ELASTIC PROPERTIES OF HOT-PRESSED ASPEN STRANDS

Vikram Yadama†
Assistant Research Professor

and

Michael P. Wolcott†
Professor
Wood Materials & Engineering Laboratory
Washington State University
P.O. Box 641806
Pullman, WA 99164–1806

(Received February 2005)

ABSTRACT

The *in-situ* elastic constants of a wood strand are affected by the physical changes that it experiences during the manufacturing process of a wood-strand composite. The hot-pressing conditions and the location in the mat govern the environmental conditions surrounding each strand, which in turn influence the adhesive cure and final strand density. Few studies have examined systematically the changes in strand elastic constants as influenced by strand density, location, and/or resin content. Understanding these interactions is important to determine the role of pressing variables on altering strand properties and to accurately model structure-property relationships in wood-strand composites. The following presentation will discuss the results of a study conducted to investigate the influence of strand location and resin content on changes in strand density and elastic properties within a pressed panel. *In-situ* properties of the strands were evaluated after isolating the strands from resinated hot-pressed oriented strandboards. Response models based on mixture design, considering the hot-pressing effects, were developed to predict the *in-situ* elastic constants of strands. Addition of resin positively influenced the strand stiffness and decreased strand's Poisson's ratio. Strand stiffness greatly increased with increasing resin content in regions of higher densification.

Keywords: Wood-strand composite, strand elastic properties, hot-pressing, oriented strand panels.

INTRODUCTION

The *in-situ* elastic constants of a strand in an oriented strand composite are affected by the physical changes that it experiences during the manufacturing process. These physical changes occur during cutting of strands and during hot-pressing. During hot-pressing, the strands undergo considerable densification. The environmental conditions in the vicinity of a strand, determined by the pressing conditions and strand's location in the mat, influence the adhesive cure and final strand density. When assembled into the composite, the strand properties and the bond quality connecting the strands dictate the physical and mechanical properties of the resulting composite (Kamke and Casey 1988). Several studies (Price 1976; Mahoney 1980; Jahan-Latibari 1982a, 1982b; Geimer et al. 1985; Casey 1987) have examined the influence of processing variables on strand properties.

Despite several studies addressing strand properties, few have systematically examined the changes in elastic constants due to strand density, location, and/or resin content. The following paper reports the results of a study investigating the effects of hot-pressing on *in-situ* elastic properties of aspen strands in an oriented strand composite. These data are paramount to systematically study the role of pressing vari-

† Member of SWST.

ables on altering strand properties and to accurately model structure-property relationships in wood strand composites.

OBJECTIVES

The goal of this study is to characterize the elastic properties of strands used in manufacturing oriented strand composites and to determine the effects of hot-pressing on these properties. Specifically, the objectives leading towards this goal are to:

1. Determine the in-plane elastic constants of strands prior to the hot-pressing process,
2. Investigate the influence of strand location and resin content on changes in strand density and elastic properties within a pressed panel,
3. Develop a response model to predict the *in-situ* elastic constants of strands.

MATERIALS AND METHODOLOGY

Strands for this study were produced from 65–70 year-old quaking aspen (*Populus tremuloides* Mich.) trees harvested locally. A total of 114 strands were conditioned to mean moisture content of 7.4% with a coefficient of variation (COV) of 7%. After testing the strands, which will be discussed later, all strands were oven-dried to determine their moisture content (MC) and density (ρ) according to ASTM D2395, Method A (ASTM 2001). Three sets of 27 strands were randomly selected from the entire set of strands to investigate the effects of hot-pressing on their elastic properties and density. These strands were then conditioned to equilibrate to 3% MC, which was the moisture content of furnish used for the hot-pressing effects study. A technique to isolate strands from a pressed mat using thin perforated Teflon® sheets as discussed by Jahan-Latibari et al. (1984) was employed in this study.

