Wettability and Impact Performance of Wood Veneer/Polyester Composites

Shayesteh Haghdan, Thomas Tannert, and Gregory D. Smith*

Fiber-reinforced thermosetting composites have been of interest since the 1940s due to their ease of use in processing, fast curing times, and high specific stiffness and strength. While the use of plant fibers in a polyester matrix has been thoroughly studied, only limited information is available regarding using wood as reinforcement. In this study, composites of thin wood veneer and a polyester matrix were made and the difficulties in the lamination and curing processes were investigated. Sheets of Douglas fir, maple, and oak veneers using a catalyzed polyester resin were assembled as unidirectional, balanced, and unbalanced cross-ply laminates. These were compared to control specimens using glass fiber as reinforcement. The impact properties of the samples, with respect to the laminate thicknesses, were characterized using a drop-weight impact tester. The wettability and surface roughness of unsanded and sanded wood veneers were also investigated. Results showed that Douglas fir cross-ply laminates had an impact energy equivalent to glass fiber laminates, making them an interesting alternative to synthetic fiber composites. Wood/polyester laminates absorbed a considerable amount of energy through a higher number of fracture modes. The balanced lay-up limited twisting of the wood/polyester composites. The lowest contact angle and highest wettability were observed in unsanded Douglas fir veneers.

Keywords: Composite; Contact angle; Roughness; Glass fiber; Wood veneer; Adhesion; Polyester; Impact

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INTRODUCTION

The use of natural fiber reinforcement in polymer composites has increased over the past few decades as an alternative to conventional structural materials including concrete and metals (Li *et al*. 2007). Natural fibers are available in abundance and are inexpensive compared with synthetic fibers (Ashori 2008). In addition, they often have lower density than synthetic fibers, which facilitates their use in automotive and construction applications where relatively low material weight is a major advantage (Felix and Gatenholm 1991; Chtourou *et al*. 1992; Li and Li 2001).

The quality of the adhesion between wood and thermoplastic or thermoset polymers significantly affects the performance of such composites. Insufficient adhesion between wood and the polymer matrix results in low tensile strength and high moisture absorption (Bledzki *et al*. 1998). The adhesion itself depends on the wood and resin chemical structures and the manufacturing method. If one ingredient is polar and the other is non-polar (as is the case in most wood/thermoplastic composites), it is necessary to use compatibilizers, also known as a coupling agents (Sabzi *et al*. 2009; Gao *et al*. 2012; Ndiaye and Tidjani 2012; Sobczak *et al*. 2012). The use of a compatibilizer improves bonding but increases the cost of the final product. Unlike wood/thermoplastic composites, there is no need to add a coupling agent to wood/thermoset composites, as both wood and polyester are polar and typically bond well during the curing process (Stevens 1999).

Extensive research on the basic physical and mechanical properties of wood and thermoplastic composites is available (Adhikary *et al*. 2008; Tajvidi and Haghdan 2008; Xiong *et al*. 2009; Tasdemir *et al*. 2009; Ashori and Nourbakhsh 2010; Nourbakhsh *et al*. 2010; Bhaskar *et al*. 2011). The objective of most of these studies was to improve the compatibility between the composite ingredients and enhance their mechanical performances, such as tensile strength and bending stiffness. The mechanical properties of unsaturated polyester composites reinforced by various plant fibers such as jute, flax, sisal, hemp, and banana have also been investigated (Gowda *et al*. 1999; Pothan *et al*. 2003; Rodriguez *et al*. 2005; Dhakal *et al*. 2007). These studies showed that a strong interphase between the reinforcement and matrix results in composites of high stiffness and strength but limits the number of energy absorption mechanisms. In addition to plant fibers, wood veneer strips have also been used as reinforcement in a polyester matrix to manufacture thin composite plates (Haghdan *et al*. 2015). Results showed that the effects of Douglas fir veneer configuration (woven, cross-ply, and unidirectional) on the impact strength of polyester composites were significant and improved the impact strength of the cross-ply wood-polyester samples. However, they found that veneer densification, did not significantly change the impact behavior of composites.

Using a combination of two reinforcements in a polyester matrix was also previously investigated. In one example of this approach, also termed “hybrid composites,” sisal and glass fibers were combined in a polypropylene matrix, improving the tensile, flexural, and impact strengths of the composites and decreasing their water absorption (Jarukumjorn and Suppakarn 2009). In similar research on hybrid composites, the dynamic mechanical properties of samples made from a mixture of banana and glass fibers in a polyester matrix were improved compared to those of composites made with banana fiber alone (Pothan *et al*. 2010).

An important aspect when considering wood as a composite component is its wettability, which can be characterized by various methods such as the dynamic Wilhelmy method and the single-fiber Wilhelmy method (Gardner *et al*. 1991; Walinder and Johanson 2001; Walinder and Strom 2001). Wilhelmy principle-based methods measure advancing and receding contact angles after immersion of the sample into the liquid and report the force exerted upon the sample (Casilla *et al*. 1981). The drawback of these techniques is the difficulty of preparation since the sample must have identical front and back surfaces to achieve similar solid-liquid interactions. As an alternative, contact angle measurement using a goniometer has recently been used to determine the wettability of wood and wood-based composites. In this technique, the contact angle of an individual droplet or several droplets can be collected quickly and easily using a high-speed camera. In addition, there are no specific requirements of the cross section shape of the solid surface. Several studies have investigated the wettability of medium-density fiberboard, laminated veneer lumber, and polymer composites using the contact angle goniometer (Thwe and Liao 2002; Ayrlmis and Winandy 2009; Ayrlmis *et al*. 2009; Favaro *et al*. 2010; Cappelletto *et al*. 2013).

Another parameter affecting interfacial adhesion is the veneer roughness, a measure of the fine irregularities on the veneer surface (Tabarsa *et al*. 2011). Several studies have reported that sanding wood veneers affects their surface wettability (Shupe *et al*. 2001; Aydin 2004; Kılıç *et al*. 2006). The surface roughness of wood and wood products also depends on structural features such as annual ring variation, wood density, cell structure, and latewood/earlywood ratio (Magoss 2008; Kılıç *et al*. 2009).

The objectives of the present work were to evaluate the potential of wood veneer as an alternative raw material for manufacturing polyester composites; to investigate the effect of wood veneer lay-up configurations on the impact resistance of the composites compared with thin composite plates and lab-made glass fiber laminates; and to investigate the roughness and wettability behavior of wood veneers to the polyester resin.

EXPERIMENTAL INVESTIGATION

Materials

Improvement of the impact strength in thin composite plates of Douglas fir veneer and polyester (Haghdan *et al*. 2015) was the motivation for this research. It was hypothesized that increasing the lay-up thickness would increase the number of fracture modes operating in these wood-based composites. If true, Douglas fir-reinforced polyester should have properties comparable to glass fiber-reinforced polyester. In addition to Douglas fir, two other species were also used to investigate the effects of wood species on its interaction with polyester.

Douglas fir (*Pseudotsuga menziesii*), sugar maple (*Acer saccharum*), and red oak (*Quercus borealis*) veneers of 0.6 mm nominal thickness were used to compare the effects of species anatomy on the manufacturing process and the resulting impact properties of the polyester composites. The Douglas fir species is native to western Canada, and maple and oak are available *via* imported hardwood veneers. The texture of the veneers depends on the difference between the size of the tracheids and vessels in earlywood and latewood. Table 1 summarizes these properties. Douglas fir exhibits an abrupt transition from earlywood to latewood and has a medium texture. Diffuse-porous sugar maple has a fine texture as the vessels across the growth ring are similar in size. Ring-porous red oak has a coarse texture with larger-diameter vessels in its early wood and smaller-diameter vessels in its latewood.

