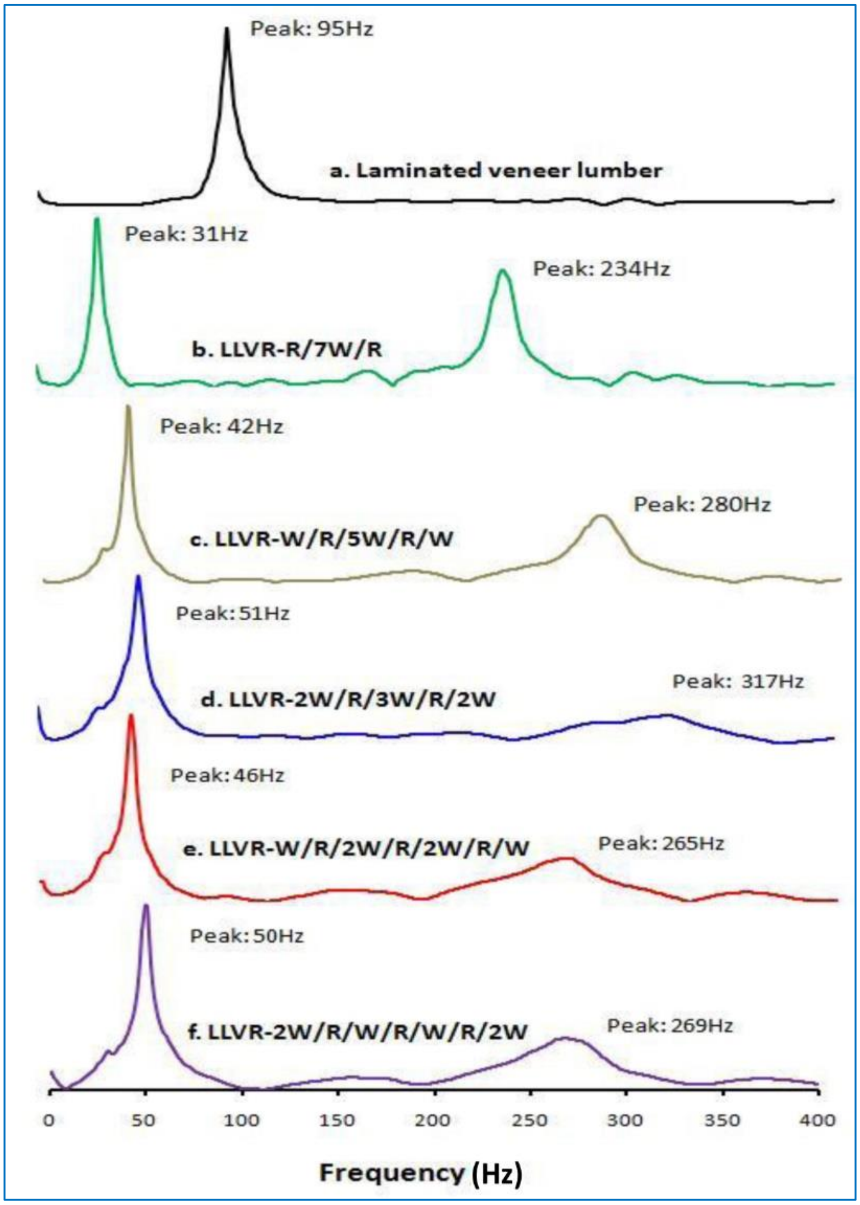


Fig. 8. Frequency response spectrograms of LVL and LLVRs

CONCLUSIONS

Laminated wood veneer lumber intercalated with rubber sheets (LLVR) was successfully fabricated using a layered adhesive system composed of polyaryl polymethylene isocyanate (PAPI) for wood-rubber inter-bonding and phenol formaldehyde (PF) resin to glue the wood veneers. The following conclusions were drawn:

1. By applying a layered gluing system of PAPI and PF resins, wood veneers, and rubber sheets can be successfully laminated to create lumber materials.

2. CR shows the strongest bonding with wood veneers compared to NBR or NR, and wood-rubber interfacial adhesion can be further strengthened by adding KH69 silane.
3. An optimized process was established in this study for LLVR fabrication (rubber type CR, PAPI content of 80 $g.m^{-2}$, and KH69 content of 9 wt.%). The nine-ply LLVRs (containing two or three CR layers) of five balanced constructions showed outstanding physio-mechanical properties with prominent toughening and buffering performance compared to LVR samples.
4. The material and processes proposed in this study are a favorable and potential alternative to traditional solid wood, plywood, or LVL for railway sleeper or sports ground floor fabrication.

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