Three oriented strand test panels, each with three different target resin contents (0%, 4%, and 6% based on dry weight of furnish), were hot-pressed under similar manufacturing conditions as the test panels made for an experimental study conducted by Meyers (2001). A predetermined mass of liquid phenol-formaldehyde (PF) resin (GP® 130C44, 45% solids) was sprayed on each face of test strands using an air-brush operated with 1290 mmHg of air pressure. Strands were weighed immediately prior to and after spraying to determine the actual percentage of resin applied. Twenty-seven test strands were embedded in each test panel through their thickness at three different locations as shown in Fig. 1 (see Yadama 2002 for details). All panels were pressed to a thickness of 19 mm and a target density of 593 kg/m^3.

Mechanical testing

Prior to embedding in the mats to fabricate test panels, all strands were tested in tension parallel to the longitudinal axis. Longitudinal and transverse strains were measured at the midsection of each strand with a 12.7-mm-gage length clip-on extensometer (measuring range of ±10% and linearity of 0.10% of full measuring range). Load was applied such that the maximum stress applied was well within the lower part of the elastic region of the stress-strain curve. The longitudinal elastic modulus, E_x, and Poisson's ratio, v_{xy}, were determined for each of the strands before and after hot-pressing (Yadama 2002). Immediately after isolating from test panels, strands were weighed and their cross-section dimensions were re-measured. After testing the strands in tension, they were oven-dried to calculate their moisture content and density.

The strands were then scribed with a needle to

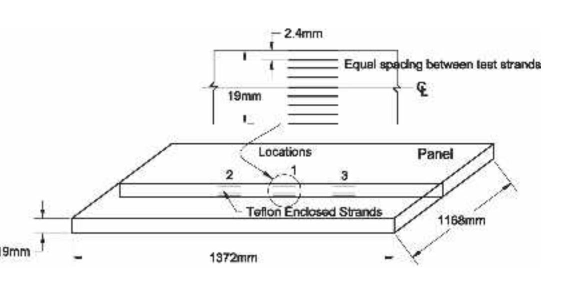

FIG. 1. Distribution of test strands within a test panel to study the effects of hot-pressing on strand properties.

determine the in-plane fiber angle, ϕ, within the gage length. Based on testing prior to hot-pressing, the Young's modulus and Poisson's ratio of aspen strands that had grain angles closest to zero (between 0 and 1 degrees) were averaged to obtain an estimate for E_1 and v_{12}. The remaining strands were grouped based on their fiber angles, and their average E_x and v_{xy} values were computed. Considering a plane-stress state, the engineering constants of an unidirectional lamina when geometric and material axes are not aligned with each other can be expressed as functions of the off-axis angle, ϕ, based on tensor transformation rules as follows (Jones 1999):

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\phi + \left(\frac{1}{G_{12}} - \frac{2v_{12}}{E_1}\right)\sin^2\phi\cos^2\phi + \frac{\sin^4\phi}{E_2} \tag{1}$$

$$v_{xy} = \frac{v_{12}(\sin^4\phi + \cos^4\phi) - \left(1 + \frac{E_1}{E_2} - \frac{E_1}{G_{12}}\right)\sin^2\phi\cos^2\phi}{\cos^4\phi + \left(\frac{E_1}{G_{12}} - 2v_{12}\right)\sin^2\phi\cos^2\phi + \frac{E_1}{E_2}\sin^4\phi} \tag{2}$$

Using the computed mean values of E_1, v_{12}, E_x, v_{xy} and ϕ, transformation equations were simultaneously solved to determine the transverse modulus, E_2, and shear modulus, G_{12}, for each fiber angle category. Then E_2 and G_{12} of all fiber angle groups were averaged to represent the corresponding E_2 and G_{12} of the strands prior to being hot-pressed.

Besides the grain angle, the elastic properties of these strands are also affected by the degree of densification as well as the temperature and moisture conditions they are exposed to depending on their relative location within a panel. Therefore the transformation equations should be applied with caution to determine the changed E_1 and v_{12} of these strands. Establishing relationships describing effects of densification during hot-pressing on these elastic constants would involve extensive testing, which was not feasible in this study. Moreover, because of lack of any other published information on this effect during hot-pressing, it was assumed in this study that the relationships between E_1 and E_2 and E_1 and G_{12} of the strands prior to being subjected to hot-pressing would still be valid after the strands were subjected to the hot-pressing process. With this assumption, E_2 and G_{12} can be replaced with c_1E_1 and c_2E_1 in Eqs. (1) and (2), where c_1 and c_2 are constants of proportionality relating E_1 to E_2 and E_1 to G_{12} ($c_1 = 1/21$ and $c_2 = 1/24$ as shown later). Then, knowing E_x, v_{xy}, and ϕ of the strands after hot-pressing, their E_1 and v_{12} can be calculated using Eqs. (3) and (4).

