VENEER SURFACE ROUGHNESS AND COMPRESSIBILITY PERTAINING TO PLYWOOD/LVL MANUFACTURING. PART II. OPTIMUM PANEL DENSIFICATION

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ABSTRACT

In Part I of this series, a novel method was proposed to assess surface roughness/quality and compressibility of wood veneer, and the wood compression theory was revised to include the first stage of "progressive contact." Based on this revised theory, the minimum compression required can be established for achieving adequate contact of veneer-to-veneer (or plate), and true veneer yield displacement can be determined. Owing to the variation of veneer compressibility and random veneer placement in the panel assembly, this study aimed to apply the revised theory to establish the optimum panel densification for performance plywood and laminated veneer lumber (LVL) manufacturing. Using 3.2-mm-thick rotary cut trembling aspen (*Populus tremuloides*) veneer as an example, the correlation between the contact area and panel compression ratio (CR) was first established in terms of veneer surface roughness. Then, the required aspen panel CR and density were identified for achieving a target 80% contact area of veneer-to-veneer (or plate). Meanwhile, through the compression tests of 30- × 30-mm aspen veneer specimens, within-sheet and between-sheet variations in density, thickness, and compressibility were revealed. Furthermore, based on the frequency distribution of the minimum compression required and yield displacement for aspen veneer, the optimum range of aspen panel densification was identified with a CR ranging from 11.3% to 18.0%. Finally, through the manufacturing of aspen panels, such densification range identified was validated for improved panel quality, material recovery, and dimensional stability while achieving superior panel bending and gluebond performance.

Keywords: Compressibility, compression ratio, contact area, density, dimensional stability, gluebond, laminated veneer lumber (LVL), material recovery, performance, plywood, surface roughness, trembling aspen, veneer.

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INTRODUCTION

In the manufacturing of plywood and laminated veneer lumber (LVL), hot-pressing is a critical stage where the glue-coated veneer constituents are heated and compressed between two platens to create close contacts and form bonds. During hot-pressing, drastic changes in heat, moisture content (MC), glue curing, and panel densification take place concurrently within a short pressing cycle. Effective bonds are achieved sequentially from panel surface to core under pressure and temperature with a certain level of panel densification. This densification, generally controlled by veneer transverse compression under changing temperature and MC, affects not only gluebond performance but also panel bending stiffness and strength. A fair amount of panel densification is required to eliminate veneer surface roughness and irregularities to create adequate veneer-to-veneer contact for bonding development and stiffness enhancement. Excessive densification, on the other hand, may cause negative effects such as heavier products, more thickness loss, higher dimensional changes after unloading or in service and lower gluebond performance resulting from wood cell-wall buckling or fracture. The optimization of the plywood/LVL hot-pressing operation will truly lead to improved manufacturing productivity, increased material recovery, and enhanced panel quality and performance.

The plywood/LVL hot-pressing has been an important subject to researchers around the world during the past decades. However, since veneer surface quality changes from species to species, mill-to-mill, log-to-log and sheet-to-sheet, most of the studies so far have been qualitative in nature, and the wide variations in veneer properties and hot-pressing parameters in these studies also made quantitative comparison very difficult. To date, some studies have been done to quantify the effect of veneer surface roughness on bond quality and glue consumption (Faust and Rice 1986; Faust and Rice 1987; Neese et al. 2004). However, due to the variation of veneer surface characteristics, how surface roughness affects veneer transverse compressibility and material recovery has not been studied. Currently, a trial and error method is still prevailing to determine the hot-pressing parameters for plywood/LVL manufacturing in terms of veneer species, MC, and panel lay-ups. As a result, panel quality, performance, and material recovery remain issues to the plywood/LVL industry.

In the preceding paper of this series (Wang et al. 2006b), a novel method was proposed to assess surface roughness/quality and compressibility of wood veneer. The transverse wood compression theory was revised to include the first stage of "progressive contact." Based on the revised theory, the minimum compression required can be established to achieve adequate contact for veneer-to-veneer or veneer-to-plate, and the true yield displacement can be determined. The relationship between contact area and load applied was further established in terms of veneer surface roughness. However, how contact area changes with panel density or compression ratio (CR) was not addressed. In the plywood/LVL manufacture, panel densification is governed by the compression behavior of individual veneer plies. Owing to the variation of veneer compressibility and random veneer placement in the panel assembly, the frequent distribution of the veneer minimum compression required and yield displacement need to be examined. Based on the distribution, the optimum range of panel densification could be established. In plywood manufacture, the target is to achieve required panel gluebond performance (shear strength and percent wood failure) while minimizing the panel thickness loss. To maximize the material recovery and reduce the manufacturing cost, the minimum panel densification required could be determined for plywood products. In contrast, in LVL manufacture, the target is to achieve desired bending and shear performance while avoiding panel over-densification and increasing manufacturing productivity (Wang and Dai 2005). An optimum range of panel densification for LVL products could be established.