Table 1. Comparison of the Three Wood Species

Species	Specific Gravity*	Origin	Veneer Color	Pore/Tracheid Size and Distribution
Douglas fir	0.48	Pacific north west	Red	Medium diameter tracheid (35 to 45 μm); medium-textured
Maple	0.63	USA and Canada	Creamy white	Diffuse porous; small diameter pores (< 50 μm); fine-textured
Oak	0.69	North east USA	Reddish-brown	Ring porous; large diameter pores (100 to 200 μm); coarse-textured

* Property measured at 8% moisture content (ASTM-D2395 2007).

An unwaxed orthophthalic general purpose polyester resin was used as the glue in this study. This resin is characterized by average mechanical properties and lower cost than epoxy (Husseinsyah and Mostapha 2011). Unsaturated polyester solutions in styrene were used and the cross-linking of the resin and styrene during the composite manufacturing process created a three-dimensionally shaped resin (Goodman 1998). An organic peroxide, methyl ethyl ketone peroxide (MEKP), was used as a catalyst to accelerate the curing process at room temperature. The resin, the catalyst, and a releasing wax (to facilitate composite demolding) were obtained from Coast Fiber-Tek Products, Burnaby, BC, Canada. A synthetic reinforcement, woven E-Glass fiber cloth (nominally 200 g/m^2) purchased from Coast Fiber-Tek Products was used to make glass fiber composites for comparison.

Specimen Description

Three parameters were varied between treatments: 1) the type of wood species (Douglas fir, softwood and maple and oak, hardwood); 2) the veneer configuration (balanced cross-ply, unbalanced cross-ply, and unidirectional); and 3) the type of reinforcement (wood and glass fiber). A total of 13 different treatments were applied to the composites, as shown in Table 2. Individual sheets of Douglas fir, maple, and oak veneer were defined as the control specimens and labeled DF Control, Maple Control, and Oak Control, respectively. Unidirectional wood polyester composites and balanced and unbalanced cross-ply polyester laminates were labeled UP, BCP, and CP, respectively. The label GP was devoted to the lab-made glass fiber/polyester composites.

Table 2. List of Treatments and Mass Fractions of Components

Treatments	Label	Mass (%)		
		W	P	GF
Control-Douglas fir veneer	DF Control	100	-	-
Control-Oak veneer	Oak Control	100	-	-
Control-Maple veneer	Maple Control	100	-	-
Douglas fir Unidirectional Polyester	DF-UP	67	33	-
Douglas fir Cross-ply Polyester	DF-CP	66	34	-
Douglas fir Balanced Cross-ply Polyester	DF-BCP	63	37	-
Oak Unidirectional Polyester	Oak-UP	73	27	-
Oak Cross-ply Polyester	Oak-CP	73	27	-
Oak Balanced Cross-Ply Polyester	Oak-BCP	70	30	-
Maple Unidirectional Polyester	Maple-UP	78	22	-
Maple Cross-ply Polyester	Maple-CP	79	21	-
Maple Balanced Cross-ply Polyester	Maple-BCP	74	26	-
Glass fiber Polyester	GP	-	47	53

Note: W denotes wood, and P polyester

The wood-based composites were 200-mm-long, 190-mm-wide, and 2.5-mm-thick. Glass fiber/polyester composites had the same length and width but a thickness of 1.2 mm. For the impact tests, 10 replicates per treatment were produced and tested. Two different tests were applied to the veneers themselves to investigate their wettability behavior and surface roughness. To investigate the wettability of the veneers, they were sanded with two different grit sizes: 120 and 320. The treatments are listed in Table 3. For example, the label DF 120 denotes Douglas fir veneer sanded with grit size 120. Sanded and unsanded veneers were prepared in 100-by-100 mm squares and five replicates of each treatment were tested to determine the average contact angle. For the roughness test, 15 veneer samples 50-by-50 mm size were used to evaluate the surface roughness of each test group.

Table 3. Average Contact Angle (initial and after 5 s) and Surface Roughness Values of Different Wood Veneers (n= 5 replicates for each angle measurement; n= 15 for each roughness measurement)

Treatment	Contact angle (°)		Roughness (μm)
	Initial	After 5 s	
Douglas fir Control	123 (0.86)	14 (0.60)	7.87 (0.46)
Douglas fir 120	123 (0.84)	14 (0.79)	6.90 (0.75)
Douglas fir 320	130 (1.02)	25 (1.10)	4.86 (0.50)
Maple Control	126 (1.10)	24 (0.30)	6.14 (0.73)
Maple 120	118 (1.78)	17 (0.80)	5.12 (0.52)
Maple 320	124 (1.59)	28 (1.52)	4.23 (0.32)
Oak Control	136 (1.86)	23 (0.65)	6.97 (0.51)
Oak 120	113 (2.35)	16 (1.33)	4.28 (0.64)
Oak 320	127 (2.60)	25 (1.30)	2.52 (0.23)

Note: Values in parenthesis are standard deviations.

Composite Manufacturing

All samples (balanced, unbalanced, and unidirectional) were made as four-layer laminates using a simple hand lay-up technique. Before starting the lay-up process, the matrix material was prepared by mixing the general purpose polyester resin and the catalyst MEKP at a weight ratio of 100:2 under controlled laboratory conditions at a temperature of 20 °C and relative humidity of approximately 65%. Table 2 shows the average mass fractions of the wood and polyester in all composites. The resin content varied among treatments as each veneer absorbed different amounts of resin.

After measuring the mass of each individual veneer sheet, the lay-up process began. Using a paintbrush, the prepared mixture of resin and catalyst was applied to the veneer. A squeegee was used individually for each lamina to eliminate air bubbles and distribute the resin evenly over the surface. The applied pressure was not measured but was rather low, with the resin being pushed over the surface with a hand held squeegee. The approximate thickness of resin/catalyst on each side of veneers was approximately 0.17 mm. A schematic of the balanced and unbalanced 4-ply lay-ups is shown in Fig. 1. The first lamina was a resin-coated veneer sheet. The second lamina was added on the top of the first layer with the grain running in the opposite direction. The orientation of the third layer depended on the type of composite: in balanced cross-ply composites, the direction of the third layer was the same as the second layer, in unbalanced it was opposite. The last layer was always glued with opposite orientation to the third layer.

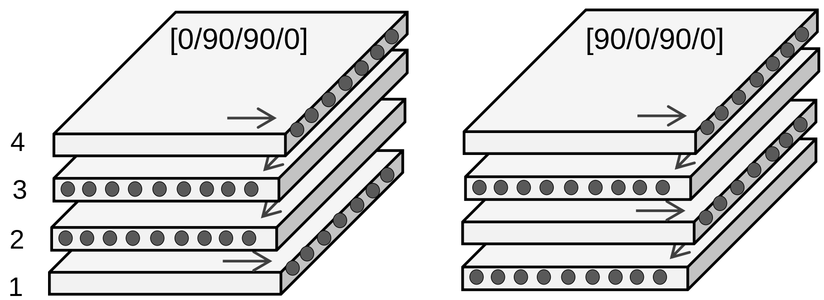

Fig. 1. Lay-up of two cross-ply wood composite laminates made of four laminae; balanced (*left*), and unbalanced (*right*); arrows indicate the fiber direction. Resin applied to the top face of the layers one to three is not shown here.

A balanced alternating lay-up is universally used in the production of plywood (wood composite panels made of wood veneer sheets and phenol-formaldehyde resin) and limits laminate warping and dimensional change (Dietz 1949; U.S. Forest Service 1999). In this study, however, both balanced and unbalanced configurations were manufactured to compare the effects of the lay-ups on the impact properties of the polyester composites. Samples were compressed using a flat metal block that generated a pressure of 500 Pa. The applied pressure assisted in resin distribution and made the final laminates flat. The wood/polyester mat was set aside for curing for about 24 h. The samples were then demolded and edge-trimmed.