$$v_{12} = \frac{v_{xy}\left(\cos^4\phi + \frac{1}{c_2}\sin^2\phi\cos^2\phi + \frac{1}{c_1}\sin^4\phi\right) + \sin^2\phi\cos^2\phi\left(1 + \frac{1}{c_1} - \frac{1}{c_2}\right)}{(\sin^4\phi + \cos^4\phi + 2v_{xy}\sin^2\phi\cos^2\phi} \tag{3}$$

$$E_1 = E_x\left[\cos^4\phi + \frac{1}{c_2}\sin^4\phi\cos^4\phi - 2v_{12}\sin^2\phi\cos^2\phi + \frac{1}{c_1}\sin^4\phi\right] \tag{4}$$

Response surface–simplex model

With the information generated regarding strand elastic properties after hot-pressing, the data were analyzed using the simplex method (Cornell 1981; Breyfogle III 1992) to develop a response model to predict E_1 and v_{12} of strands in a hot-pressed panel based on their constituent ratios. To empirically model the properties of a strand with varying levels of density and resin, the system can be considered as mixture of three ingredients: cell-wall material (C), void space (V), and resin content (R).

Specific gravity, G, of the material that constitutes the cell walls is a constant, about 1.5 on the basis of oven-dry weight and volume (Bodig and Jayne 1982). Therefore, for all strands in this study, wood and void volume fractions were determined using the measured density and assuming a specific gravity of 1.5 for the cell-wall material. Past research (Johnson and Kamke 1992) indicates that PF resin typically used in manufacturing of composite panels penetrates primarily into the cell lumens and vessel elements. Thus, assuming that the resin primarily occupies void space in the strands, the percent void volume was adjusted by subtracting the corresponding percent resin added. The ternary plot for the three components (C, V, and R), relevant to this study is shown in Fig. 2. The partial region, depicted in the plot, is determined by the volume fraction limits of the components of the mixture. A general form of regression function that can be fit to the data collected at the points of a {q,m} simplex lattice (q components and m spaces between 0 and 1) is the canonical form of the polynomial, which is derived by applying a restriction that the terms in a standard polynomial of a mixture design sum to one (Cornell 1981). In matrix notation, the equation can be written as

$$\{y\} = [X]\{\beta\} + \{\varepsilon\} \tag{5}$$

Estimates of the β_i parameters are determined using the method of least squares which minimizes the square of the error. Knowing strand density and the amount of resin used, the proportions of the components of each of the test strands were determined. Knowing proportions of the three constituents, the ADX module in the statistical package SAS (SAS Institute Inc. 1999) was utilized to analyze the data and fit a response model, as per the mixture design, to predict E_1 and v_{12} of strands after subjecting them to the hot-pressing process. This response model is only valid for the manufacturing parameters and ranges of strand constituents examined in this study (Fig. 2).

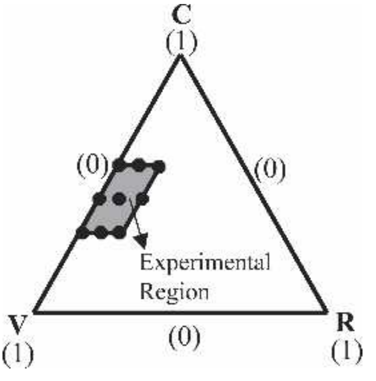

FIG. 2. {3, 2} simplex factor space. Shaded area is the experimental region for this study, and the points are the design points where response was measured (C = cell wall, V = void volume, and R = resin content).