The key objective of this paper was to apply the revised wood compression theory to establish optimum panel densification based on surface roughness/quality and compressibility of wood veneer. First, the correlation between contact area veneer-to-veneer (or veneer-to-plate) and CR was established in terms of different levels of veneer surface roughness. Then, the relationship between contact area and density of compressed veneer panels was explored. Subsequently, the required CR and panel density were identified for achieving a target 80% contact area. In addition, through a case study with rotary-cut trembling aspen (*Populus tremuloides*) veneer, within-sheet and between-sheet variations in veneer thickness, density, and compressibility were revealed. Based on the frequency distribution of the minimum compression required and yield displacement from compression tests of the representative aspen veneer, the optimum range of panel densification was identified for manufacturing performance plywood/LVL products. Finally, aspen veneer panels with different CRs were manufactured to validate the optimum densification in terms of panel gluebond performance, stiffness, and dimensional stability.

MATERIALS AND METHOD

To establish the relationship between contact area and veneer (panel) CR, the data from Part I of this series were adopted (Wang et al. 2006b). After conducting compression tests for veneer-to-veneer and veneer-to-plate, the thickness and weight of each parallel veneer-ply and veneer specimen were measured to calculate the CR and density after compression. The relationship between contact area and veneer (panel) density was then established.

Variation of veneer compressibility

To investigate the difference in compressibility between smooth veneer and rough veneer, two 3.2-mm-thick dried 1.2- × 1.2-m aspen veneer sheets, one smooth and the other rough, were visually selected from 150 dried aspen veneer sheets (1.2 × 1.2 m) obtained from a mill as described in Part I of this series (Wang et al. 2006b). First, an area of 300 × 300 mm was marked and a 30- × 30-mm matrix was then drawn on the marked area. Then, one hundred 30- × 30-mm veneer specimens were cut from each sheet and labelled sequentially. After that, the five-point veneer thickness, weight, length, and width of each specimen were measured to calculate veneer density. At the time of testing, the average MC of veneer specimens was about 5.0%. Under the ambient temperature (20°C), the transverse compression tests were conducted using an Instron machine for each specimen following the procedures established in Part I of this series (Wang et al. 2006b). The t-tests were conducted to determine whether there was a significant difference in dry veneer density, thickness, the minimum compression required, and yield displacement between the two sheets. Also, the correlation between the minimum compression required and veneer thickness and density was investigated.

Distribution of the minimum compression required and yield displacement

To establish the optimum range of panel densification, thirty-five aspen veneer sheets (1.2 × 1.2 m) were randomly selected from the total sheets obtained (Wang et al. 2006b). First, three hundred and fifty 30- × 30-mm aspen veneer specimens were cut and marked for compression tests with ten specimens from each sheet. These specimens were then compressed in an Instron machine with a load control mode. At the time of testing, the average veneer MC was 5.0%. The five-point veneer thickness, weight, length, and width of each specimen were measured to calculate veneer density. The testing procedures were the same as described in Part I of this series (Wang et al. 2006b). Based on the load-displacement curve, the minimum compression required at the threshold load of 120-kg and the yield displacement were derived respectively for each veneer specimen to establish their frequency distribution.