The glass fiber-reinforced polyester composite was made by first cutting the woven glass fiber cloth into the appropriate mold size. The mold was covered with a thin layer of release agent, and then filled with the reinforcement. The glass fiber reinforcement was woven E-Glass fiber cloth. Therefore, there was no 0/90 configuration for composites made of this fiber. A squeegee was used to spread the resin over the glass fiber sheet. The rest of the manufacturing process was similar to that of the wood composite samples. The glass fiber/polyester composite contained only glass fiber and polyester resin as described in Table 2. The goal of producing these laminates was to compare the results of impact testing with the wood/polyester samples. After making the wood composite samples, the average amount of polyester resin in each lamina was calculated. Douglas fir veneers contained 4.75 g of resin and oak veneers contained 3.28 g of resin in each lamina and had the highest and lowest resin absorption, respectively. Each maple veneer absorbed an average of 4.02 g of resin during the lamination process.

Impact Test

The energy absorbed by the various polyester composites samples was measured according to ASTM (ASTM-D5420 2010). To limit sample movement during impact, a clamping assembly with precise dimensions was made of medium-density fiberboard (MDF). Samples were then placed between two pieces of MDFs of 254 mm by 241 mm with a 93 mm by 80 mm opening. These pieces were clamped by eight wood screws, equally spaced along the perimeter of the frame with a torque of 20 Nm each (Haghdan *et al.* 2015). Impact tests were performed by pushing a 224-g chrome steel ball through holes in a guide tube at various heights and the damage to the samples was noted. The presence of any crack or split created by the impact of a falling mass visible by the naked eye under normal laboratory lighting conditions was defined as failure. Specimen failure can also include complete shattering, radial cracking within or outside the impact area, brittle splitting of the bottom surface, and glass-type breakage. The potential failure energy was then computed using Eq. 1,

$$\boldsymbol{E = hwf} \quad (1)$$

where E is the impact energy [J], h is failure height as applicable [mm], w is the mass [kg], and f is factor for conversion to joules (9.81×10^{-3} for h measured in mm and w measured in kg).

Contact Angle Measurement

The wetting behavior of the wood veneer sheets of different species was characterized by contact angle measurement. Two grit sizes (120 and 320) were used to determine the effect of sanding on veneer wettability. Angle measurements were conducted with a Contact Angle Goniometer connected to a high speed camera capable of generating 25 images per second. A drop of polyester was applied to the wood surface using a pipette. The image of the liquid drop was captured immediately after the polyester droplet was deposited on the wood surface and every 0.25 s for 15 s.

The images were then processed with the commercially available software ImageJ (Stalder *et al*. 2006, 2010). Using the sessile drop method, the contact angle of the polyester drop was determined by aligning a tangent with the sessile drop profile at the point of contact with the wood surface. Each contact angle value was taken as the average of five different measurements on different parts of the veneer surface. The results were evaluated using ANOVA (Bulmer 1979) to determine whether the differences between treatments were statistically significant.

Surface Roughness Measurement

A laser confocal microscope was used to measure surface roughness of the veneers before and after sanding. Before surface roughness measurements, all veneer samples were conditioned at 20 °C and 65% relative humidity until constant mass was achieved. After conditioning, the average surface roughness (R_a) of the samples was determined according to ISO (ISO-4288 1999). Fifteen veneer samples 50 mm by 50 mm in size were used for each test group to evaluate surface roughness. Results were statistically analyzed using analysis of variance (ANOVA).

RESULTS and DISCUSSION

Laminating Process

Figure 2 shows the unidirectional and cross-ply wood veneer/polyester and woven glass fiber/polyester composites after curing and edge trimming. All composite laminates were observed under a light microscope to inspect the cross sections and determine the presence or absence of polyester resin among the layers. Laminates of Douglas fir veneer and polyester matrix were laid flat without edge-twisting and a well-bonded composite was achieved. The manufacture of maple/polyester composites was possible using the hand lay-up technique, but complete adhesion between the four layers was not accomplished. It was expected that balanced lay-up with the grain directions of adjacent veneers perpendicular to each other would reduce shrinkage and warping in the laminates. Despite this reduced edge-twisting in the oak/polyester laminates, viable flat samples could not be manufactured.

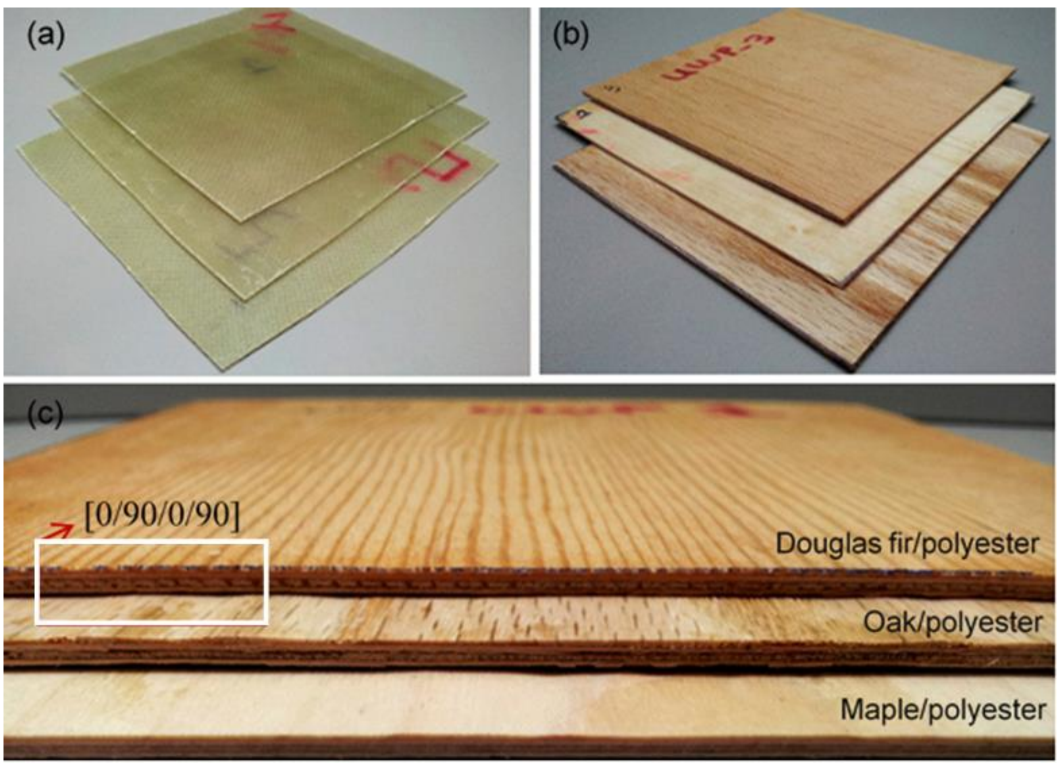

Fig. 2. Composite laminates after curing (a) glass fiber/polyester, (b) unidirectional wood/polyester, and (c) cross-ply wood/polyester

According to ASTM-D 5420 (2010) for the impact testing of polymer composites, all samples should be flat with no imperfections. Hence, oak and maple laminates were not impact tested. The Douglas fir laminates were visually examined to ensure they were free of cracks and other obvious imperfections before impact testing.

The medium-textured anatomy of Douglas fir contributed to better resin distribution by evenly absorbing it, resulting in flat laminates of this species compared to those of maple and oak. In contrast, there were difficulties in manufacturing oak laminates even when using a balanced lay-up. Resin was easily absorbed in oak veneers during the lamination process, but since oak has large diameter-pores, the resin flowed out of the bottom face and only a small amount of resin was retained. The maple and oak veneers used in this study were cut tangentially, and the Douglas fir veneer was cut radially. Ring-porous oak veneers with the coarse texture twisted during the curing process as they shrank more in the tangential direction. Rays in radially cut veneers usually restrain dimensional change. Softwoods with gradual earlywood-latewood transition (such as Douglas fir) and diffuse porous hardwoods (maple) have lower shrinkage rates because of their finer texture. Veneer shrinkage was also noticed in tangential maple veneer laminates, but was controlled using the balanced lay-up. In addition to the effects of veneer texture on the lamination process, the heat generated from the exothermic curing reaction in polyester composites may have also contributed veneer deformation (Vargas *et al*. 2012).