RESULTS AND DISCUSSION

Strand properties prior to hot-pressing

Transformation equations along with strand fiber angle, E_x, and v_{xy}, were utilized to determine strand properties prior to hot-pressing. Since the variation in density of strands is significant, measured strand elastic properties were normalized to the average specific gravity of 0.39 using a linear relation suggested by others (Palka 1973; Kellogg and Ifju 1962). Then, strands were grouped by their fiber angles and transformation equations (Eqs. 1 and 2) were applied based on average E_x and v_{xy} to determine E_2 and G_{12} for each of the groups. E_2 and G_{12} determined for each of the angle groups were averaged to obtain mean elastic constants for all strands (E_2 = 573 MPa and G_{12} = 494 MPa). There is, however, a lot of variation in the values of E_2 (coefficient of variation (COV) of 61%) and G_{12} (COV of 39%), which could be a result of the high degree of variation in v_{xy} of strands and relatively small fiber angles within strands. The longitudinal Young's modulus in the material direction, E_1, of aspen strands was 12,060 MPa with a COV of 13%. In this study, based on strand properties prior to hot-pressing, it was established that $c_1 = E_2/E_1 = 1/21$ and $c_2 = G_{12}/E_1 = 1/24$.

A plot of normalized Young's modulus, E_x, against the fiber angle for all tested strands, as well as mean normalized Young's modulus for strand groups based on fiber angles is shown in Fig. 3. The plot also shows the theoretical curve relating fiber angle to E_x based on the transformation relationship (Eq. 1) and experimentally determined E_1, E_2, G_{12} and v_{12} (0.5). The results indicate that tensor transformation is an effective way to describe the effect of fiber angle on the longitudinal elastic modulus of aspen strands. It is well established in the literature that E_x rapidly decreases with an initial increase in fiber angle. As the graph indicates, E_x at a 10-degree fiber angle is about 60% of its value at a zero degree fiber angle. Using Eq. (2), Poisson's ratio, v_{xy}, was plotted against changing fiber angle in Fig. 4. Variation in measured Poisson's ratio is very high, illustrating the degree of difficulty

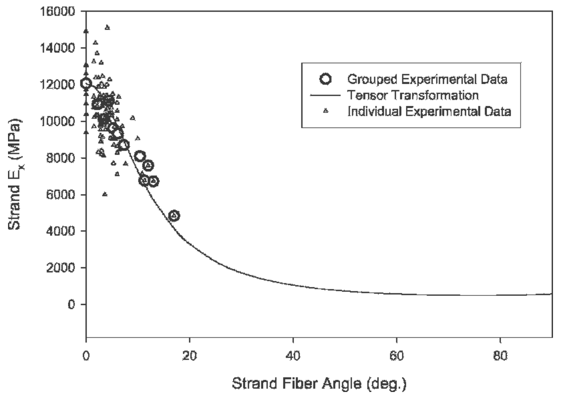

FIG. 3. Normalized Young's modulus versus strand fiber angle–experimental data and theoretical fit using transformation equation based on tensor transformation rules (experimental data grouped based on fiber angles of strands).

in determining Poisson's ratio experimentally. As the transformation equation indicates, the value of Poisson's ratio, v_{xy}, becomes relatively small (0.02) at very high fiber angles. This corresponds well to an average of v_{RL} and v_{TL} values of 0.044 and 0.027 published for hardwoods (Bodig and Jayne 1982).

Hot-pressing effects

To study the influence of hot-pressing on physical and mechanical properties, the property ratio was computed as the ratio of that property after and before hot-pressing. This ratio was computed separately for strand density ($\hat{\rho}$), Young's modulus ($\hat{E}_x$) and Poisson's ratio ($\hat{v}_{xy}$). Mean changes in densification ratio through the thickness of the three panels for three different resin levels are illustrated in Fig. 5. Determination of actual resin contents gave a mean resin content of 5% and 7.5% with COV of 3%.

A relative strand location through the panel thickness corresponds to the top and bottom (1,–1) surfaces and panel center (0). As expected, the densification ratio profile is similar to the through-thickness density profile (also referred to as vertical density profile in panel products) one would expect in an oriented strand composite panel (Fig. 5). In general, strands with resin experienced higher densification ($\hat{\rho}$ = 2.15) compared to those without resin ($\hat{\rho}$ = 1.9) near the panel surfaces. A logical explanation for this difference could be the differences in the amount of springback or recovery from compression in strands with and without resin. The resin penetrating the strand is curing and restraining springback. At the core, the density ratio for strands averaged 1.3 to 1.45 for strands with and without resin, respectively. An earlier study by Casey (1987) supports these findings.