Veneer panel manufacturing

To validate the optimum range of densification in terms of panel performance, seventy

86- × 60-cm (34- × 24-in.) veneer sub-sheets were cut with two from each of the 35 sheets (1.2 × 1.2 m) selected for the above-mentioned compressibility tests. The average veneer MC was 5.0%. The nine-point veneer thickness, weight, length, and width of each sub-sheet were first measured to calculate veneer density. Then, ten lines were drawn along the grain direction at the loose side of each veneer sheet with a lateral interval of 5 cm. A portable Metriguard 239 stress wave timer was used to measure stress wave time along these ten lines for each sheet. The modulus of elasticity (MOE) was calculated for each veneer sheet based on average veneer stress wave time and veneer density. After that, 33 two-ply veneer assemblies (86 × 60 cm) were prepared in a loose-to-tight pattern along the same grain direction. For each panel, a commercial plywood phenol formaldehyde (PF) glue (45% solids content) was uniformly spread onto the loose side of one veneer sheet at an application rate of 170 g/m^2 (35 lb/1000 ft^2). A press (96 × 96 cm) was used with 155°C platen temperature and 180 s pressing time. The platen pressure was from 0.69 MPa (100 psi) to 2.41 MPa (350 psi) with an increment of 0.17 MPa (25 psi). For each platen pressure, 3 panels (replicates) were made. During hot-pressing, blows were carefully monitored. After pressing, all 33 panels were hot-stacked for 24 h. The nine-point thickness and weight of each panel were measured to calculate panel density. Subsequently, ten readings of the stress wave time were measured at two sides of each veneer panel to calculate the average stress wave time. Based on the average stress wave time and panel density, the panel MOE was calculated. Hence, the MOE ratio of the panel over veneer was determined. In addition, ten 81- × 25-mm specimens were cut from each panel for dry shear tests. After testing, percent wood failure and failure mode were determined for each shear specimen. Furthermore, ten 150- × 150-mm specimens were cut for water absorption (WA) and thickness swell (TS) tests after 24-h water soaking. The weight and 9-point thickness before and after soaking were measured to calculate WA and TS.

RESULTS AND DISCUSSION

Relationship between contact area and CR

Veneer-to-veneer contact.—Figure 1 shows the correlation between contact area of veneer-to-veneer and CR for 30- × 30 -mm aspen parallel veneer-ply samples with an R^2 of 0.58. Based on the limited data points from smooth, medium rough, and rough veneer, it seemed that the required CR for achieving a target 80% contact area was about 10.5%.

Veneer-to-plate contact.—Figure 2 shows the relationship between contact area of veneer-to-plate and CR for 63.5- × 63.5-mm aspen veneer specimens with the rough veneer having a higher R^2. Based on the compression results from the smooth and rough veneer specimens, it was

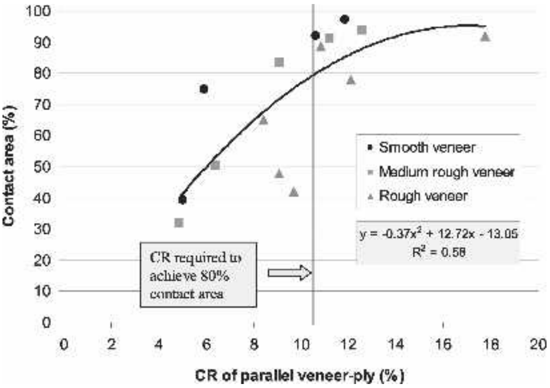

FIG. 1. The relationship between contact area of veneer-to-veneer and CR for parallel veneer-ply in terms of veneer roughness.

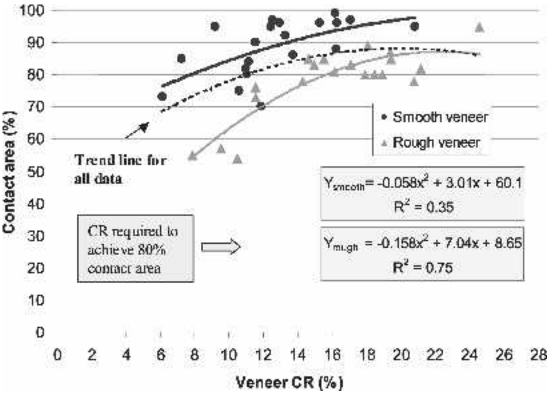

FIG. 2. The relationship between contact area of veneer-to-plate and veneer CR in terms of veneer roughness.