Microscopic Observation

To determine the color of the polyester resin under a light microscope, a block of polyester was made with one wood veneer submerged inside the resin block. After curing, the block was cut, sanded, and the surface was blown off using compressed air for observation under the microscope. As shown in Fig. 3, the polyester resin, which appears as white color, was absorbed by both earlywood and latewood tracheids, mostly however by the earlywoods. The black areas at the top and bottom of the veneer are corresponding to the polyester block material. Some air bubbles appeared at the interface.

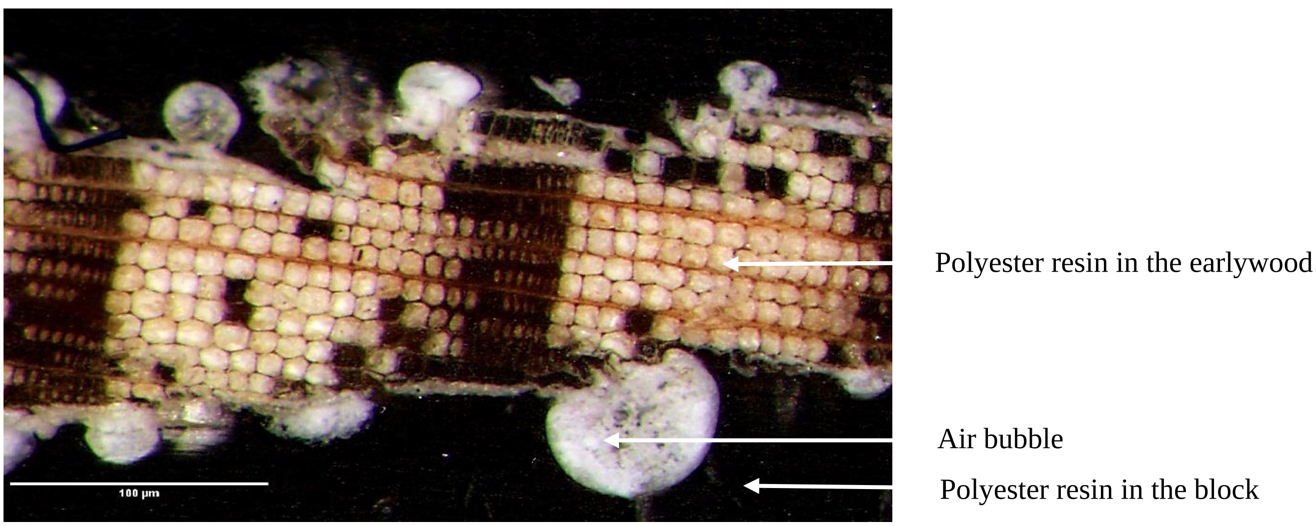

Fig. 3. Light micrograph of the resinated veneer sheet in a polyester block

Light micrographs of wood/polyester composite laminates are presented in Fig. 4. The polyester matrix is visible as a white strip between the layers of Douglas fir unidirectional laminates, as shown in Fig. 4a. The four Douglas fir veneer sheets were laid flat without any twisting. All layers were wetted by the polyester, and there were no gaps between them. The good adhesion of the Douglas fir composite is a contributing factor leading to flat laminates. This good adhesion was also seen in the cross-ply samples where all cross sections of longitudinal tracheids were filled with the polyester resin, as shown in Fig. 4b. In contrast, unidirectional maple/polyester composites had voids and areas lacking resin. Moreover, the polyester strips between other lamina were not as flat as those found in the Douglas fir samples, as shown in Fig. 4c. Cross-ply maple samples exhibited a neat flat laminate, as shown in Fig. 4d, but this was not observed consistently in all samples subjected to this treatment.

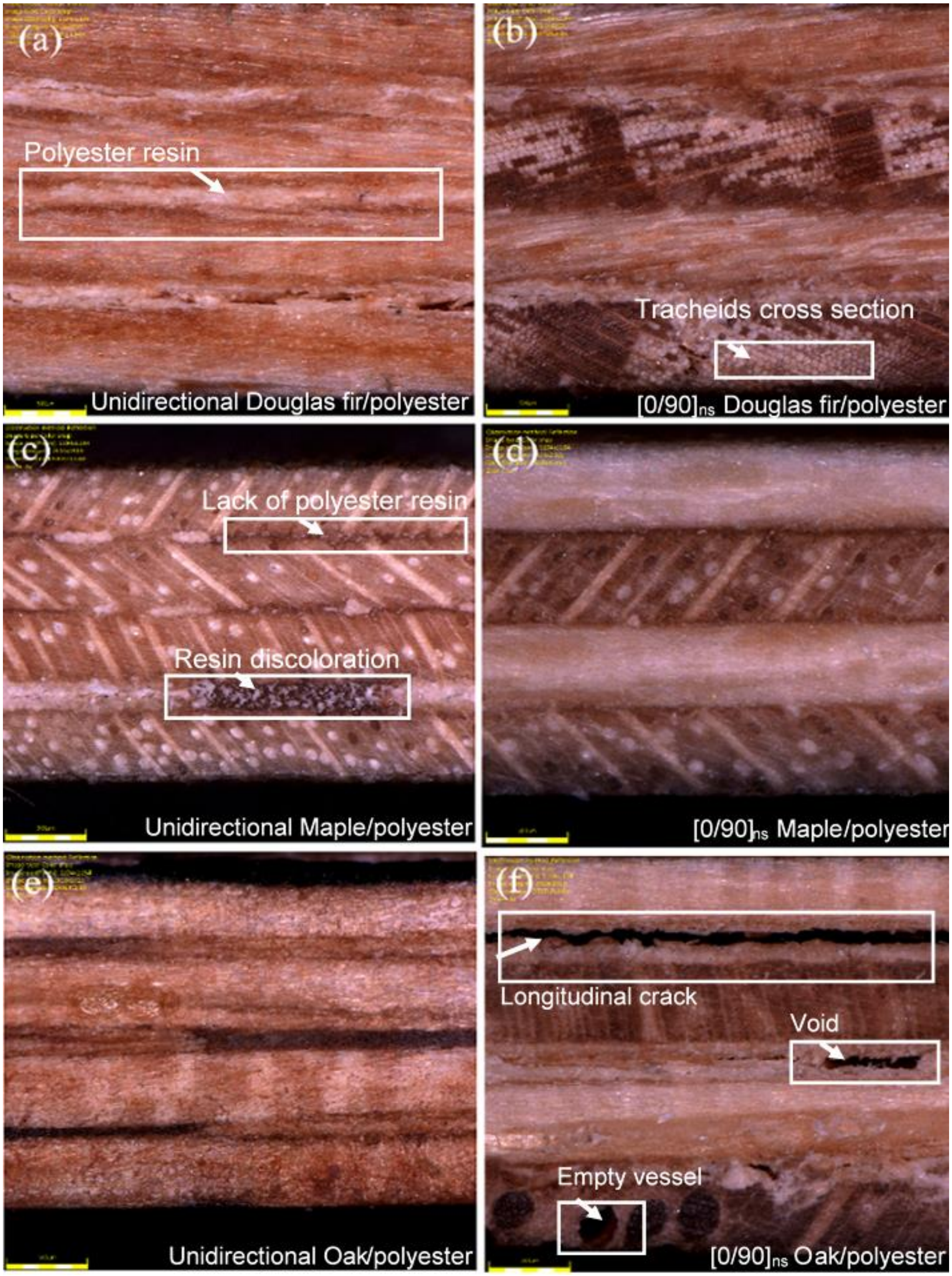

Fig. 4. Light microscopic images of unidirectional and cross-ply polyester laminates: (a) polyester as a white strip between layers; (b) filled cross sections of longitudinal tracheids with resin; (c) resin discoloration and area of lack of polyester; (d) neat adhesion among layers; (e) insufficient adhesion and voids; and (f) crack, void, and vessel elements

Figure 4e clearly shows areas lacking resin in oak/polyester unidirectional composites. For cross-ply oak samples, a considerable amount of voids and empty wood vessels were observed, as shown in Fig. 4f. As explained earlier, the polyester resin was observed as a white strip between the veneer sheets. This layer in the Douglas fir samples was uniform and had approximately constant thickness (Fig.4a), whereas the thickness of this layer in the maple composite was much less uniform (Fig. 4c). To achieve consistent resin thickness in all laminates, an automated manufacturing method would be better than the hand lay-up technique used.