To further understand the influence of strand location and densification through the panel thickness on Young's modulus of strands, the thickness of a panel was divided into three re-

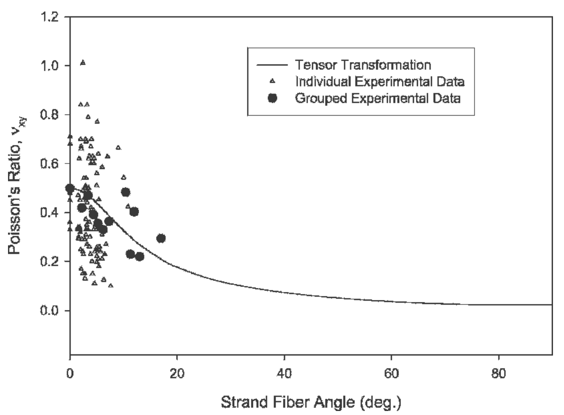

FIG. 4. Poisson's ratio of strands versus strand fiber angle–experimental data and theoretical fit based on tensor transformation rules (experimental data grouped based on fiber angles of strands).

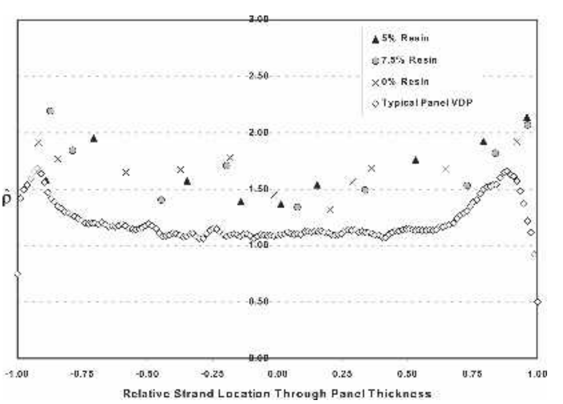

FIG. 5. Mean strand densification ratios through panel thickness for three resin levels. Also included is a typical panel vertical density profile (VDP) (Yadama 2002).

gions as illustrated in Fig. 6: outer region (Region A) closer to the surfaces, middle region (Region C) closer to the mid-plane, and intermediate region (Region B) between the outer and middle regions. The mean $\hat{E}_x$ for these regions was calculated within each resin level. In panels without resin, $\hat{E}_x$ does not vary significantly between Regions A and B; whereas, in panels with resin, $\hat{E}_x$ decreases substantially moving from Region A to B. This trend reinforces the role of resin in strand recovery and also suggests that the cured resin may act to repair strand damage or defect induced during pressing. On average, $\hat{E}_x$ in the region around mid-plane is significantly lower than in the other two regions in panels with or without the resin. The average moisture content of all strands isolated from pressed panels was 6.4% with a COV of 10%.

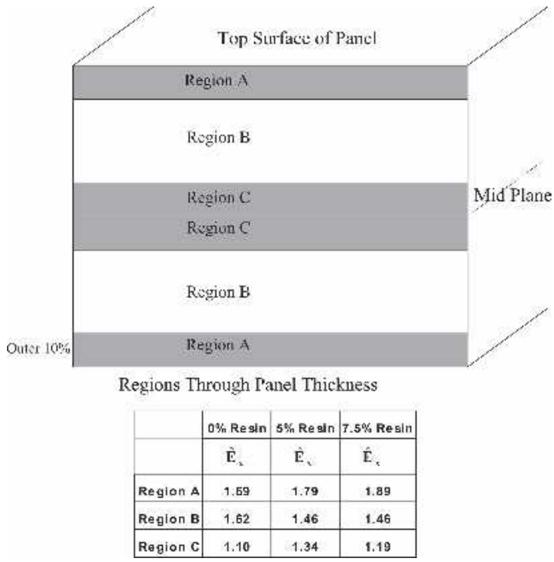

FIG. 6. Mean $\hat{\mathbf{E}}_\mathbf{x}$ for different regions through thickness of a test panel at three resin levels investigated in this study.