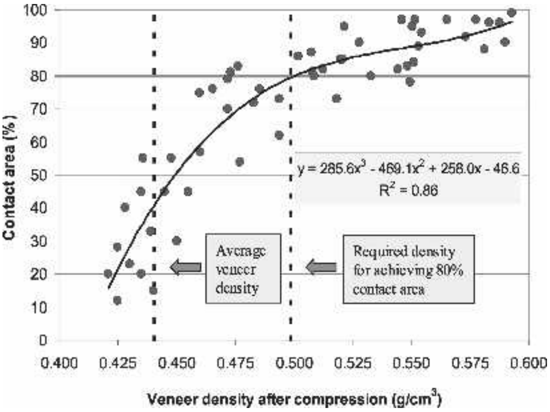

FIG. 3. The relationship between contact area and veneer (panel) density.

found that the rougher veneer generally required more compression to achieve the same contact area. Overall, as shown from the trend line for all data points, the required CR for achieving a target 80% contact area was about 11.0%.

By combining the data from the compression tests of veneer-to-veneer and veneer-to-plate for all roughness categories, the relationship between contact area and veneer (panel) density was established. As shown in Fig. 3, the relationship followed a polynomial pattern with an R^2 of 0.86. Note that the data points were widely spread due to the variation of veneer density. For this aspen veneer, the average veneer density before compression (ρ_0) was 0.440 g/cm^3 with a standard deviation of 0.036 g/cm^3. A target 80% contact area was achieved when density of veneer (panel) after compression (ρ_1) reached about 0.495 g/cm^3. At this density level, the average CR required was 11.2%, which was calculated with the formula as follows:

$$CR = \left(1 - \frac{\rho_0}{\rho_1}\right) * 100\% \tag{1}$$

Note that the ratio of panel density (ρ_1) over veneer density before compression (ρ_0) is sometimes defined as compaction ratio (CR′). Based on Eq. (1), there is a one-to-one relationship between CR′ and CR as follows:

$$CR' = \frac{1}{1 - CR} \tag{2}$$

When CR is 11.2%, the CR′ is about 1.13.

Comparison of veneer compressibility

The load-displacement curves for the two hundred 30- × 30-mm veneer specimens, half from smooth sheet and the remaining half from the rough sheet, were obtained. The data were then reconstructed in a 10 × 10 matrix and then plotted. The t-tests (Table 1) demonstrate that the smooth veneer was significantly denser than the rough veneer ($p < 0.05$), and the rough veneer was significantly thicker than the smooth veneer ($p < 0.05$). Note that for the area of 300 × 300 mm, there was a significant within-sheet variation in both density and thickness. On average, the smooth veneer had the larger variation in density but smaller variation in thickness compared to the rough veneer. The t-tests (Table 2) also show that both the minimum compression required and yield displacement of the smooth veneer were significantly smaller than

TABLE 1. *The t-test results comparing smooth and rough veneer in terms of dry density and thickness.*

	Dry density (g/cm^3)		Dry thickness (mm)	
Comparison	Smooth sheet	Rough sheet	Smooth sheet	Rough sheet
Mean	0.482	0.429	3.063	3.085
Variance	0.0007	0.0006	0.0025	0.0046
Observations	100	100	100	100
Hypothesized mean difference	0		0	
df	99		99	
t stat	18.08		−2.67	
$P(T \leq t)$ one-tail	0.0	$t > t_{critical}$	0.004	$\lvert t \rvert > t_{critical}$
t critical one-tail	1.66		1.66	
$P(T \leq t)$ two-tail	0.0		0.009	
t critical two-tail	1.98		1.98	

TABLE 2. *The t-test results comparing smooth and rough veneer in terms of compressibility (minimum compression required and yield displacement).*

	Minimum compression required (mm)		Yield displacement (mm)	
Comparison	Smooth sheet	Rough sheet	Smooth sheet	Rough sheet
Mean	0.234	0.320	0.578	0.611
Variance	0.0023	0.0062	0.0121	0.0127
Observations	100	100	100	100
Hypothesized mean difference	0		0	
df	99		99	
t stat	−9.06		−2.11	
$P(T \leq t)$ one-tail	0.0	$\lvert t\rvert > t_{critical}$	0.019	$\lvert t\rvert > t_{critical}$
t critical one-tail	1.66		1.66	
$P(T \leq t)$ two-tail	0.0		0.038	
t critical two-tail	1.98		1.98	

those of the rough veneer ($p < 0.05$). On average, the minimum compression required of the rough veneer was about 35% higher than that of the smooth veneer. This indicates that the rough veneer requires more compression to achieve adequate veneer-to-veneer contact. In addition, the yield displacement of the rough veneer was about 5% larger than that of the smooth veneer. This indicates that the rough veneer could sustain more compression prior to the cell-wall buckling or fracture. Furthermore, the within-sheet variation of the minimum compression required and yield displacement for the rough veneer was larger compared to those for the smooth veneer.