Figure 4f shows the presence of an intralaminar crack between the layers of the oak laminate. A very small band-saw was used to cut the boards and prepare them for the subsequent microscopic investigation. This preparation, however, resulted in longitudinal artifactual cracks in the oak composite, as poor adhesion among the layers made them more susceptible to cracking than the Douglas fir and maple laminates.

The void areas, areas without the presence of wood or polyester, appeared black under the light microscope, as shown in Fig. 4f. There are also resin discoloration areas where the polyester exists but has been discolored (Fig. 4c). The thermosetting resins have low thermal conductivity. The energy generated during the exothermic crosslinking reaction may increase the internal temperature of the thick laminates and result in discoloration (Sung and Hilton 1998). However, the laminates in this study were manufactured 2.5-mm thick and it is unlikely the heat generated during the curing process caused the discoloration. The specific constituents of the general-purpose polyester resin used in this study were unknown (confidential to the manufacturer) but for applications require extreme clarity and absence of color, a clear casting polyester resin, a water-white resin, can be used to avoid discoloration. As shown in Fig. 4f, there were empty vessel and vessels covered with wood dust. This was the result of the sanding performed before laminates observed with the microscope.

Fracture Mechanisms

Figure 5 shows the surface of Douglas fir laminate samples after the impact test. The type of failure was different for unidirectional and cross-ply composites. While failures of both unidirectional and cross-ply composites were brittle, there were more modes of fracture operating for the cross-ply samples, including longitudinal cracks and delamination of veneer sheets. Despite the greater energy absorption of cross-ply composites, they exhibited no sign of failure on their front surface. Figure 5a shows the front face of the unidirectional laminate after being hit by the impact ball. The crack initially formed on the first layer and then broke through each successive layer. Figure 5b shows the back face of this laminate. Longitudinal crack propagation along the fibers was accompanied by delamination of the third and fourth layers.

In contrast, the cross-ply laminates absorbed more energy than the unidirectional samples and did not exhibit any macroscopic sign of failure on their front surface, indicating that the higher impact resistance imparted by this treatment postponed crack initiation, as shown in Fig. 5c. The cross lay-up of the veneers stopped the crack propagation generated in the first layer of the laminate. This energy absorption mechanism continued until the last layer when fracture of the veneer on the back face was visible, see Fig. 5d. One would expect the unidirectional samples to be more brittle than the cross-ply samples as all fibers are aligned and there is no reinforcement in the transverse direction to resist splitting. The cross-ply samples, in contrast, are reinforced in this direction and as a result resist the splitting and exhibit an increase in impact energy. The bonding between the veneer sheets of the Douglas fir samples was sufficiently high that there were no significant differences between the balanced and un-balanced configurations.

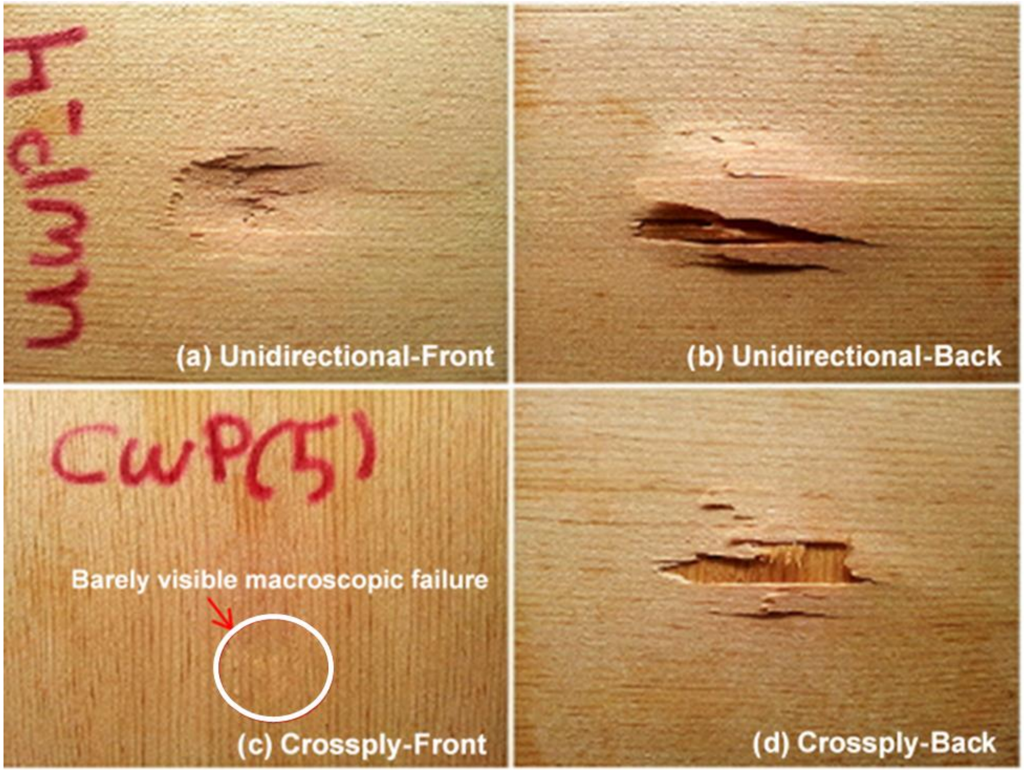

Fig. 5. Unidirectional and cross-ply Douglas fir laminates after impact testing: a) unidirectional, front surface; b) unidirectional, back surface, fracture in all layers; c) cross-ply, front surface; and d) cross-ply, back surface, controlled fracture in alternative layers

Impact Energy

The failure energy of Douglas fir/polyester and Glass fiber/polyester composite laminates was calculated using Eq. 1. The average failure energies of the treatments are shown in Fig. 6. To compare the impact energy values of different species and reinforcement configurations, one-way ANOVA was performed on the results using an α level of 0.05, showing that there was a significant difference between the Douglas fir unidirectional/polyester, Douglas fir balanced and unbalanced cross-ply/polyester, and glass fiber/polyester composites. The effect of lamination orientation (unidirectional and cross-ply) on the impact properties of the wood veneer/polyester composites was significant, with cross-ply laminates absorbing more impact energy (1.36 J) than the unidirectional laminates (0.96 J). Veneers in cross-ply laminates had more cracks in comparison with the unidirectional samples. The greater fracture of the veneers indicates the creation of more surface areas resulting in greater energy absorption.

A comparison between cross-ply Douglas fir/polyester and lab-made glass fiber/polyester composites showed that, despite the greater impact energy absorbed by the glass fiber composite, the difference between these two treatments was not statistically significant. The difference between balanced and unbalanced cross-ply composites was also statistically insignificant.

The determined impact properties of the laminates were compared with the findings of a previous study on thin composite plates (Haghdan *et al*. 2015). It was found that increasing laminate thickness significantly improved the impact energy absorption of wood composites. The mean impact energies of the four tested treatments of this study and the two composite plates of the previous study are presented in Fig. 6.