Simplex analysis

Based on the post-pressing strand density, volume fractions for each of the three constituents were determined.

$$\text{Resin volume fraction} = R = 0, 0.05, \text{ or } 0.075 \qquad (6)$$

$$\text{Void volume fraction} = V = (1 - G_{OD}/1.50) - R \qquad (7)$$

$$\text{Cell-wall volume fraction} = C = G_{OD}/1.50 \qquad (8)$$

G_{OD} is oven-dry specific gravity and 1.50 represents cell-wall specific gravity. These proportions of constituents must be non-negative and sum to unity. Considering the calculated proportions of the three mixture components in this study, the constraints for each of the components were:

$$0.35 \leq C \leq 0.50$$

$$0.42 \leq V \leq 0.65$$

$$0 \leq R \leq 0.08$$

The response surface for strand E_1 and v_{12} after hot-pressing in the experimental region (Fig. 2) can be expressed with the following best fit canonical polynomials as per mixture design discussed earlier.

$$E_1 = \beta_1 C + \beta_2 V + \beta_3 R + \beta_4 VR \qquad (9)$$

$$v_{12} = \beta_1 C + \beta_2 V + \beta_3 R \qquad (10)$$

The values of coefficients along with the corresponding correlation coefficients are given in Table 1. The response surfaces within the experimental region for both response variables are graphically illustrated in Figs. 7 and 8.

The correlation coefficient for Poisson's ratio is extremely low indicating that the reduction in v_{12} is basically a constant due to hot-pressing (Fig. 8). The predictive model did not include any cross product terms indicating that the interaction between the components was not significant. As Table 1 indicates, the r^2 value of the predictive equation describing v_{12} as the com-

TABLE 1. *Values of coefficients for canonical polynomials to predict the response of E_1 (MPa) and v_{12}. β_1, β_2, and β_3 relate to the contributions from cell-wall, void, and resin volume fractions, respectively; whereas, β_4 relates to the cross product contribution of void and resin volume fraction.*

Elastic constant	Estimates of coefficients				
	β_1	β_2	β_3	β_4	r^2
E_1	32488	4677	318001	−615926	0.54
v_{12}	0.007272	0.572264	0.132851	0	0.04

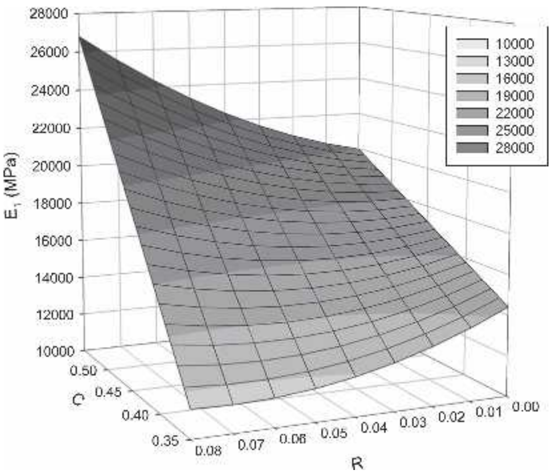

FIG. 7. Graphical representation of strand E_1 response equation accounting for the effects of hot-pressing based on mixture design.

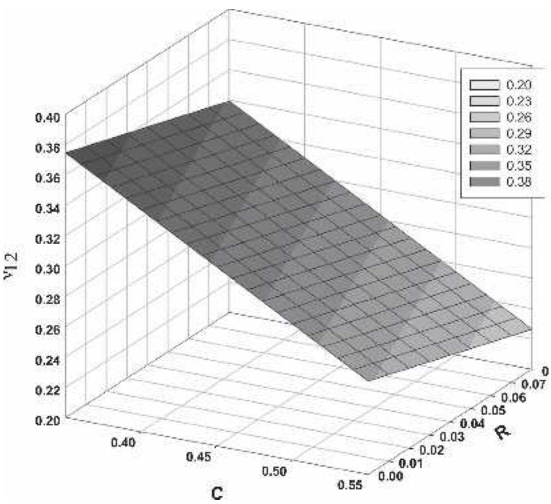

FIG. 8. Graphical representation of strand v_{12} response equation accounting for the effects of hot-pressing based on mixture design.