Figures 4 and 5 show the correlation between the minimum compressions required and veneer thickness and density for these two hundred 30- × 30 -mm veneer specimens, respectively. Neither average veneer thickness nor veneer density seemed to have any effect on the minimum compression required. Recall from Part I of this series (Wang et al. 2006b) that the correlation between the minimum compression required and roughness parameters R_a and R_q gave R^2 values of 0.87 and 0.85, respectively. It is concluded that along with some effect of veneer thickness variation and possibly lathe checks, the minimum compression required was a main indicator of the veneer surface roughness/quality.

Establishment of the optimum panel densification

Figure 6 shows the frequency distribution of the minimum compression required (d_{min}) for

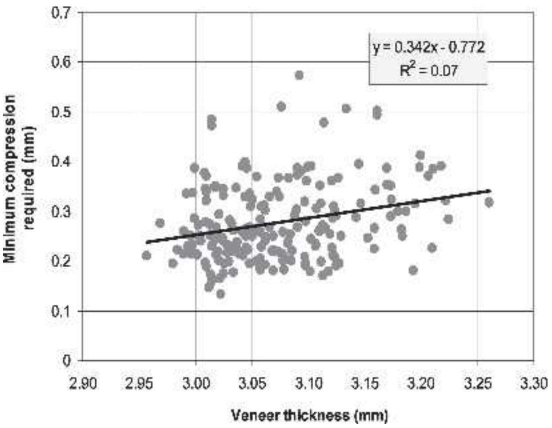

FIG. 4. The correlation between the minimum compression required and veneer thickness.

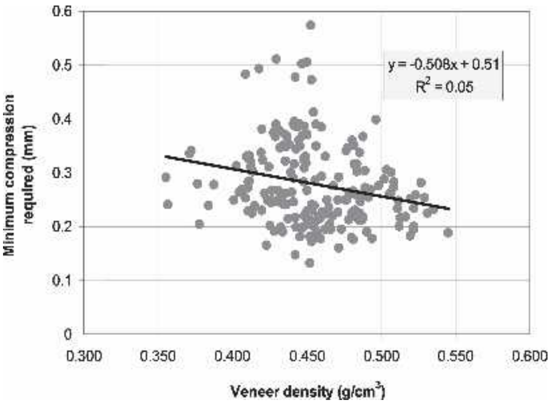

FIG. 5. The correlation between the minimum compression required and veneer density.

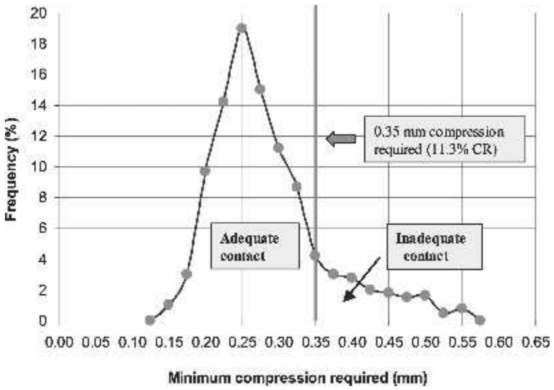

FIG. 6. Frequency distribution of the minimum compression required for 3.2-mm-thick mill peeled aspen veneer.

the three hundred and fifty 30- × 30- × 3.2-mm representative aspen veneer specimens. It demonstrates that for the population of this mill-peeled aspen veneer, in order to achieve a target 80% contact area, the minimum compression required is about 0.35 mm. At this compression level, about 82% of the population of veneer specimens have gone through the first stage of progressive contact, creating about 80% contact area. The remaining 18% of the population of veneer specimens still have not achieved 80% contact area, which could still be acceptable based on the standard requirements of plywood products. Note that for this nominal 3.2-mm-thick aspen veneer, the average dry veneer thickness was 3.07 mm. As a result, to make quality plywood/LVL products, the actual CR required was about 11.3%, which was very close to those identified from the compression tests for veneer-to-veneer and veneer-to-plate. Note that the CR is veneer thickness dependent. If the actual veneer thickness is 3.3-mm, the actual CR required ($\mathrm{CR}_{\min}$) will be reduced to about 10.6%.