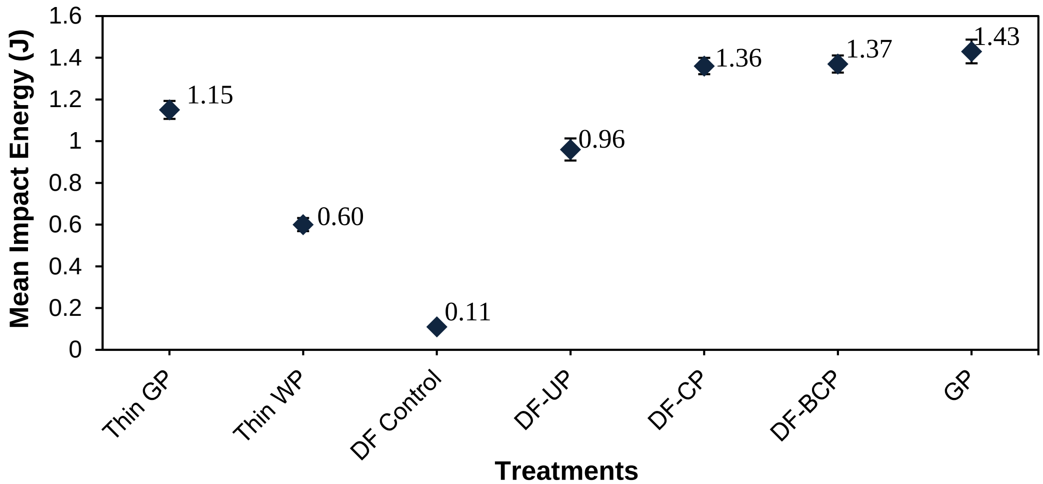

Fig. 6. Comparison of the mean impact energy of wood/polyester and glass fiber/polyester composite laminates (error bars represent 95% confidence intervals). Note: Impact energy values of Thin GP and Thin WP were taken from a previous study (Haghdan *et al*. 2015).

Wettability of Wood Veneers

The wettability of the veneer surface was characterized by measuring the contact angle of a drop of polyester resin on the wood surface (Fig. 7).

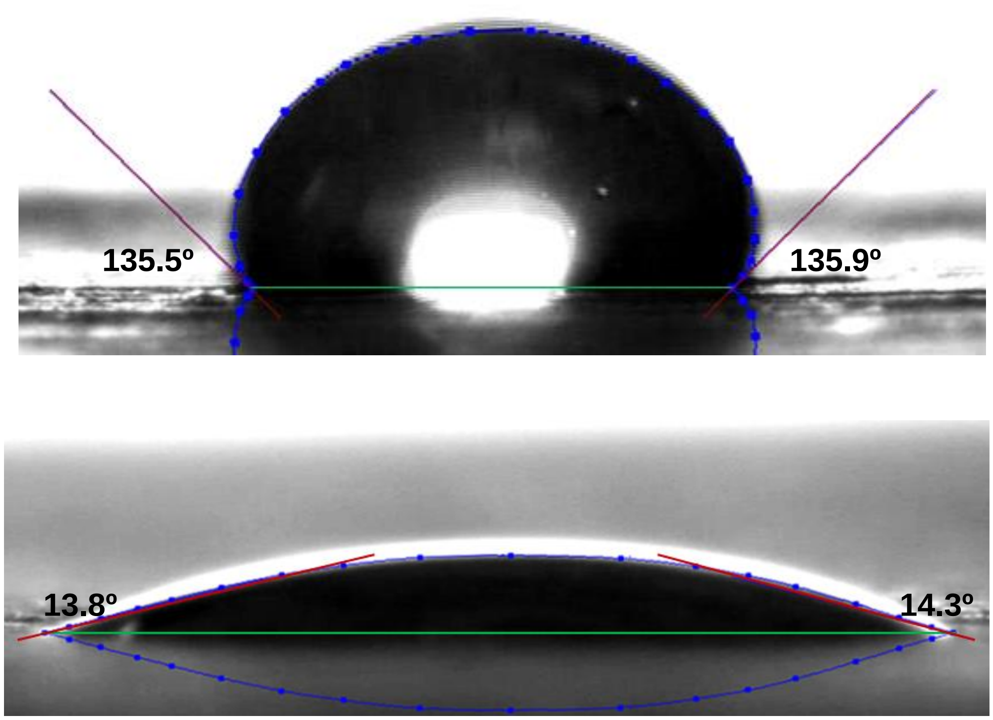

Fig. 7. Highest initial angle of polyester droplet on Oak Control (top), and lowest angle of polyester droplet after 5 s, DF 120 (bottom)

The resin used in this study was unwaxed acetone-free polyester resin. Acetone evaporation can significantly change the volume of the liquid; the applied resin did not have acetone but styrene with negligible evaporation. The mass of polyester resin was measured after it was poured in the aluminum foil, immediately afterwards and every 30 seconds for 5 minutes. The weight of the resin did not change over this time. Considering the duration of contact angle test was only 15 s, it was concluded that no resin evaporated.

The average initial contact angle and that after 5 s for both sanded and unsanded wood veneers are presented in Table 3. The lowest average contact angle, 14°, was observed for the DF 120 and DF Control after 5 s. The highest value, 136°, was the initial angle measured in the Oak Control. Typical droplet shapes are shown in Fig. 7. ANOVA showed that there was no significant difference between the left and right contact angles in all samples. However, significant differences in the average contact angles ($p < 0.05$) between all groups were found.

Figure 8 illustrates that the measured contact angles for a drop of polyester on the sanded and unsanded wood veneers decreased with time.

As shown, sanding the Douglas fir, maple, and oak veneer sheets with 120-grit improved their wettability by reducing their contact angles compared to the unsanded veneers. However, this improvement was not significant for Douglas fir veneers.

Sanding with 320-grit reduced the initial contact angle in the maple and oak controls, as shown in Table 3, but generally reduced the wettability of all veneers. The highest wettability to polyester among the species used in this study was exhibited by Douglas fir, followed by maple and oak. In the contact angle tests, the location of the polyester drop on the surface of the veneer was chosen randomly. This location could be either earlywood, latewood, or a combination thereof. Since the test was conducted in five randomly chosen spots, the results are assumed to represent the average contact angle.

As mentioned in the Materials section, the cells in Douglas fir and maple are smaller than those of oak (tracheids in softwood and pores in hardwood). When the polyester drops were placed onto the veneers, they were absorbed by the capillary action of these elements. This absorption is slower in oak wood as the adhesive force of large pores is smaller than that of the pores of Douglas fir and maple, consequently limiting the wettability of oak.

The 120-grit sandpaper cleaned the surface of the veneers from dust and contamination, creating a fresh, smooth surface by blowing off the contaminants using compressed air. The surface of the sanded Douglas fir veneer was much lighter in color indicating that the old surface had been removed. It is widely recognized that a fresh surface is created by sanding with 120 grit size with a subsequent increase in veneer wettability (Moura and Hernandez 2006; Jarusombuti and Ayrilmis 2011; Cappelletto *et al*. 2013; *Wan et al*. 2014). As shown in Fig. 9, the improved wettability was significant for maple and oak veneers when compared to the unsanded veneers.

Using 320-grit sandpaper made the veneer surface very smooth. The dust generated from sanding filled in the open pores and reduced the absorption of polyester. It should be noted that the effect of the 320-grit sandpaper was not significant on oak wettability as oak has very large vessels and the dust generated from sanding could not fill the pores. If a sanded hardwood veneer is preferred, medium grit size improves the veneer wettability.