ponent ratios were varied was four percent. The results are indicative of the difficulty in measuring transverse strain on a distorted strand surface with a clip-on extensometer after isolating it from a hot-pressed panel. In future, a strain measuring device such as a laser extensometer is recommended. However, this method of analysis provides an insight into trends in changes in response variable as control variables are changed. For instance, the v_{12}-response surface is a flat surface with a slight decrease in slope as cell wall and resin percents increased, indicating an increase in transverse stiffness of strands with increased densification and higher resin content. These results suggest that changes in strand structure during hot-pressing are taking place with temperature changes and the presence of moisture introduced by the addition of resin. The v_{12} varied between 0.25 and 0.4 within the region.

Examination of the E_1 response surface (Fig. 7) indicates a decrease with decreasing densities and increasing resin content. However, at higher density levels, this trend is reversed. A possible explanation for this effect of resin content on E_1 could be stiffening of the strands as resin interacts with cell-wall material with increasing densification ratios due to more penetration of resin into cell wall. This interaction between resin and cell-wall material is probably initiated due to an increase in wood plasticization at higher densification ratios (Laborie 2002). More research is needed in this area to establish definite trends and interactions. An increase in densification has direct impact on strand elastic modulus. A similar trend was also found with increase in resin content; however, it was not statistically significant. The r^2 value of the predictive equation describing E_1 as the component ratios were varied was 54%. Casey (1987) also reported an increase in dynamic bending modulus with increase in flake densification. Although she reported that increases in mat moisture content increased the dynamic bending modulus of strands, she did not examine the effects of changes in resin amounts.

Gardner et al. (1993) examined changes in polymer structure of wood strands when heated under conditions similar to the hot-pressing of wood composites. Results indicated that the cellulose crystallinity in the wood increases slightly in response to heat treatment, thus supporting the findings of this study that hot-pressing of wood strands increases their elastic modulus. This effect is further magnified with an increasing presence of moisture. The addition of adhesive has a dual effect on strand properties. It influences the strand stiffness and affects the heat and moisture movement within the mat through adding more water to wood furnish. Moisture added to furnish through adhesive plays an important role in determining the dynamics of heat and moisture transfer within the mat during hot-pressing. Also, it affects the properties of strands since wood is a viscoelastic material. Andrews et al. (2001) showed in their study that the moisture content of the wood furnish influences the amount of densification in all zones through the thickness of a panel.

SUMMARY AND CONCLUSIONS

This study contributes to the scientific knowledge of understanding how hot-pressing of resinated strands influences their elastic properties. Resinated strands were isolated from lab-manufactured panels and tested to study the effects of manufacturing process during hot-pressing, such as densification. The results of this study support findings by other researchers that hot-pressing increases strand elastic properties due to densification and plasticization, and this effect is further enhanced as resin content is increased due to addition of moisture. The addition of adhesive has a dual effect on strand properties. It influences the strand stiffness and affects the heat and moisture movement within the mat through adding more water to wood furnish. Resin content tends to show a positive affect on strand's Young's modulus. A possible explanation for this effect of resin content on E_1 could be stiffening of the strands as resin interacts with cell-wall material with increasing densification ratios due to more penetration of resin into cell wall. This interaction between resin and cell-wall material is probably initiated due to an increase in wood plasticization at higher densification ratios.

ACKNOWLEDGMENTS

The authors would like to thank Louisiana Pacific Corporation's Advanced Technology Center in Portland, Oregon, for assisting with preparation of strands. The research was supported by USDA CSREES Inland-Northwest Forest Products Research Consortium Wood Utilization Special Grants Program.