Figure 7 shows the frequency distribution of the yield displacement ($d_{\max}$) for this aspen veneer. It can be seen that at the compression level of 0.55 mm, about 15% of veneer population would experience cell-wall buckling or fracture. In general, the wood-cell wall buckling or fracture will result in more panel thickness loss and less dimensionally stable products in service. It could also lead to lower shear strength, and sometime reduced tensile and bending strength. For performance LVL products, an upper level of compression ratio ($\mathrm{CR}_{\max}$) can be determined as follows:

$$\mathrm{CR}_{\max} = \frac{d'_{\max}}{t_{actual}} * 100\% \qquad (3)$$

where $d'_{\max}$ is the upper compression level for the LVL manufacturing, which can be determined from the frequency distribution of the yield displacement for this aspen veneer. And t_{actual} is the average veneer thickness measured. For this nominal 3.2-mm-thick mill peeled aspen veneer, $d'_{\max}$ was about 0.55 mm, t_{actual} was 3.07 mm, hence the resulting $\mathrm{CR}_{\max}$ was about 18.0%.

For plywood products, to reduce the thickness loss while achieving the target percent wood failure, the optimum panel CR for this aspen veneer is about 11.3%. Similarly, for LVL products, to increase panel quality, material recovery, and dimensional stability, the optimum range of panel CR appears to be from 11.3% to 18.0%.

Validation of the optimum panel densification

Thirty-three aspen two-ply panels, made with 11 different platen pressures from 0.69 MPa to 2.41 MPa, had a range of panel CRs from 2.0% to 25.7% when average veneer MC was about 5%. Note that of the total 33 panels made, seven panels with the CR greater than 18.0% had serious blows during press opening. This is probably because at a CR greater than 18.0%, both

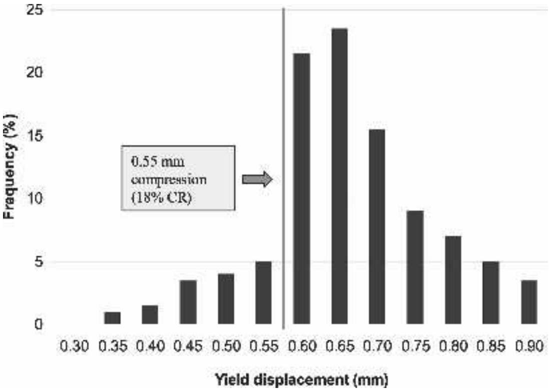

FIG. 7. Frequency distribution of the yield displacement for 3.2-mm-thick mill peeled aspen veneer.

veneer transverse permeability and lateral permeability are substantially reduced. The former is due to the closure of interconnected pits (Wang et al. 2006a); the latter is probably due to the buckling or fracture of the cell walls. According to the classic Carman-Kozeny theory (Dullien 1992; Nield and Bejan 1998), the lateral permeability is not only related to the effective porosity but also is proportional to the square of equivalent hydraulic diameter of the porous media. It is anticipated that the buckled or fractured cell walls will block the air or moisture movement from vessel to vessel (or fiber to fiber) along the grain direction due to a drastic reduction in both effective porosity and equivalent hydraulic diameter. Although blows occur only locally within the panel, they are always seen as the severe product failure in the panel production. Note also that the surface of panels with CR greater than 18.0% was not smooth, which may result from within-sheet variation of springback behavior after press unloading. As the panel CR reached or exceeded 18.0%, a portion of veneer would experience a plastic stage of transverse compression (Wang et al. 2006a). It is envisioned that the amount of veneer springback after compression differed between the linear stage and the plastic stage. As shown in Fig. 8, on average, the MOE ratio of the panel over veneer increased with the increase of panel CR within the range tested. However, as shown in Fig. 9, the 24-h panel thickness swell (TS) increased dramatically with the increase of the panel CR. The higher the panel CR, the larger the panel TS because the buckled or fractured cell walls can freely recover to their original shape from water penetration. In addition, the relationship between the panel shear strength and panel CR appeared to be a polynomial pattern. The panel shear strength first increased notably with the panel CR due to the increased interfacial bonding contact of veneer-to-veneer. At a panel CR level of about 13.7%, the maximum shear strength resulted with an average value of about 3.2 MPa. After that, the panel shear strength reduced significantly with the panel CR probably due to the weakening effect of wood from buckled or fractured cell walls.