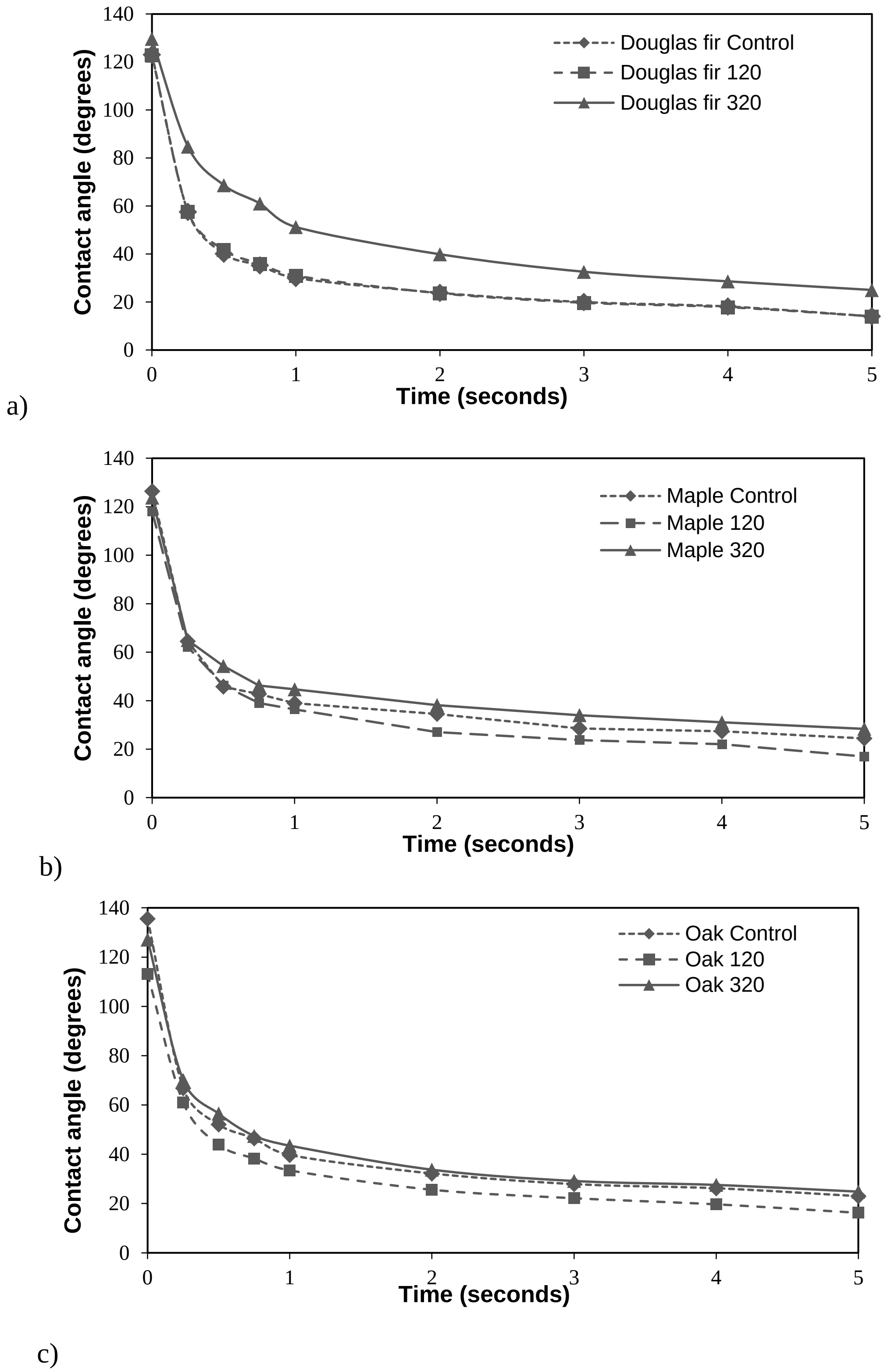

Fig. 8. Contact angle of polyester droplets on wood veneers (before and after sanding) vs. time: a) Douglas fir veneer; b) maple veneer; and c) oak veneer

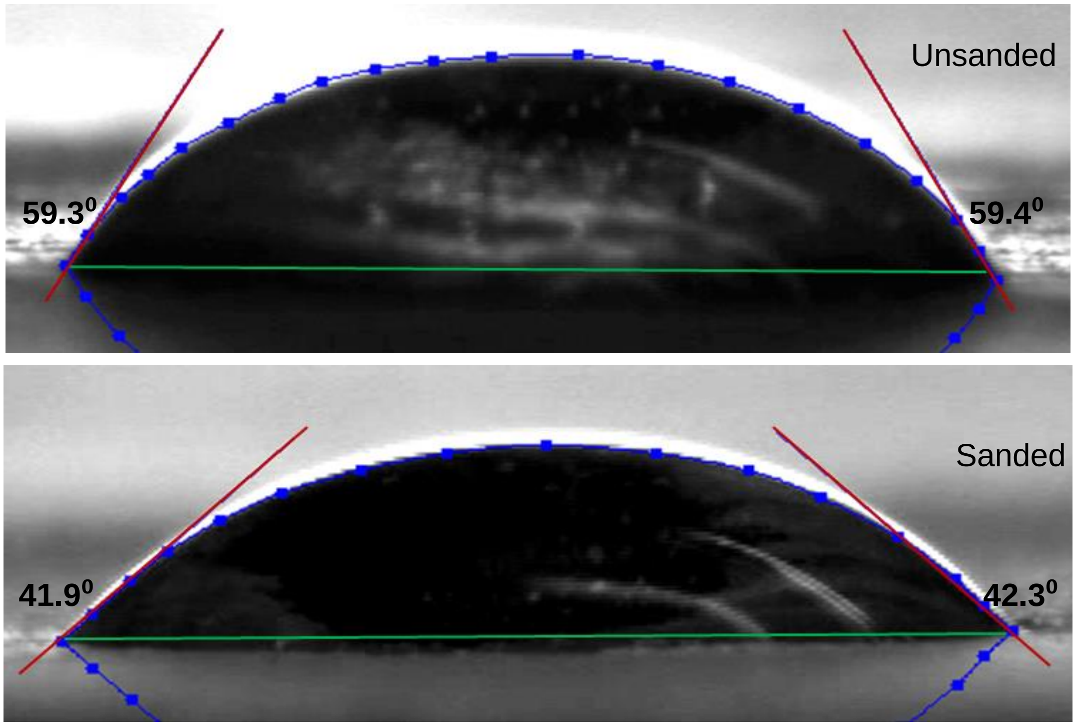

Fig. 9. Contact angles of polyester droplets on oak veneer before and after sanding with grit size of 120 (angles at 0.5 second)

The edge boundaries of the polyester droplet moved wider as the droplet spread; an example of that is presented in Fig. 7. The examination of the micrographs of Fig. 4 reveals that the resin did indeed penetrate into the veneer over long time frames. There was likely absorption of the resin into the surface of the veneer during the 15 s of the measurement, but it is not known how quickly this occurred.

Grinding, brushing, and sanding do not cause chemical modification of the material's surface; rather a clean surface results, and it has a characteristic structure corresponding to the composition of the material (Habenicht 2009). To chemically modify the surface, one should consider physical and chemical pre-treatment methods. Previous research findings, however, are not conclusive. For instance, Sinn *et al.* (2004) investigated the chemical changes of the veneers after sanding with different grit sizes. Spruce and beech veneers became slightly more acidic after sanding with 400 grit size while veneers sanded with medium grit size (grit 100), were less acidic on the outer surface. Considering that the largest grit size used in our study was 320, it is assumed unlikely to have significant chemical changes on the veneer surface.

Surface Roughness of Wood Veneers

The average surface roughness of the veneer sheets sanded with each grit size is given in Table 3. The results showed a reduction of the surface roughness of the veneers as the grit size increased. The Douglas fir veneer sanded with 320-grit had a smoother surface than that sanded with 120-grit. According to ANOVA, the effect of grit size was significant for each species. In all tested veneers, using higher grit size sandpaper significantly reduced the roughness. Similar statistical results were found for the effects of the type of wood species: the roughness differences among Douglas fir, maple, and oak veneers were also statistically significant.