REFERENCES

ANDREWS, C. K., P. M. WINISTORFER, AND R. M. BENNETT. 2001. The influence of furnish moisture content and press closure rate on the formation of the vertical density profile in oriented strandboard. Forest Prod. J. 51(5):32–39.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM). 2000. Standard Test Methods for Tensile Properties of Plastics. Standard D 638-99. American Society of Testing and Materials. Volume 8.01. Conshohocken, PA.

———, 2001. Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials. Standard D 2395-93. American Society of Testing and Materials. Volume 4.10.

BODIG J., AND J. R. GOODMAN. 1973. Prediction of elastic properties for wood. Wood Science 5(4):249–264.

______ AND B. A. JAYNE. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold Company, New York, NY.

BREYFOGLE III, F. W. 1992. Statistical Methods for Testing, Development, and Manufacturing. John Wiley & Sons, Inc., New York, NY.

CASEY, L. J. 1987. Changes in wood-flake properties in relation to heat, moisture, and pressure during flakeboard manufacture. Master's Thesis, Dept. of Forestry and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, VA. 162 pp.

CORNELL, J. A. 1981. Experiments with mixtures: Designs, Models, and the Analysis of Mixture Data. John Wiley & Sons, New York, NY.

GARDNER, D. J., D. W. GUNNELLS, M. P. WOLCOTT, AND L. AMOS. 1993. Changes in wood polymers during the pressing of wood-composites. In Cellulosics: Chemical, Biochemical and Material Aspects. Editors J. F. Kennedy, G. O. Phillips, and P. A. Williams. Ellis Horwood, New York, NY. pp. 513–518.

GEIMER, R. L., R. J. MAHONEY, S. P. LOEHNERTZ, AND R. W. MEYER. 1985. Influence of processing-induced damage on strength of flakes and flakeboards. USDA Forest Service Research Paper FPL 463. 15 pp.

JAHAN-LATIBARI, A. 1982a. The response of aspen flakes and flake-board to flake surface modifications. Proceedings of 6th Washington State University International Symposium on Particleboard. pp. 331–351.

______. 1982b. The response of aspen flakes and flakeboard to flake surface modifications. Ph.D. Dissertation, Washington State University. 135 pp.

______, W. E. JOHNS, AND R. V. SUBRAMANIAN. 1984. Technique for isolating flakes from the pressed mat. Forest Products Journal. 34(2):33–34.

JOHNSON, S. E. AND F. A. KAMKE. 1992. Quantitative analysis of gross adhesive penetration in wood using fluorescence microscopy. Journal of Adhesion. 40:47–61.

JONES, R. M. 1999. Mechanics of composite materials. 2nd Edition. Taylor & Francis, Philadelphia, PA.

KAMKE, F. A. AND L. J. CASEY. 1988a. Fundamentals of flakeboard manufacture: internal-mat conditions. Forest Products Journal. 38(6):38–44.

KELLOGG, R. M. AND G. IFJU. 1962. Influence of specific gravity and certain other factors on the tensile properties of wood. Forest Products Journal. 12(10):463–470.

LABORIE, M-P. G. 2002. Investigation of the wood/phenol-formaldehyde adhesive interphase morphology. Ph.D. Disseration. Virginia Polytechnic Institute and State University, Blacksburg, VA.

MAHONEY, R. J. 1980. Physical changes in wood particles induced by the particleboard hot-pressing operation. M.S. Thesis. Washington State University. 35 pp.

MARRA, A. A. 1992. Technology of Wood Bonding Principles in Practice. Van Nostrand Reinhold, New York, NY.

MEYERS, K. L. 2001. Impact of strand geometry and orientation on mechanical properties of strand composites. Master's Thesis. Dept. of Civil and Environmental Engineering, Washington State University. 115 pp.

PALKA, L. C. 1973. Predicting the effect of specific gravity, moisture content, temperature and strain rate on the elastic properties of softwoods. Wood Science and Technology. 7:127–141.

PRICE, E. W. 1976. Determining tensile properties of sweetgum veneer flakes. Forest Products Journal. 26(10):50–53.

SAS INSTITUTE INC. 1999. SAS for Windows Version 8. Cary, North Carolina.

YADAMA, V. 2002. Characterization and modeling of oriented strand composites. Ph.D. Dissertation. Washington State University.