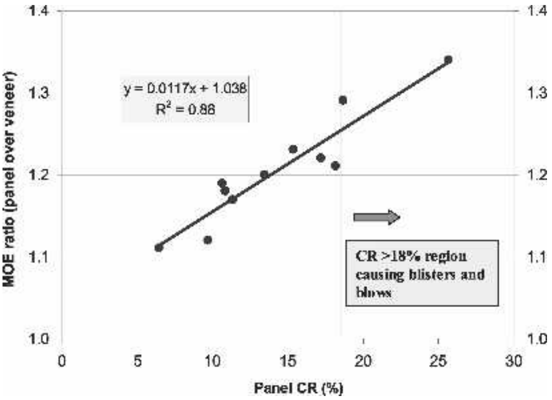

FIG. 8. The changes of MOE ratio of panel over veneer with panel CR.

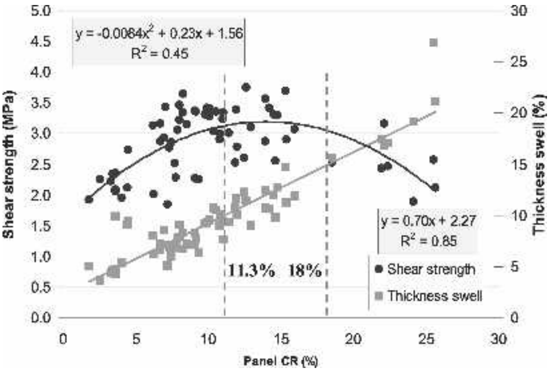

FIG. 9. The changes of shear strength and thickness swell with panel CR.

The panel CR ranging from 11.3% to 18.0% resulted in shear strength greater than 3.0 MPa. All these results demonstrate that the allowable panel CR for the normal panel manufacturing should be about 18.0% at which most of wood cell walls are not buckled or fractured. This maximum panel CR recommended agreed well with that identified through the compression tests of the three hundred and fifty 30- × 30-mm representative aspen veneer specimens. At a panel CR level of about 11.3%, the MOE ratio of the panel over veneer was about 1.18, and the panel 24-h TS was about 10% whereas the average shear strength was greater than 3.0 MPa with about 92% percent wood failure. As a result, for this mill-peeled aspen veneer, the optimum range of panel densification should be from 11.3% to 18.0% for achieving superior panel performance in bending, gluebond (shear) and dimensional stability.

Practical implications

Based on the distribution of the minimum compression required and yield displacement of wood veneer, an optimum range of panel CR can be established to balance panel quality, performance, and material recovery. The case study demonstrated that veneer surface roughness/quality has a great impact on the panel densification required for achieving adequate bonding contact. Based on the veneer compression tests, the required CR for aspen plywood to achieve adequate interfacial contact generally ranges from 6% to 16% (Fig. 2). Such wide range provides an opportunity for the industry to reduce plywood thickness loss while achieving target gluebond performance. Currently, owing to the larger variation in dry veneer surface roughness and thickness, plywood mills are generally using a larger-than-normal platen pressure for panel manufacturing. To deal with increased rougher veneer, the glue spread level has to increase with additional glue cost. It is hoped that through improved process control in plywood/LVL manufacturing, thinner and smoother veneer could be peeled, and veneer surface roughness and thickness variation could be better controlled. As a result, the required panel CR can be significantly reduced for normal panel manufacturing. It is conservatively estimated that with a 1% increase in veneer recovery from improved control of panel CR, a mill can realize about $300,000 savings annually.

SUMMARY AND CONCLUSIONS

With the revised wood compression theory, the optimum panel densification can be established in terms of veneer surface roughness/quality and compressibility for performance plywood and LVL manufacturing. As a case study with 3.2-mm-thick mill-peeled aspen veneer, the correlation between the contact area and panel CR was first established. Then, the required panel CR and density were identified for achieving a target 80% contact area. Through the compression tests of 30- × 30-mm aspen veneer specimens, within-sheet and between-sheet variations in density, thickness, and compressibility were revealed. Furthermore, based on the frequency distribution of the minimum compression required and yield displacement of representative aspen veneer specimens, the optimum range of aspen panel densification was identified with a CR ranging from 11.3% to 18.0%. Finally, through manufacturing two-ply aspen veneer panels with different platen pressures, such densification range identified was validated for improved panel quality, increased material recovery, and dimensional stability while achieving superior panel bending and gluebond (shear) performance.

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