A decrease in contact angle (Θ) leads to an increase in veneer wettability. The reduced roughness of the veneers sanded with the 120-grit sandpaper, increased their wettability to the polyester. The lower contact angles of these veneers as compared to those of control samples indicate this improved wettability. One exception was in the case of Douglas fir, for which there was no significant difference between the wettability before and after sanding with 120-grit paper.

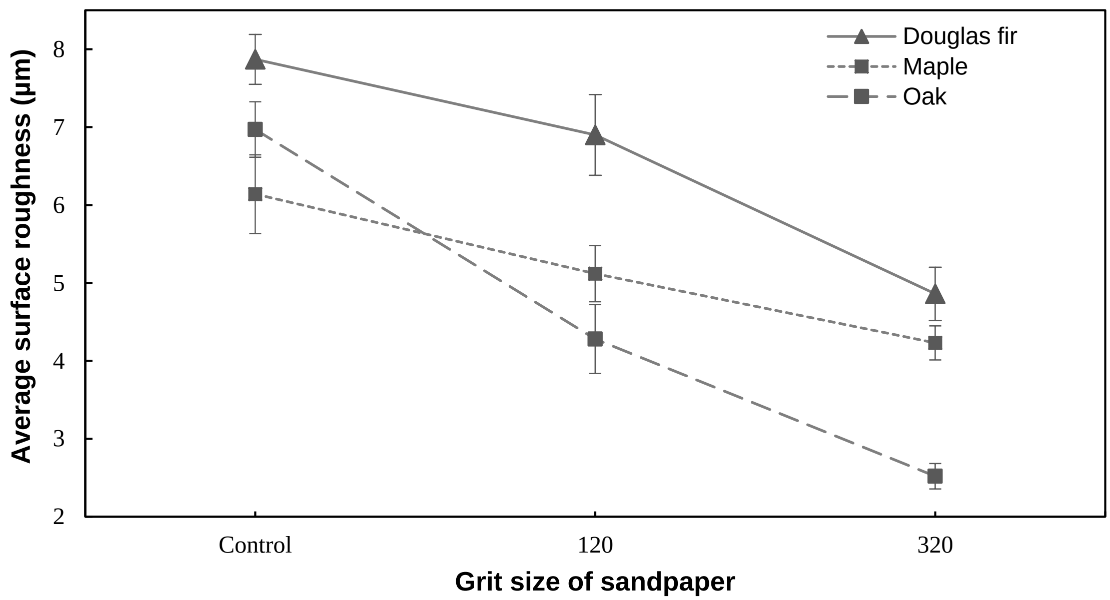

Fig. 10. Surface roughness of veneers as a function of sandpaper grit size; Error bars represent 95% confidence intervals.

The 120-grit sandpaper reduced roughness in the maple and oak veneers and increased their wettability to polyester by reducing their contact angles, as shown in Table 3. Using a higher-grit sandpaper, however, reduced the surface roughness in all used veneers, as shown in Fig. 10. This is in agreement with the results of a similar study on the effects of sanding (Sulaiman *et al*. 2009). Grit size affected surface roughness as sandpaper with higher grit size contains a finer abrasive (Demirkir *et al*. 2014). In fact, the finest sandpapers provided smooth surfaces having considerably less surface area to be wetted in comparison with the rougher surfaces. It is believed that using grit size higher than 120 significantly reduces the surface area available for wetting.

The very smooth surface created by 320 grit absorbed less resin than those sanded with 120-grit sandpaper. Figure 11 compares the surface roughness profiles of oak veneer (control, sanded with 120-grit, and sanded with 320-grit). Figure 11a shows the rough surface of the oak veneer. This roughness, however, decreased after sanding with 120-grit sandpaper, as shown in Figure 11b. The results of wettability testing showed that this level of smoothness reduced the contact angle. The smooth surface of the oak veneer after sanding with 320-grit sandpaper, as shown in Figure 11c, provide little resistance to resin flow over that surface.

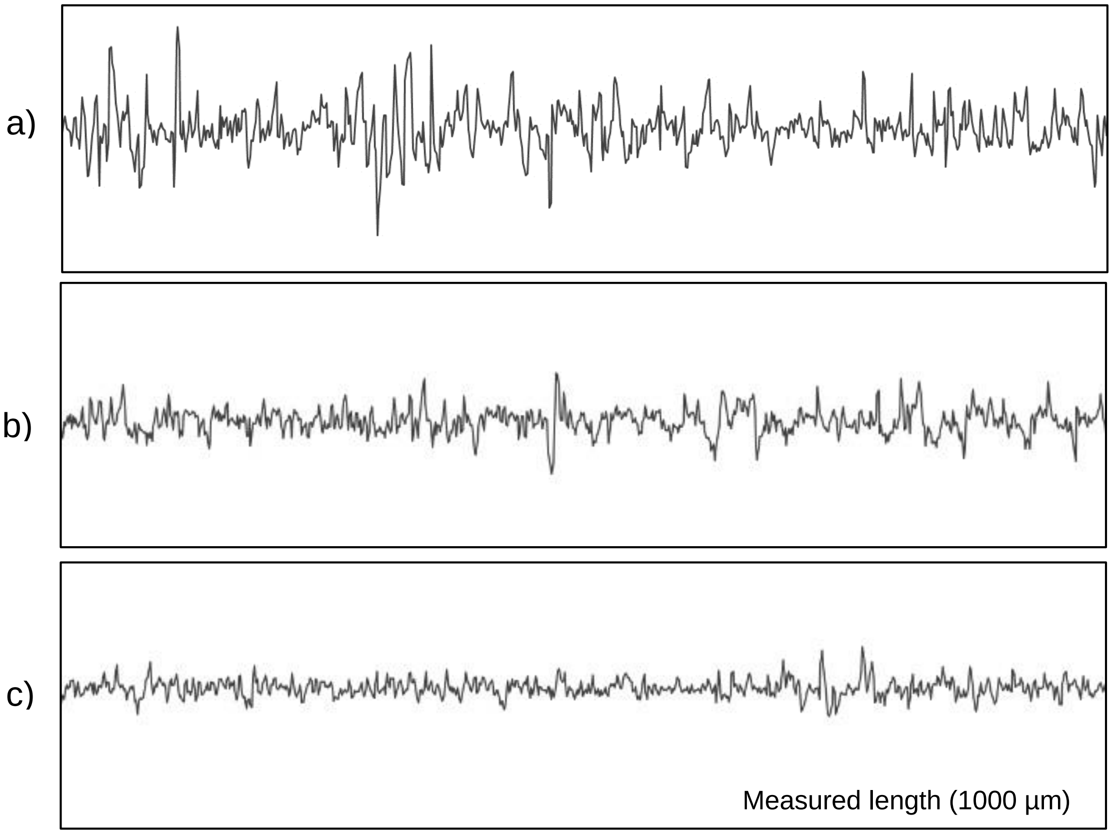

Fig. 11. Roughness profiles of the oak veneer before and after sanding: (a) control oak; (b) sanded with grit 120; and (c) sanded with 320-grit sandpaper

CONCLUSIONS

This study investigated the impact properties of wood veneer reinforced polyester composites, their fracture mechanisms, and the wettability of wood veneers to the polyester matrix. Based on the results obtained, the main conclusion points can be summarized as follows:

1. Douglas fir cross-ply laminates had an impact energy equivalent to glass fiber laminates, making them an interesting alternative to the use of synthetic fibers as reinforcement.
2. Increasing wood/polyester laminate thickness resulted in a higher number of fracture modes and greater impact energy absorbed by the composites.
3. The cross-ply veneer configuration in wood/polyester composites had significantly higher impact properties than the unidirectional ones. Using a balanced lay-up also limited twisting of the wood/polyester laminates.
4. The wettability of Douglas fir veneer was greater than that of oak and maple. Sanding with medium-grit sandpaper increased the wettability of the veneers.

The results of this study may help other researchers who work on developing new composites of wood and polyester for industrial applications.

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